Passive Solar Heated (PSH) Buildings

Training Module

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Aim

This training module is aimed at local people (non-engineers and non-architects) who want to build passive solar-heated buildings but are unaware of how to do so.

Architectural and structural understanding is not in the purview of this document. The reader is assumed to follow the best safety practices at all times.

Abbreviations Used

LEC – Low Energy Consumption

PSH – Passive Solar Heated

DG – Direct Gain

PSB – Passive Solar Building

EEB – Energy Efficient Building

IPS – Indian Patent Flooring

PCC – Plain Cement Concrete

RCC – Reinforced Cement Concrete

TMT – Thermo Mechanical Treatment

SW – Solar Wall

TW – Trombe Wall

Contents

1. What is PSH?

PSH means **Passive Solar Heated**. The main goal of a PSH is straightforward - To stay warm in the cold weather without using any active heating devices with only the Sun as the primary source of heating.

The strategy for a Passive Solar Building is simple:

- To **decrease heat loss** of the building insulating its envelope, control ventilation, and reduce air infiltrations.
- To **increase and store heat gains** with the help of passive solar techniques in order to provide thermal comfort to its users.

These two actions will reduce heating energy demand without decreasing thermal comfort.

Hence, a successful PSH combines two main factors – **Design** and the **material** used for construction.

There are five (3+2) inter-related components that work together to make the buildings energy-efficient –

1. **Collection** and absorption of the maximum amount of solar radiation during the day;
2. **Storage** of the heat collected from the suns' radiation during the day;
3. **Release** of this heat into the interior of the building during the night;
4. **Insulation** of the whole building to retain as much of the heat as possible inside the building;
5. **Ventilation** is limited to supply fresh air to the occupants only.

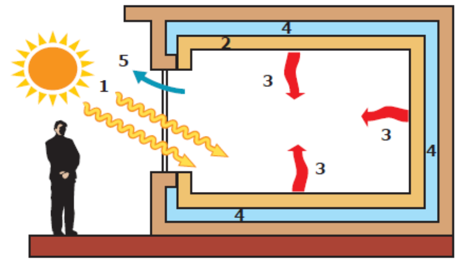

Figure 1: Passive Solar Building Concept [8] – Replace - refer first figure in topic Direct Gain: add a window on the front wall + flat roof

Appropriate location and direction are essential for the successful realization of a Passive Solar Heated Building. At least 6 hours of sunlight (daily) are recommended on average.

Further booklet has been divided into the following sections –

- Collection & Absorption
- Storage & Release
- Insulation
- Design Considerations
- Air Infiltraton Precautions
- How it all comes together: Solar Gain Techniques & Energy Efficient Buildings
- Case Study: HIAL

Collection & Absorption

2. Site Selection - Obstructions

Sun duration - 90% of sun radiations reaching the South face can be collected between **9 AM and 3 PM** in **Winter** (Solar time). So it is essential to collect sun radiation by **South face** during this period and to be sure that no obstruction can avoid this collection:

Distant obstruction - obstructions mainly created by mountains.

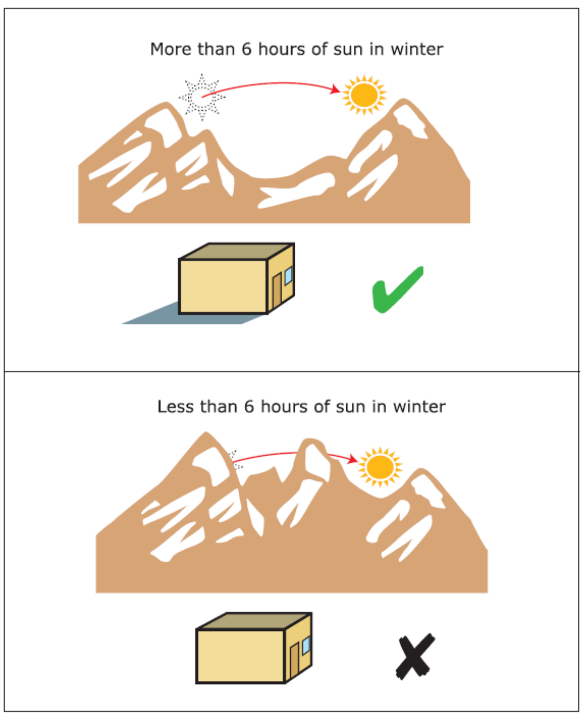

Figure 2: Distant Obstructions [8] – (change the color scheme & emphasis on shadow & remove door, window from the west)

Near obstructions - obstructions surrounding a PSH Building like other buildings or trees which can create shadows.

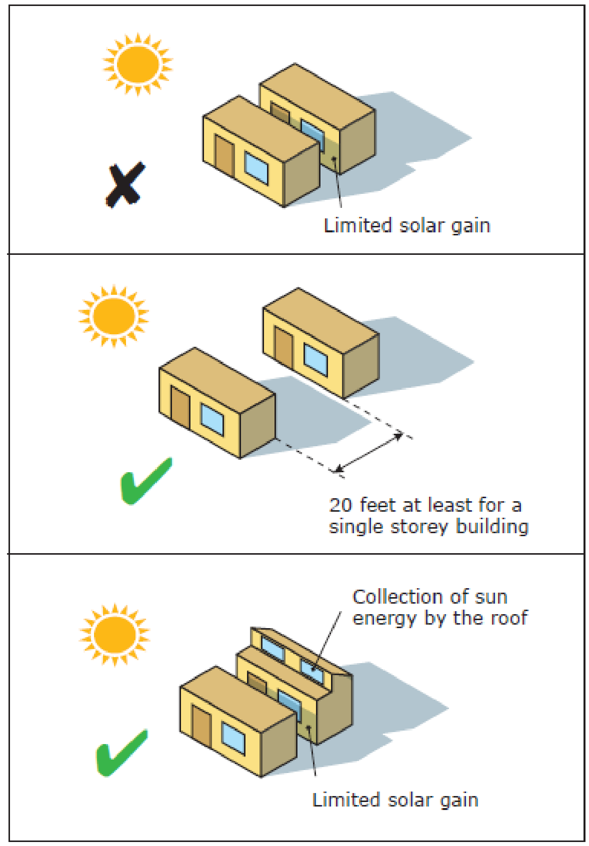

Figure 3: Near Obstructions [8] – (show sun path & show only glazing on the south instead of a door and a window + color scheme)

Thumb Rule: The distance to the obstruction shall be at least twice the height of the obstruction.

In case of impossibility to increase the distance to the obstruction, another solution consists in collecting solar radiation by the roof (as shown in the Figure – Near Obstructions).

Once the site has been selected, we need to think of sourcing the raw materials.

3. Orientation of the building

To design a PSB, it is essential to know well the main properties and characteristics of the Sun (especially the local sun path) in order to implement the most appropriate technical solutions to optimize solar energy collection in Winter and avoid solar gains during summers.

Sun path varies according to two main parameters:

- The location (latitude);
- The time (month, day, hour).

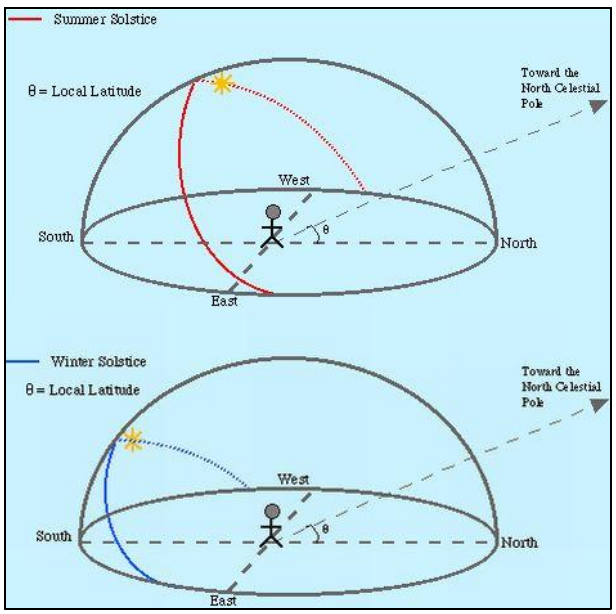

Figure 4: Path of Sun in the Sky in Summer (red line) and Winter (blue line) [15] – (bg – white; instead of person show a house)

With simple tools like sun charts which take into account these parameters, it is possible to predict the position of the Sun for any location throughout the year.

With this information, it is simple to evaluate if the chosen site to build PSB is suitable for collecting sun energy in Winter (effect of near and distant obstruction on solar energy collection) and designing effective solar protections to avoid overheating in summer.

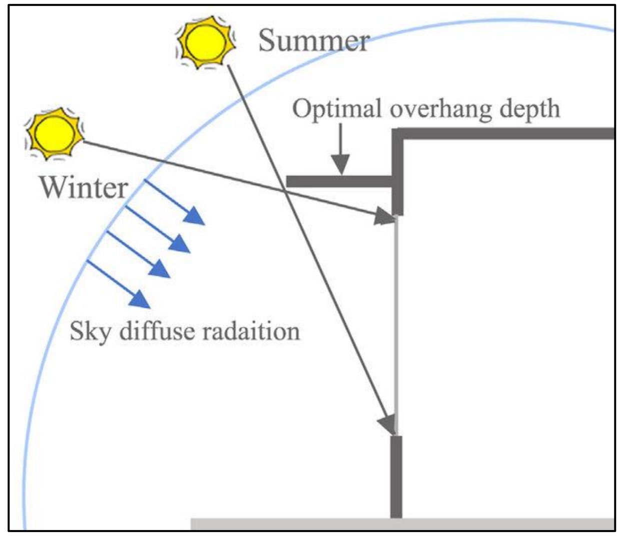

Figure 5: Position of sun in the sky during winters and summers [22] (color scheme)

Because of the Sun's position, which varies in the sky throughout the year, the faces of a building receive solar radiation throughout the year.

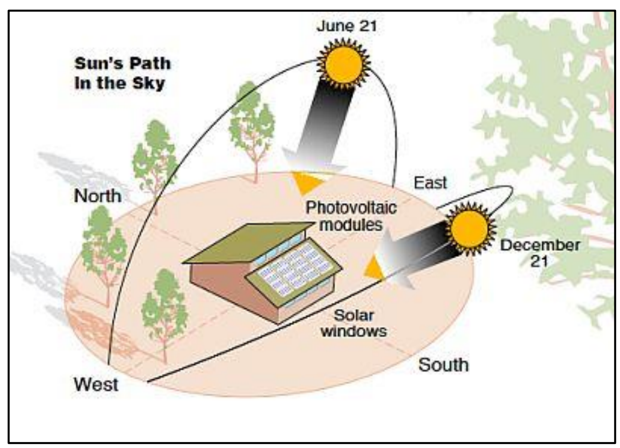

Figure 6: Variation of Sun Position in the sky during the year [16] (mountains instead of trees; flat roof, show glazing on the south (solar South), color scheme)

The following figure shows the distribution of solar radiation reached by each face of a building:

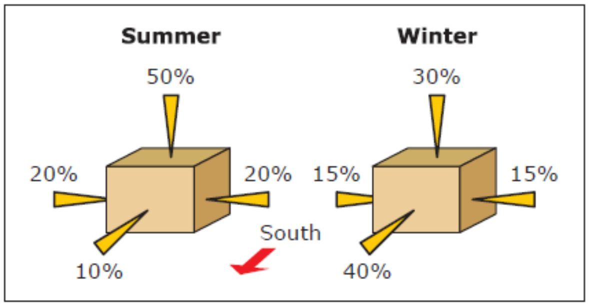

Figure 7: Radiation received by each face of a building in Ladakh [8] (show glazing and sun path, rotate the traingles 180 deg,& size based on percentage)

In Winter, the building face with the highest potential for sun radiation collection is the South face (40% of sun radiation received by the South face). Furthermore, this face is reached by only 10% of solar radiation in summer.

So, the **best choice** to collect solar energy in Winter and limit sun radiation in summer is to **orient buildings toward the South (Solar South/True South)**.

This orientation towards the South can be adjusted according to the building's use to improve the collection of solar radiation. For example,

- if the building is used during the **daytime**, it is crucial to catch sun radiation as soon as possible and **modify** the South building orientation **a bit towards the East**.
- if the building is used during **nighttime**, it is better to collect sun radiations until the end of the afternoon and so **turn the** South face of the building **a bit toward the West**.

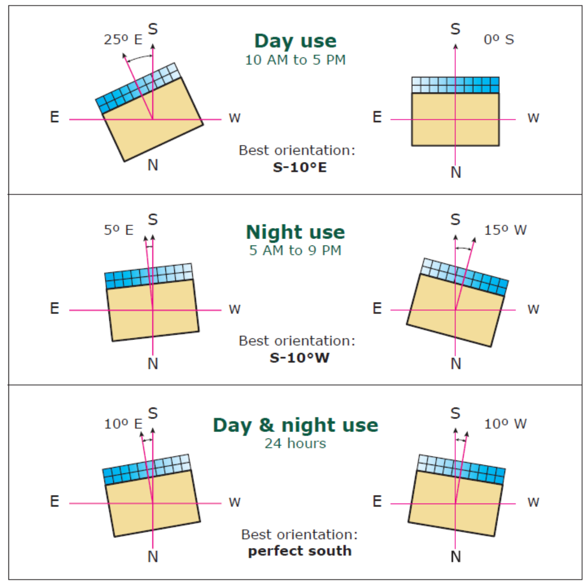

Figure 8: Building orientation according to building's schedule [8] (show overhang instead of blue glass; show sun in day use; moon & stars in night use; both in day & night use as shown in the figure on next page

Storage & Release

4. Thermal Mass

In building design, thermal mass is a property of the mass of a building that enables it to store heat, providing "inertia" against temperature fluctuations.

In simple terms, thermal mass is the **ability of a material to absorb, store and release heat.**

Materials used as thermal mass should be placed inside the room with a layer of insulation (between the exterior and the thermal mass wall or between the structural wall and thermal mass wall). This layer of insulation reduces the release of stored heat towards the exterior and facilitates the release of heat stored in the thermal mass wall towards the inside.

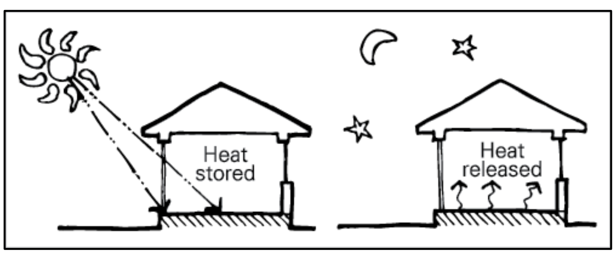

Figure 9: Thermal Mass in the Floor [14] (flat roof, overhang show only on south side)

Thermal mass can be implemented into the walls, into the roof (with RCC slab and insulation above, for example), into the floor (mud or cement slab without carpet), or the partition walls.

For an efficient daily storage/release of heat during the day and night, it is advised to have a high surface of thermal mass with a small thickness (4 inches to 1 ft maximum). For the same volume of thermal mass, if the thickness of thermal mass is higher (more than 1 ft), the storage/release of heat during day and night will be less efficient (less reactive) but useful in case of accumulation of cloudy days. In Ladakh, it is rare to have more than three consecutively cloudy days. In this case, the daily storage/release of heat thanks to thermal mass should be preferred (high exchange surface, low thickness of thermal mass).

Generally difficult to calculate with simplified calculations - requires the utilization of specialized software called Dynamic Thermal Simulation.

Insulation

5. Heat Loss in a Building

If the temperature inside the building is higher than the temperature outside (winter case), a flow of heat is created between inside and outside. The direction of this flow goes from inside to outside.

Heat is the **energy transferred** from one body to another due to a temperature difference.

Suppose two bodies at different temperatures are brought together. In that case, energy is transferred—i.e., heat flows—**from the hotter body to the colder.**

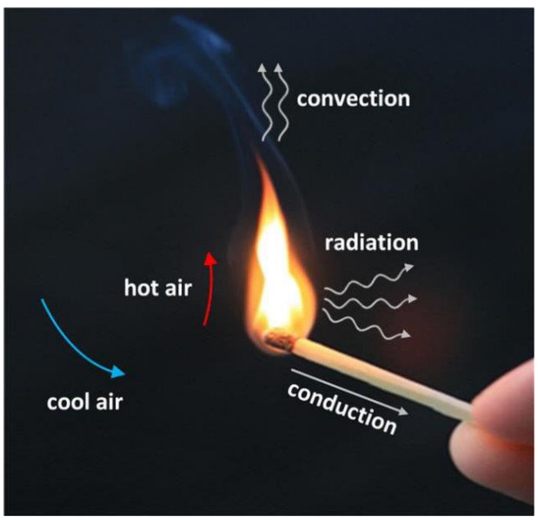

Figure 10: Modes of Heat Transfer [5]

The vital distinction between heat and temperature is that **heat** is a **form of energy. In contrast,** temperature is a measure of the amount of that energy present in a body.

The SI unit of Heat Energy is Joules (J). [4]

There are **three modes** of heat transfer, which can be described as –

1. The transfer of heat by **conduction** in solids or fluids at rest,
2. The transfer of heat by **convection** in liquids or gases in a state of motion, combining conduction with fluid flow,
3. The transfer of heat by **radiation** takes place with no material carrier.

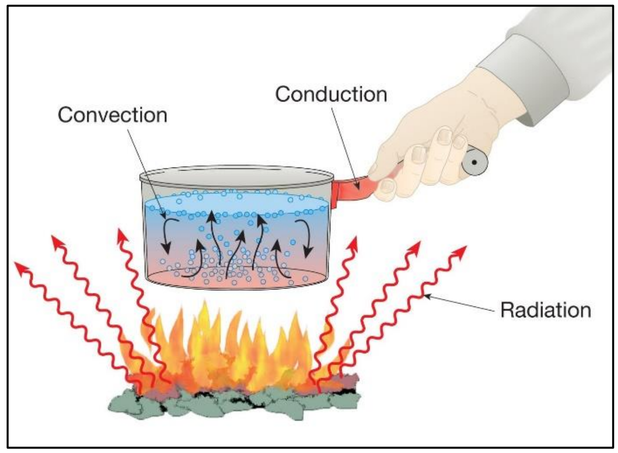

Figure 11: Modes of Heat Transfer [6]

The major **heat loss of a building** can be divided in two types:

1. Heat loss by **conduction** through the envelope of the building (walls, roofs, floors, windows, doors);
2. Heat loss by **convection** through exchange of air between interior of the building and exterior (mostly by air infiltration but also sometimes by mechanical or natural ventilation)

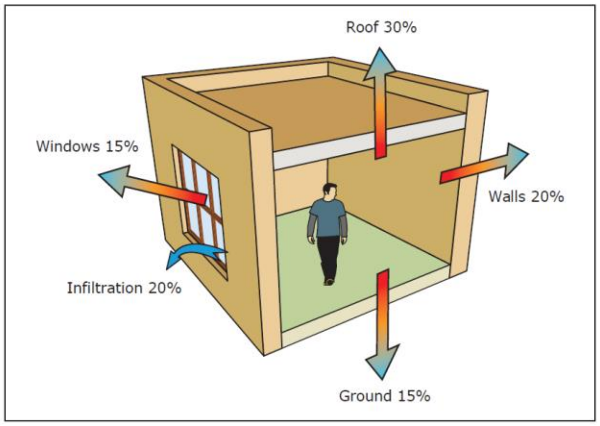

Figure 12: Heat Loss in a Building in Ladakh and similar climates [8] (show door for infiltration in the empty wall & color scheme)

6. Insulation techniques

Insulation of the building or a house is needed and essential to keep inside the energy collected from the Sun during daytime (PSB) or retain the energy released by the heating system as much energy as possible (EEB).

The **lower the material's thermal conductivity** is, the **better** the material can **insulate**. It is advised to use the values published in the ECBC (Energy Conservation Building Code of India).

Thumb rule: To simplify and remember which kind of material can be used as insulators, a simple rule can be used:

1. Light materials (low density) like straw, wood shaving, polystyrene (…) are generally **good insulators,**
2. Heavy materials (high density) like stone, mud, and cement (…) are **bad insulators**.

Insulation level	Material	λ [W/m°C]	Benefits	Drawbacks
Very Good Insulator	Polyurethane	0.032		
	Polystyrene	0.04		
	Rockwool	0.04		
	Glasswool	0.04		
Good Insulator	Sawdust	0.07		
	Straw	0.08-0.12		
	Wood Shavings	0.10		
	Plastic Bottles	0.10		
Medium Insulator	Plywood	0.14		
	Wood	0.18		
	Cardboard	0.20		
Bad Insulator	Rammed Earth	0.90		
	Mud	0.90		
Very Bad Insulator	Concrete	1.8		
	Stone	2.5-3		

Table 1: Insulation Level of Usual Materials [8]

6.1. Roofs

Warm air rises to the top of the house which increases air pressure near the ceiling. The difference between the pressure at the top and outside on a cold day then forces the warm air through any crack, crevice, or gap.

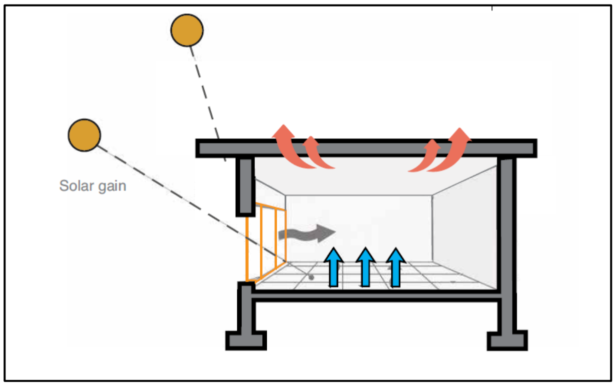

Figure 13: Heat Loss through the roof [24] (either add ground or remove the base legs)

Furthermore, this high pressure at the top of the room also creates low pressure near the bottom of the house, hence, pulling cold air inside through any openings around the foundation. This leads to heat loss. Insulation should be added to the roof to prevent the heat loss, which maintains the indoor temperature and leads to savings in energy cost.

Insulation can be added from the inside or from the outside:

1. **Insulation on the outside** - The main advantage of this technique is that it provides sufficient thermal insulation internally, while the slab can acts as a thermal mass. This solution consists in installing an insulation layer (eps , xps or perlite vermiculite mixed with concrete) above the rcc slab and protect it with an efficient waterproof layer.

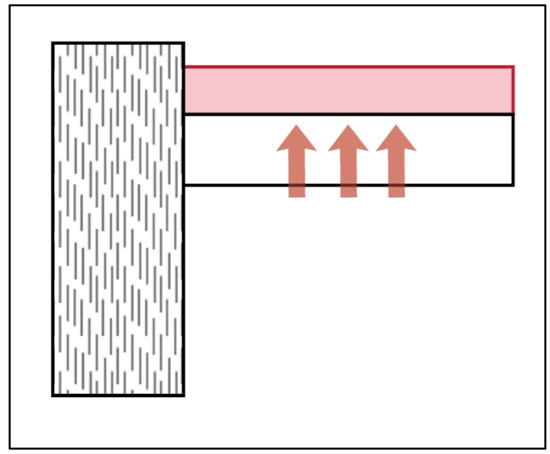

Figure 14: Insulation on the outside (add marking for roof)

2. **Inuslation on inside –** This solution consists in installing insulation below the structural layer of the roof (above false ceiling or above flat part of the roof). This technique sometimes may not be efficient due to formation of thermal bridges. The slab may also crack due to thermal stress.

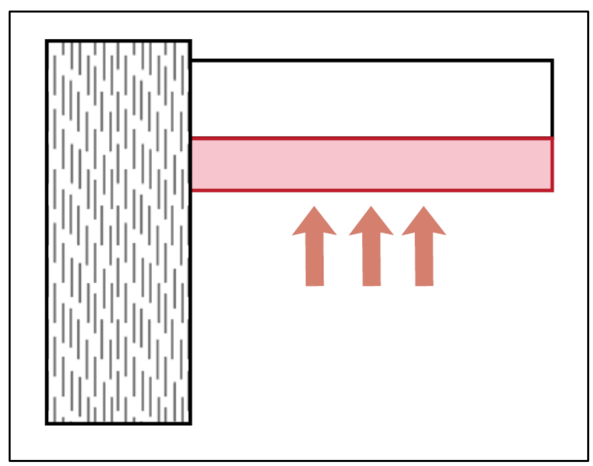

Figure 15: Insulation on the inside of roof

6.2. Walls

1. Inner insulation –

Figure 16: Inner Wall Insulation (need similar illustration)

2. Insulated Double Wall –

Figure 17: Insulated Double Wall (need similar illustration or HIAL Picture)

6.3. Floor

1. **Vertical insulation** - Vertical insulation is suitable for day-use and day & night or night-use buildings. This solution is generally cheap and easy to implement. Continuity with wall insulation can be implemented to avoid thermal bridges. The depth shall be at least up to the frost level.

Figure 18: Vertical Insulation (similar illustration)

2. **Horizontal insulation** – Horizontal insulation is advised for day & night or night-use buildings. Xps is required below a concrete slab reinforced by an iron net. Continuity with wall insulation can be implemented to avoid thermal bridges. An alternative solution consists in replacing rcc floor by mud floor and branches to reinforce it. The xps layer is replaced by sawdust in bags.

Figure 19: Horizontal Insulation (need similar illustration)

3. **Alternative: Insulation with Polymattress** - This solution consists in installing insulation with the help of poly mattress (thickness = 12 mm) in priority on the corners of floors/outside walls (2 to 3 ft vertically and 3 ft horizontally) to limit thermal bridges created by foundations. Poly mattress layers can be protected by plywood (vertically) or mattress (horizontally). In option, the rest of the floor can also be insulated to improve floor insulation efficiency.

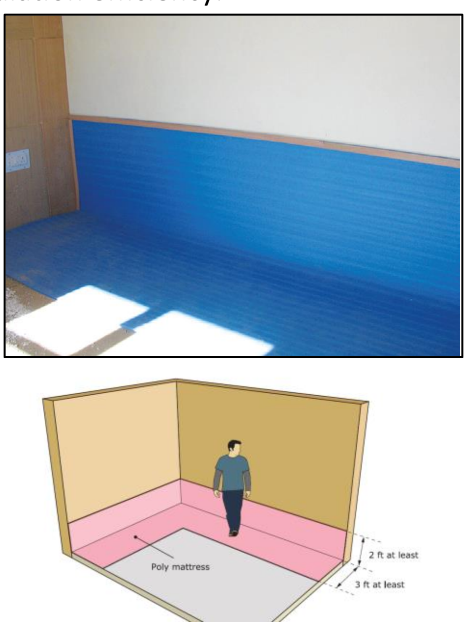

Figure 20: Insulation with Polymattress (need similar illustration – remove person)

6.4. Doors & Windows

To limit heat loss during winter night time, the doors of LEC rooms should be insulated (especially if they are in contact with the exterior).

To insulate doors easily, **sawdust** can be used to fill air gaps created by the wooden frame of doors.

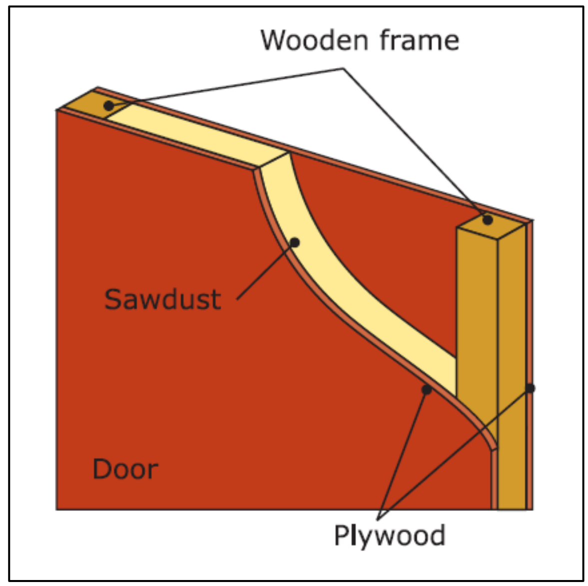

Figure 21: Insulation Technique for a Door [8] (color scheme)

As for windows, insulation of doors' ledges can be envisaged, especially if doors are in direct contact with the exterior.

Integrating a window on a wall can create or a weakness of a discontinuity thermal insulation at the intersection between window frame and wall. To limit heat loss, windows ledges should be insulated with EPS (at least 1 inch) and cover it with plywood (6 mm). If EPS is not available, wooden planks or plywood can be used.

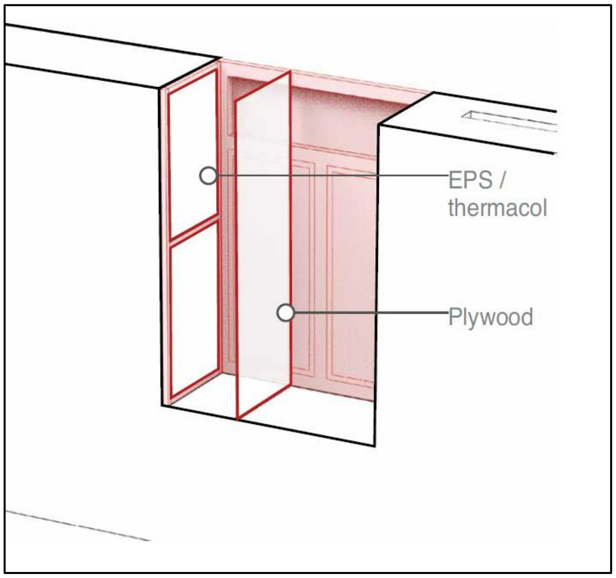

Figure 22: Insulating Window Ledges [24]

7. Thermal Bridges

Thermal bridges (also called cold bridges) are **weaknesses or discontinuities of thermal insulation of the building envelope**. They are situated in every corner and junction of constructions (Fig. 7).

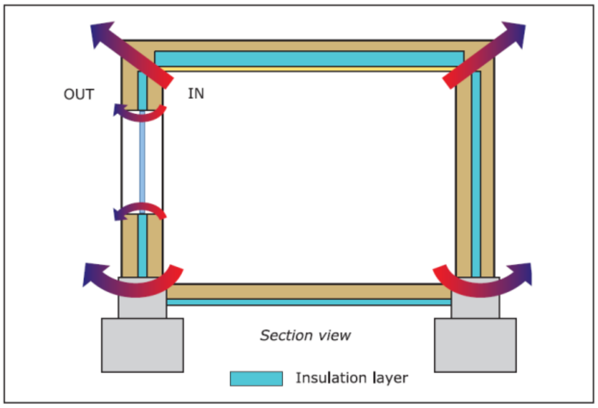

Figure 23: Building with thermal bridges [8] (show a wall with a window in the front s.t. it looks like a house; make OUT & IN text more prominent; color scheme)

Heat loss created by **thermal bridges** can represent **10 to 15% of total heat loss** in a standard building and more (in proportion) in LEC buildings if they are not removed or limited.

The main rule to limit heat loss by thermal bridges consists of joining each wall's thermal insulation (example: joining wall and roof insulation – as shown in Fig. 8).

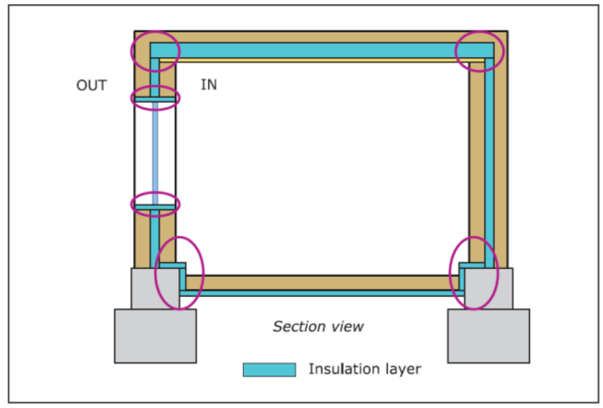

Figure 24: Building without thermal bridges [8] (color scheme; show arrows representing heat reflecting back into the room)

Furthermore, some additional thermal insulation can be added to reinforce the thermal insulation of the envelope (for example: adding insulation on the ledges of windows).

Design Considerations

8. Size and Shape of a PSH

To minimize heat loss towards exterior, a good way is to find a building shape that can offer the required volume with a minimum envelope surface (which will be directly in contact with the exterior).

To assess if the building shape is compact, a coefficient called "surface-to-volume ratio" can be easily calculated:

$$\text{Surface to volume ratio} = S/V = \frac{\text{Total enveloppe surface of the building [sqft]}}{\text{Total volume of the building [cqft]}}$$

The smaller the surface-to-volume ratio is, the lower the heat loss of the building is.

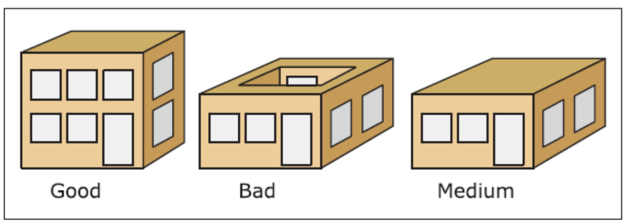

Figure 25: Building shape – Surface to Volume Ratio [8] (color scheme, all buildings should have same height (just ground floor), depth of medium building should be double the good building)

The lower the ratio between the **South face** and **floor surface**, the more difficult it is to heat the room with passive solar techniques.

Dimension	Limitaton
Width	Width <= 14 ft.
Height	Height <= 8.5 ft.
Length	No limitation

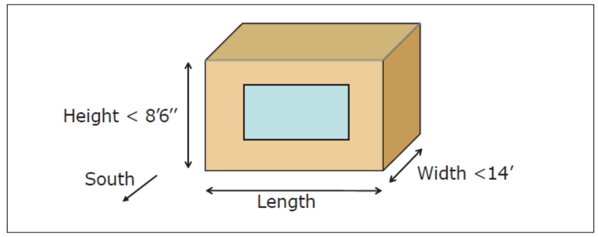

Figure 26: Room Size Limitation [8] (color scheme)

The width of the building (as shown in fig. 29) can be adjusted according to the thermal mass present in the building (Buildings in HIAL have a width of more than 16 ft. [Refer Section Case Study: HIAL])

9. Room Arrangement

Correct room arrangement is important to keep the most occupied rooms warm. Some general guidelines are -

- Rooms that have to be **warmed** are located on the **southern side**;
- Rooms that need to be warmed at the earliest in the day are located on the southeast corner (Room 2 in the adjoining Figure);
- Rooms that are not used during the morning but in the afternoon are located in the southwest corner (Room 1 in the adjoining Figure);
- Rooms that shall not be warmed (storage room, toilet blocks, kitchen, etc.) are located on the north side to create efficient **buffer zones** for warmed rooms (a buffer room is a room with a lower temperature than the other rooms but higher than outside and almost constant. When a room is in contact with a buffer room, heat loss is reduced);
- **Air block** (or SAS) is advised to limit cold air infiltration
- **The entrance** shall be located on the East, West, or North (and preferably not in front of wind direction) but not on the south side.

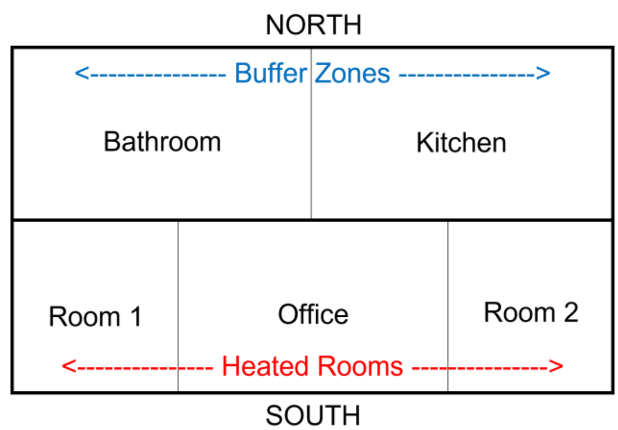

Figure 27: Room Arrangement (Top View)

10. Glazing and Overhangs

Main idea – to maximize collection of sunlight in winters and to prevent overheating in summer.

Figure 28: Installation of Overhangs

Example: Horizontal overhang for a window oriented toward the South

Step – 1: Draw on the design a line starting on the bottom of the window and with an angle I_{summer} representing the incidence angle of the Sun in summer (this angle can be known with the help of a sun chart)

Step – 2: Draw a second line starting on the top of the window with an angle I_{winter} representing the incidence angle of the Sun in Winter (this angle can be known with the help of a sun chart)

Step – 3: Draw a horizontal line between the outer face of the building and the intersection of the two lines drawn previously (summer and winter elevations of Sun for the given orientation).

This line represents the **horizontal overhang needed to collect solar energy by the window in Winter and minimize sun energy collection in summer**.

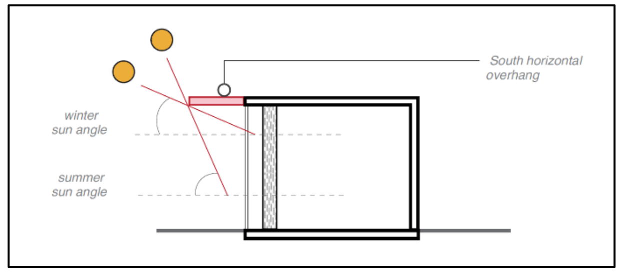

Figure 29: South Horizontal Overhang Design rule [24] (darken the text?)

To limit heat loss during winter night time, the DG windows should be double glazed. Distance between the two glass panes should be minimum 0.5 inch and not exceed 1.5 inch to be efficient.

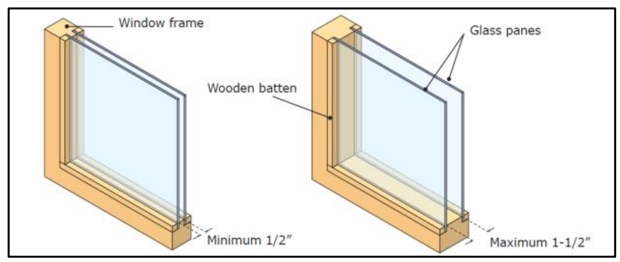

Figure 30: Double Glazing [8] (color scheme)

Installation Precautions:

The glass panes should be cut 2 mm smaller than the frame to avoid their breakage due to expanding with the effect of heat. Desiccants should be added between the two glasses to avoid condensation.

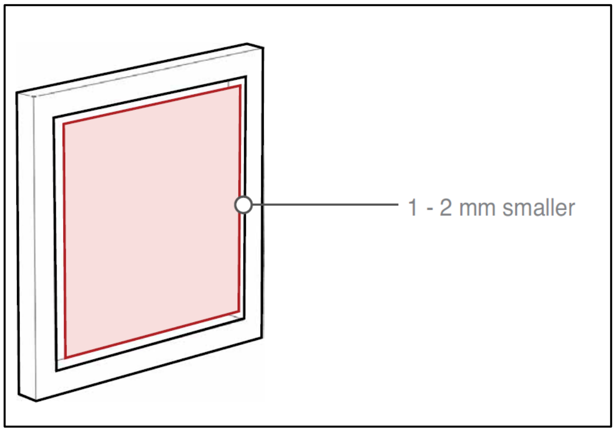

Figure 31: The glass panes should be cut 1 – 2 mm smaller than the frame

Fit the glass panes properly using glass putty or silicon. If not available, the fabric can be used to ensure no air infiltrations between opening shutters and window frames. Add fabric between opening shutters and DG window frame to limit air infiltration.

Special attention should be given to making an airtight window to limit air infiltrations.

A great alternative to timber frames is **UPVC windows**. They provide efficient thermal insulation and air tightness resulting in minimum heat loss.

Figure 32: UPVC Windows

Polycarbonate sheets can also be used for glazing instead of glass. They provide better thermal insulation, is easy to install, cost effective, and is also easy to transport.

Figure 33: Polycarbonate Sheets

Air Infiltration Precautions

Even if the envelope of LEC rooms is properly insulated (roof, walls, floor, windows), a large part (20% for a standard room but more for a LEC properly insulated) of heat loss is due to air exchange between exterior and interior. The main sources and associated technical solutins to avoid air infiltrations are listed below. The **essential thing to remember** is that airtight construction means **no air can get in or out unintentionally**!

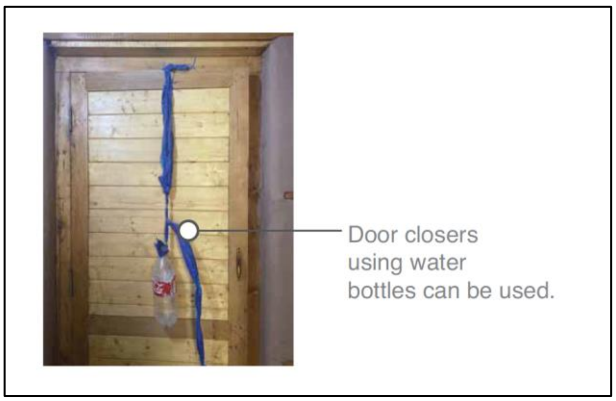

Figure 34: Self-closing doors

The doors should open outwards, such that the force of wind automatically closes the door and the wind does not enter inside easily. Alternatively, the door shutters are fixed at a slight angle for automatic closure due to self weight.

Figure 35: To prevent any air leaks while the door is closed

Special attention should be given to making an airtight door to **limit air infiltrations** (add fabric between door shutter and door frame if needed).

Figure 36: Don't forget to close the door

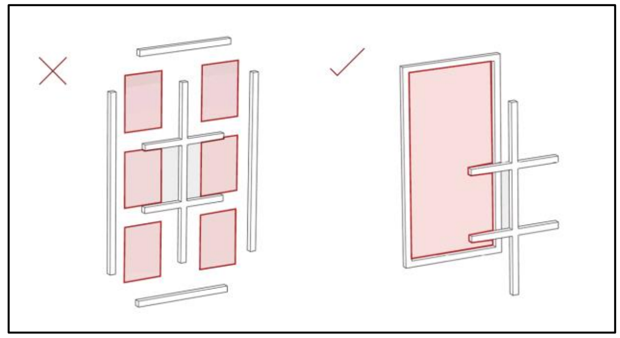

Figure 37: Single glass pane instead of multiple smaller panes reduces infiltration

Figure 38: Replace Broken glass

A special attention should be given to make windows airtight in order to limit air infiltrations. Smaller windows should be provided on the east-west side, to limit the air filtration by prevailing winds.

Infiltration would reduce if single glass pane is used on which transom is fasten instead of smaller panes assembled in a wooden frame.

Figure 39: No Air Gaps Between frame and opening shutter

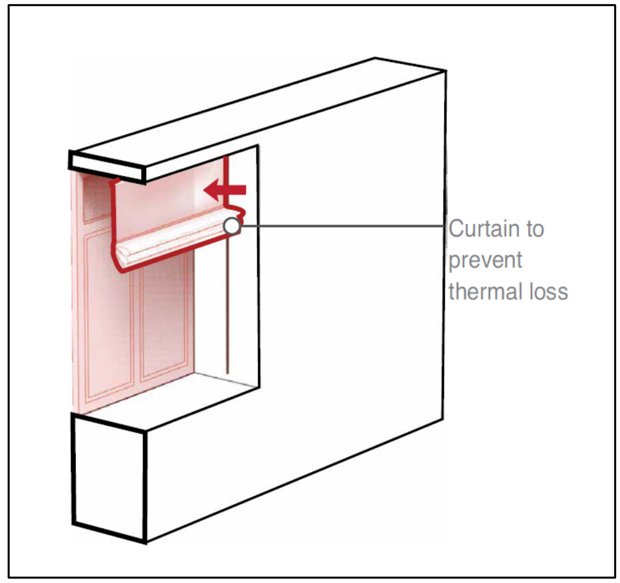

Figure 40: Install thick curtains to prevent heat loss

Putting it all together

11. Solar Gain Techniques

11.1. Direct Gain

The Direct Gain (DG) Technique consists in enlarging south-oriented window(s) to maximize the collection of solar radiation during winter daytime.

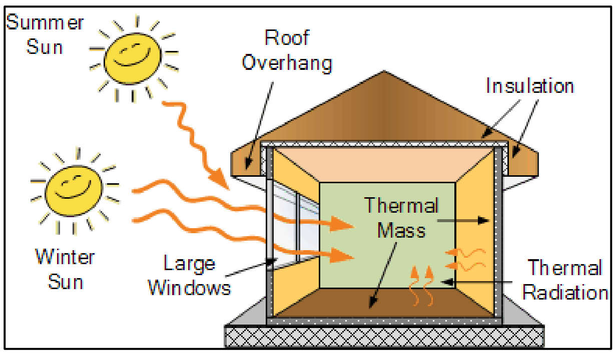

Figure 41: Direct Gain Technique [20] (Replace by the illustration in New Mexico handbook Pg. 24)

In order to minimize heat loss during evening and nighttime, DG windows are double glazed and equipped with thick inner curtains.

This technique can be implemented in new and retrofitted buildings with Day, Day & Night, or Night schedules.

In case of utilization of the building during evening and night time, a high level of thermal mass is required inside DG rooms to allow storage (daytime) and release (evening and night time) of energy and limit collapse of inside temperatures after sunset in Winter.

Size of DG windows is generally optimized in order to ensure a maximum of sun energy collection during winter daytime and, in the same time, limit heat loss through them during winter night time. To calculate proper size of DG windows, a simplified equation can be used –

$$R(gl/fl) = \frac{glazing\ area}{floor\ area} = \frac{gl}{fl}\ [\%]$$

Equation 1: Ratio of glazing area and floor area

With:

3. R (gl/fl): Ratio between net glazing area (gl) of DG windows of a room and its corresponding floor area (fl). [%]
4. gl: net glazing area of DG windows of a room [sqft]
5. fl: floor area of the room [sqft]

At preliminary design step, it is sometimes difficult to know exactly net glazing area. In first approximation, percentage of net glazing area can be taken at 60% of window area.

Best ratio (gl/fl) for DG technique is 20% for Ladakh (2% tolerance acceptable)

Advantages	Drawbacks
• Rather Cheap • Exterior aesthetic in line with traditional local architecture • Applicable from South-20°E to South-20°W	• Efficiency questionable during cloudy days

Table 2: Advantages & Drawbacks of Direct Gain Technique

11.2. Solar Wall

A Solar Wall is a thick south-facing (with a range of +/- 20°) masonry wall made of a material that absorbs a lot of heat. The best materials to build the wall are cement bricks, burned or mud bricks, Rammed Earth or cement hollow blocks filled with cement or mud.

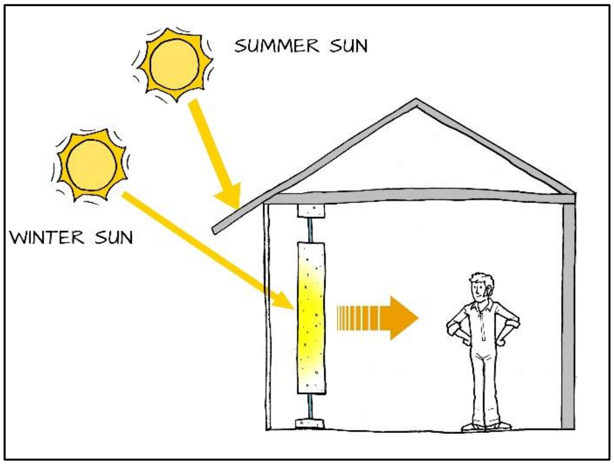

Figure 42: Solar Wall Technique [21] (show complete wall - no vents above and below; flat roof; color scheme)

The wall is plastered and painted with black color on its outer side. The best choice is to paint Solar Wall in black (matt color) to maximize the absorption of solar energy.

The outside surface is covered with a double-glazed frame with one or several windows. (covered with a double-glazed frame to increase the outer surface temperature of the wall by trapping sun energy between glazing and wall during daytime (greenhouse effect) and insulate the wall during evening and nighttime)

Sunlight passing through the glazing generates heat. The wall heats up slowly during the day and retains the heat. It gives off its heat in the early evening into the living area when temperatures are cold.

The time that energy takes to go from the outer face of the wall to the inner face called **Lagtime** depends principally on two parameters:

- The type of material used to build the SW;

- The thickness of this material (the thicker the SW is, the more it will take for the SW to release energy collected during daytime inside.)

The heatwave amplitude will also be attenuated throughout its propagation (**Damping**), i.e., when the collected heat of the solar wall reaches the inside surface, some of the collected energy has been lost in heating the wall.

Advantages	Drawbacks
• 24 hours warmed • Efficient even after one to two cloudy days • Applicable from South-20°E to South-20°W	• Expensive • 'Strange' aesthetic • Room may be considered dark • Less/not efficient if thickness of solar wall is higher than 1 foot (30 cm)

Table 3: Advantages & Drawbacks of Solar Wall Technique

In a conventional wall, bricks are placed in alternate directions. This method could cause air gaps in a Solar Wall and prevent proper heat transfer within the wall. When building a Solar Wall, all rows of bricks should be placed in the same direction as the first row.

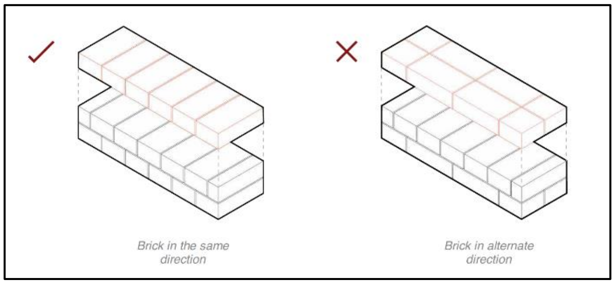

Figure 43: Position of Bricks in a Solar wall [24]

In a Solar Wall, the double-glazed frame should be stuck to the Solar Wall. The air gap between double glazing and the outer face of the solar wall should be 1 inch to 2 inches.

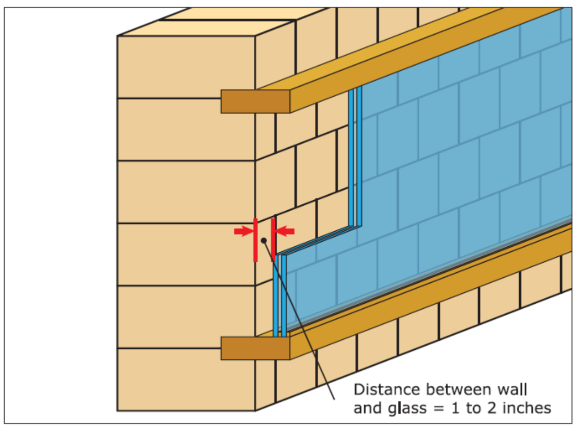

Figure 44: Double Glazed frame in a solar wall [8] (color scheme)

The SW efficiency can be improved by adding insulation on its sides. In fact, the SW can lose energy on its sides and lose a part of the efficient surface, which is used to release energy collected during the daytime.

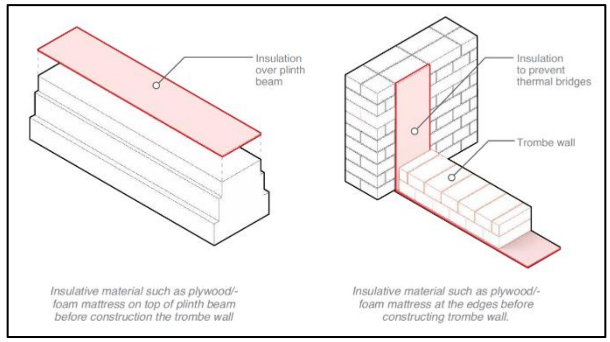

Figure 45: Insulation of vertical and horizontal sides of an SW [24]

The materials and the respective thickness advised for construction are presented below -

Material	Acceptable Range
• Cement Bricks	• 8 inches – 1 foot
• Mud bricks	• 8 inches – 1 foot
• Burnt Bricks	• 8 inches – 1 foot
• Cement blocks filled with cement or mud mortar	• 8 inches – 1 foot

Table 4: Thickness of Solar Wall according to material used

A small window equipped with double glass, generally in the centre of the SW, is installed to provide enough light in the living space. To calculate the proper size of this window to have enough light in the room and in the same time, to not lose too much energy through this window during winter night time, Equation 1 can be used. **Appropriate ratio (gl/fl) for SW technique is 10% to 12%.**

Note that with SW windows, natural sunlight is sufficient in the room. No other additional windows should be added to not increase heat loss of SW rooms.

11.3. Trombe Wall

A Trombe Wall (TW) is a **ventilated Solar Wall**. Two main differences can be mentioned between an SW and a TW:

- A TW has vents on the top and bottom of the wall

- There is a 4 to 6 inches air gap between the double glazed frame and the storage wall.

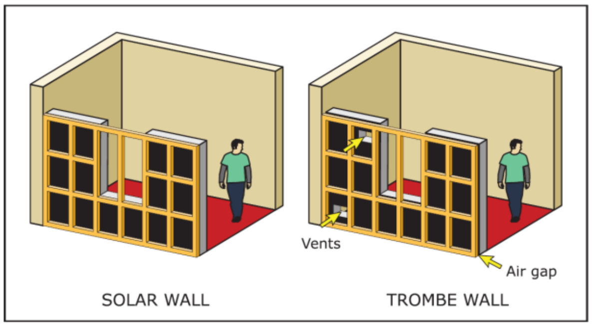

Figure 46: Solar Wall vs. Trombe Wall [8] (color scheme; show more gap in trombe wall)

These two differences allow, during winter daytime, a circulation of air (natural convection loop) between the Frame/Wall air gap and the room and so warm up the room also during daytime by convection.

1) Sun energy is trapped between double glazing and wall (greenhouse effect)

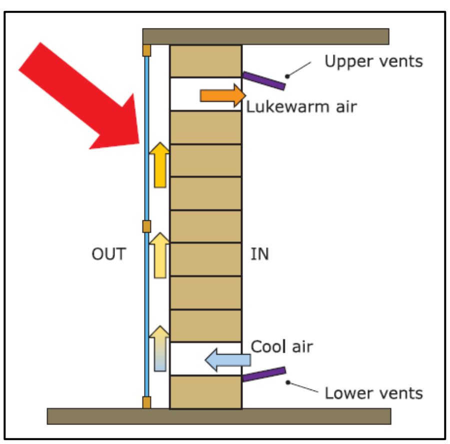

Figure 47: Trapping of solar energy in between the wall and glazing [8] (color scheme)

2) A part of this energy warms up the air between the frame and the wall, allowing a natural convection loop creation. Warm air goes naturally inside the room, and cold air in the room goes through lower vents between the wall and glazing.

3) At the same time, the other part of sun energy warms the wall and starts to be stored in the wall (same functioning as for a Solar wall)

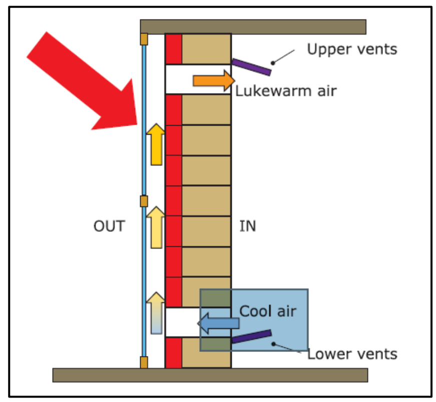

Figure 48: Storage of heat in the Trombe Wall [8] (color scheme)

4) Natural convection loop is stopped thanks to the closing of upper and lower vents in the evening (if vents are not closed, the convection loop can be reversed and cool the room.)

5) Energy stored during daytime within the wall is slowly released inside the room during evening and nighttime (same as Solar Wall functioning)

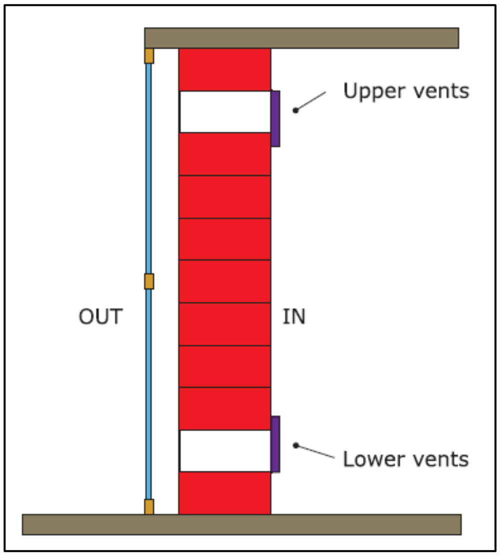

Figure 49: Closing of upper and lower vents in the evening [8] (color scheme)

11.4. Isolated Gains

A **veranda** is a **single-glazed room attached to the southern wall of a building** that is used as a collector of solar energy during winter daytime to warm up adjacent rooms of the building during day and nighttime.

The heat (radiation) collected by the veranda is transferred to the adjacent rooms:

- by **radiation** during daytime through double glazed windows.

- by **convection** during daytime through opening shutters of double-glazed windows and doors.

- by **conduction/radiation** through the storage wall (storage phase during daytime/release phase during evening and night time) separating the veranda and the adjacent rooms.

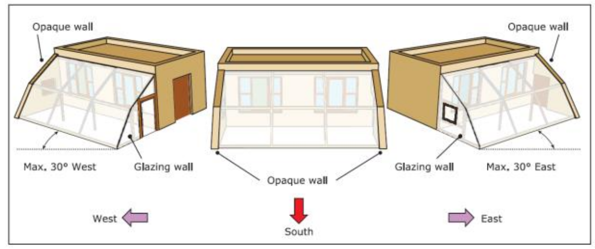

Figure 50: Veranda Orientation [8] (color scheme)

In remote rural areas and primarily for housing purposes, glasses are replaced by polythene mainly to decrease investment and maintenance costs. This technique, a bit less efficient but easier to implement and cheaper, is called **Attached GreenHouse (AGH).**

Figure 51: Veranda technique (top) vs. Attached Greenhouse (AGH) technique (bottom) [8]

Windows equipped with 100% of double glazed opening shutters should be installed on the partition wall between the veranda and rooms to warm up. They play an important role to transfer heat by convection from the veranda to the rooms to warm up during daytime. In order to provide enough sunlight to the rooms and in the same time, to allow a sufficient heat transfer by convection during day time, the size of the window(s) should be designed according to the following rule - **Ratio (gl/fl) should be 13% to 16%.** (Refer Equation 1)

Note that with Veranda/AGH windows, natural sunlight is sufficient in the room. No other additional windows should be added to not increase heat loss of the rooms to warm up.

12. Energy Efficient Buildings (extra topic)

Sometimes, it is not possible to build or retrofit a building with passive solar concepts and techniques (SW, DG, Veranda) because:

- Building orientation is not suitable;

- Near or distant obstructions create too much shading on the South face of the building.

In this case, it is **still possible to save fuel and increase the thermal comfort** of buildings by focusing only on Building Insulation (opaque and transparent walls insulation; infiltration reduction). This type of building is called **Energy Efficient Buildings (EEB).**

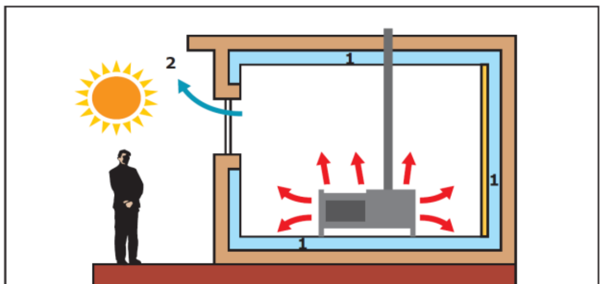

Figure 52: Energy Efficiency Technique (color scheme; south glazing + bukhari + window in the front wall)

Thanks to efficient insulation of opaque (walls, roofs, floors, doors) and transparent (windows) walls and a drastic reduction of air infiltrations, the EE technique permits to decrease enormously heat loss by the envelope of the building and conserve longer the energy released by heating systems.

Advantages	Drawbacks
• Always Applicable (no orientation or obstruction constraints) • Heating consumption highly reduced compared to standard buildings (generally 45 % of fuel savings)	• Less efficient than passive solar buildings • Require artificial heating (even though the fuel consumption is reduced)

Table 5: Advantages & Drawbacks of Energy Efficient Building

In order to provide enough natural sunlight to the rooms and in the same time to not increase too much heat loss through windows, the size of EE windows should be calculated with the help of the following rule:

Ratio (gl/fl) should be between 10% to 12% (Refer equation 1).

13. Case Study: HIAL

All the buildings at HIAL are Passive Solar Heated (PSH) – they use only sunlight as the source of heat and no other mechanical heating technique.

This creates a thermally comfortable environment inside the buildings, even when the temperatures drop to subzero outside. The buildings at HIAL do not need any active heating, even in the -15°C temp of winters in Ladakh. Using the Sun's light, the buildings stay at +15°C. This is achieved by combining **passive solar design strategies** and the correct use of **building materials.**

The five PSH buildings constructed at HIAL are prototypes to test the efficiency of the different construction techniques. All The buildings are oriented toward the True South (Solar South).

The buildings have a **Modified Trombe wall system** with a double-glazed façade in the South to maximize solar gains.

The Trombe walls use concrete blocks with filled water bottles embedded inside to increase the thermal mass of the Trombe wall system.

All the other walls and openings (including door shutters) are very well insulated. Special care has been taken to prevent any heat losses due to air infiltration.

General features of the buldings have been discussed in the following pages.

DIY Adobe Pre-FREB Straw-clay Rammed Earth

Figure 53: Buildings at HIAL

1.) **<u>Plan</u>** – The following set of figures shows the detailed plans of the buildings at HIAL along with the dimensions.

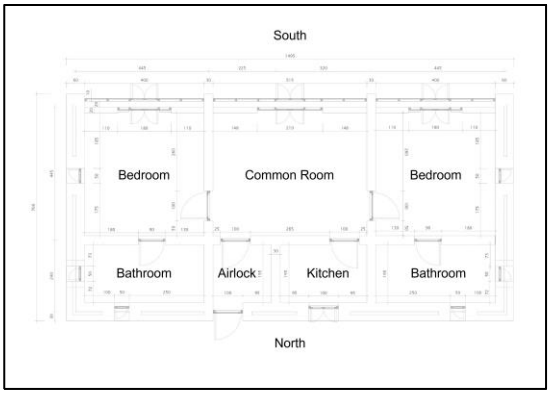

Figure 54: Floor Plan

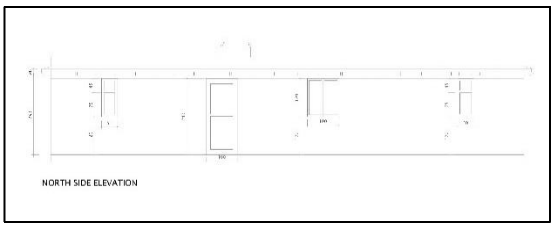

Figure 55: North Side Elevation (these should be like new Mexico booklet pg 61-62)

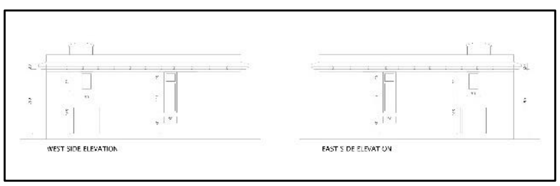

Figure 56: East-West Elevation

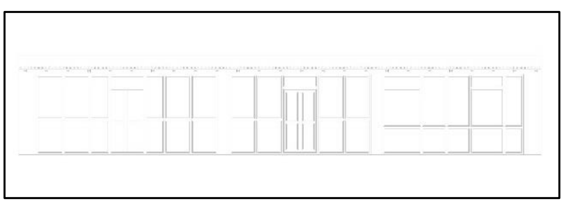

Figure 57: South Side Elevation

2.) **<u>Modified Trombe wall system at HIAL</u>** –

The basic principle of operation of the Modified Trombe wall system is the same as explained before. There are **two major modifications**:

- the **vents** have been **replaced by large opening doors** which can be comfortably opened and closed as required. Having such large windows/doors ensures that they are operated daily, unlike the smaller vents of the traditional Trombe wall. Moreover, these opening ensure efficient heat transfer through convection besides allowing direct gain of sunlight in winters.

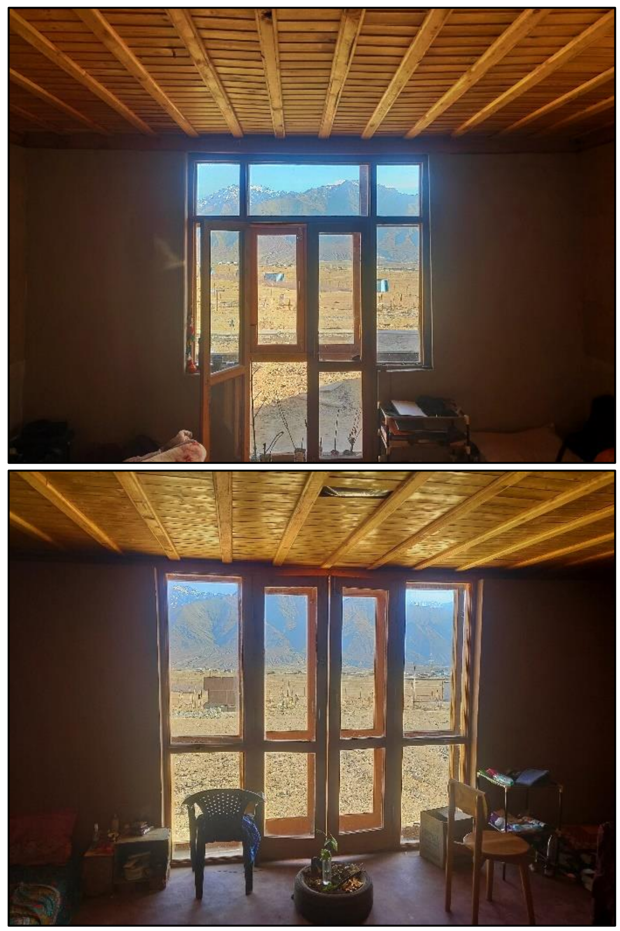

Figure 58: Modified Trombe Wall

- The South facing wall is 20cm thick and made of a special type of brick called a **thermal block**. A thermal block is a unique brick constructed using **water-filled plastic bottles embedded inside plain cement concrete (PCC) block**. The combination of concrete & water in the block enhances the thermal mass while utilizing the high thermal conductivity of concrete for efficient heat transfer in the Trombe wall (with an apt time lag). The block has a **dimension** of **30 cm x 30 cm x 20 cm**. Attention is paid to keep the bottles upright when the blocks are stacked for the wall.

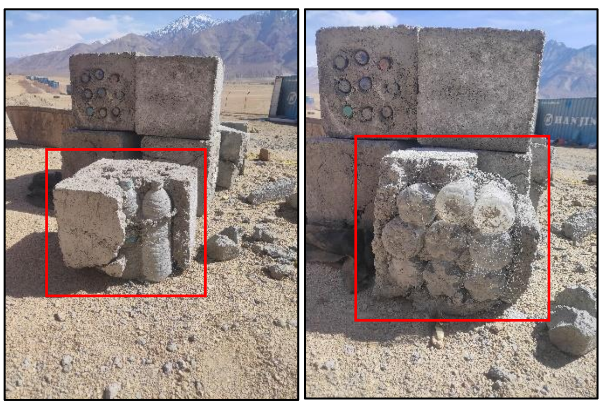

Figure 59: (i) Front view, (ii) Bottom view - Thermal block

It was observed that this Modified Trombe Wall is more efficient (energy-wise) than the traditional Trombe Walls.

The distance between the glazing and Trombe wall is 20 cm.

The outer surface of the TW (i.e., the surface facing the South) is painted black to increase surface absorption.

2.) **<u>Overhang</u>** – The overhang extends **45 cm** (for a 2.5 m height floor) over the double glazing on the south façade. It protects the Trombe Wall from unwanted solar gain in summer.

Figure 60: Overhang shadow during spring (11 April)

3.) **<u>Foundation</u>** – All the building at HIAL have used **Dry Stone Foundation**. The foundations are composed of ~ 900 mm deep stone masonry that is wider than the thickness of the wall to be built on top of the foundation. The masonry is below the ground level and does not require any form of waterproofing. CLC blocks are used in the periphery to prevent heat loss.

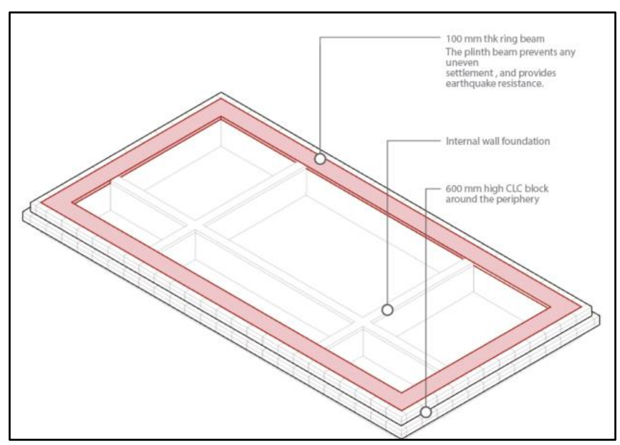

Figure 61: Plinth Beam (Isometric View) [24]
(text black)

The abundance of stone as a natural material, makes dry stone masonry as the most feasible method of construction in the area. It also prevents the risk of moisture travelling upwards through capillary action.

Figure 62: Dry Stone Foundation on-site work

Dry Stone Masonry is one of the oldest methods of construction. The position and weight of the stones themselves keep the structure in place. It requires skilled masons. The largest stones, called foundation stones are put at the bottom. Stones which connect both the faces of the walls are called "through stone/tie stone". These are important for the structural integrity. Smaller stones used to fill gaps are called heart stones.

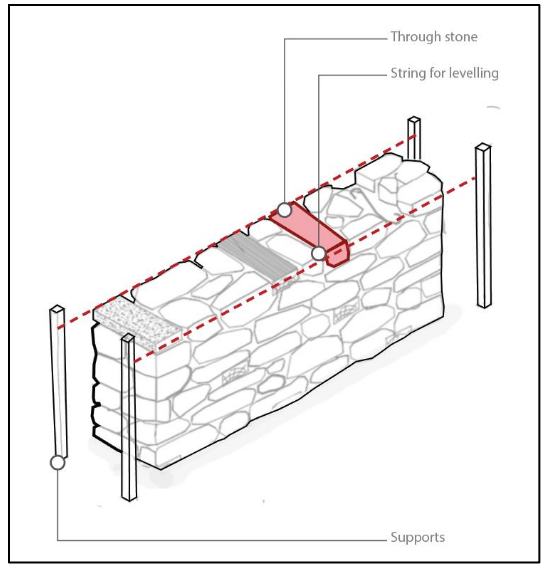

Figure 63: Dry Stone Masonry [24]

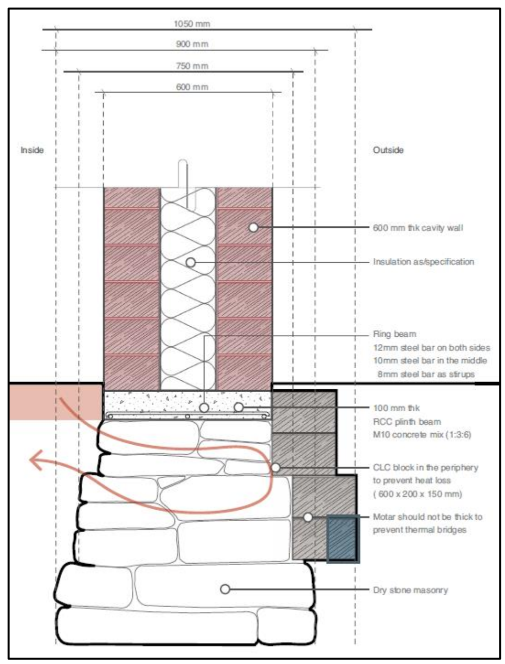

Figure 64: Foundation Section [24] (write inside & outside vertically and make it more prominent)

4.) **<u>RCC Lintel Tie Beam</u>** – An RCC lintel tie beam of dimensions – 15 cm (height) & 60 cm (width) ties the peripheral walls to incorporateearthquake-resistant properties.

5.) **Insulative Roof** – The roof has an insulated false ceiling of 30 cm which is filled with insulation from waste material such as pashmina wool waste. Aove this, the roof is covered with a 20cm layer of straw clay, finally rain proofed by a thin layer of cement plaster. (edit needed?)

6.) **Insulative Flooring** – Below the actual flooring, lies two layers of insulation. The bottom layer consists of random rubble soling with successive layers of rocks (~ 20 cm), pebbles (~ 5 cm) and small aggregates (~ 1 cm) to seal the gaps and create air pockets. This alaso works against capillary action for moisture ingress. The soling layer in total is ~ 30 cm deep. This layer is topped with insulative straw clay bricks of 20 cm depth. The gaps between the bricks are packed with small aggregates to make them rodent proof.

13.1. Adobe

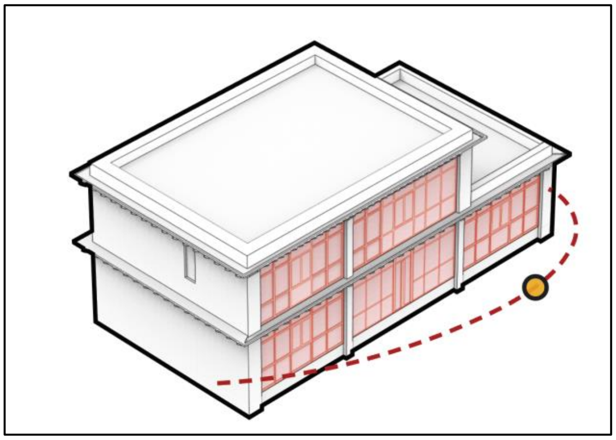

Figure 65: Schematic view of Adobe at HIAL [24]

This is the oldest building at HIAL. The ground floor (residential – day & night use) of this building was built in 2018 and the first floor (office – day use) was built in 2019.

Adobe is a traditional sun-dried brick made out of mud, locally known as '**Pagbu**'. This building has been made by using Pagbu with cavity filled with insulating materials. Insulation materials like wood shaving, saw dust, cardboard blocks, straw, thermocol, pashmina waste or foam are filled in the cavity.

Figure 66: Adobe at HIAL

Figure 67: Adobe under construction at HIAL

- Cavity Dimensions keep in mind

- mixture of soils (more clay content, fine soil) from shey thiksey

13.2. Straw Clay

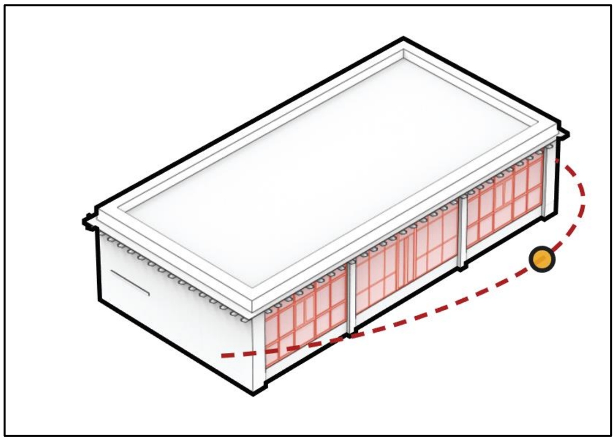

Figure 68: Schematic view of Straw Clay at HIAL [24]

This PSH Building uses **Straw** ("rescued" from Punjab) for reinforcement, **wood shavings** to make the brick highly insulating, and **clay** for bonding.

Figure 69: Straw-Clay Building at HIAL

This building was made at HIAL in 2018. The western, eastern and northern walls are made up of straw clay bricks. The bricks are 60cm x 30cm x 20cm in dimension.

The composition of the straw-clay brick makes it **low-density** and hence **highly-insulating**. The straw clay bricks are **light-weight** and have higher water holding capacity as compared to the other traditional bricks.

Figure 70: Straw (left) & sawdust (right)

Figure 71: Clay slurry

Figure 72: Wood Shavings & Sawdust

Figure 73: Mixing Everything (caption?)

Figure 74: Final Mixture being poured

Figure 75: Pouring everything in the brick making machine

Figure 76: Final Product – Wet Straw Clay Bricks

The bricks are made using saw dust, straw and clay. Straw & wood shaving are mixed in the ratio of 1:4 by volume. In olden times, straw has been used only for plaster reinforcing, but now using the similar technique the bricks are treated in a way that additional insulation is not required.

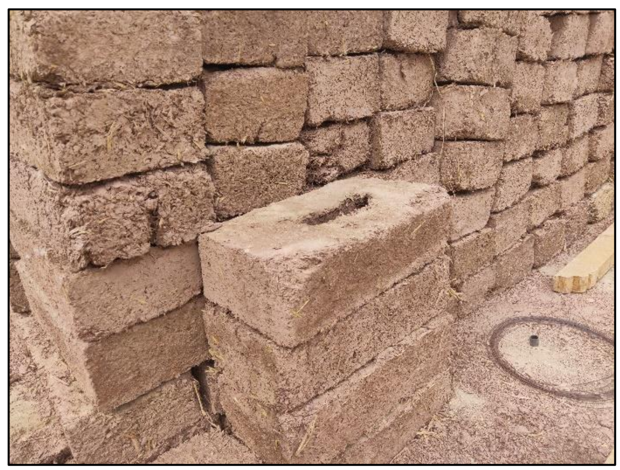

Figure 77: Dry Straw Clay Bricks

brick orientation (stretcher & header), cavity wall – stretcher (keep in mind while constructing), (caption?)

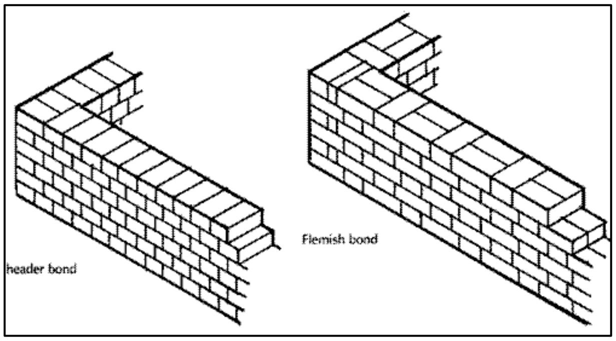

Figure 78: ask construction team for an apt illustration for brick orientation

Load Bearing Properties mention and advice number of floors

Thermal properties (will help decide thickness of walls & also placement of materials)

13.3. PreFREB

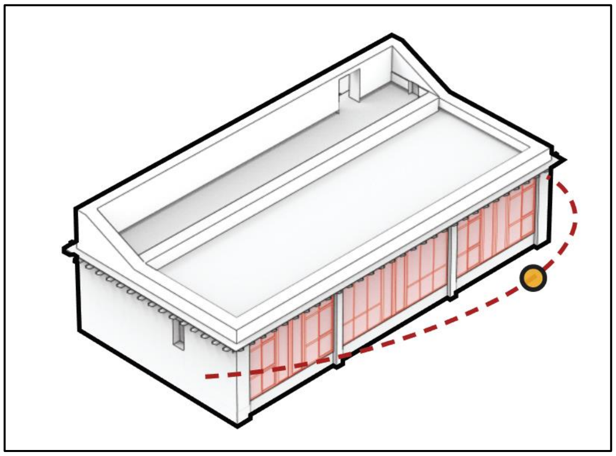

Figure 79: Schematic view of Pre-FREB at HIAL [24]

Pre-FREB stands for Prefabricated Fibre-Reinforced Earthen Block. This building was built in 2019.

Figure 80: Pre-FREB building at HIAL

Pre-FREB wall system enables ease of construction and allows for time-saving in conventional construction systems.

The blocks are pre-cast and have high insulation. The straw helps in making the blocks low-density as well as provides good compressive strength. The blocks can also be reinforced using TMT bars, cement and sand. The steel bars go from foundation to tie beam.

Figure 81: Pre-FREB Block filled with concrete

The blocks are Lego-like structures that can fit one above the other and be constructed in a matter of few weeks. The structure is modular, consisting of two leaves which can accommodate different thickness of insulation depending upon the location of the building.

Figure 82: PreFREB Block Arrangement

block size

13.4. Rammed Earth

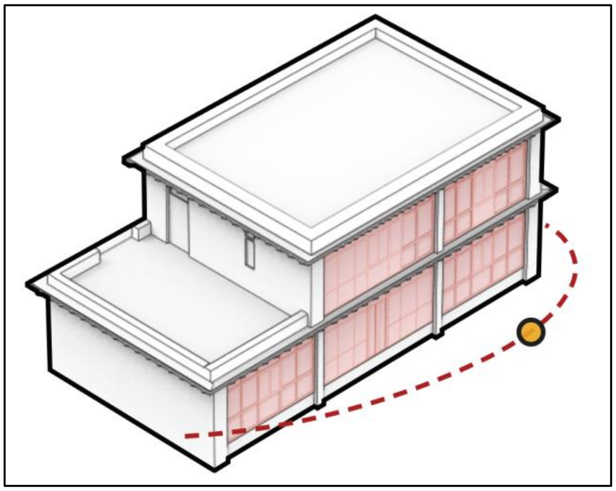

Figure 83: Schematic view of RE at HIAL [24]

Rammed Earth (RE), as the name suggests, is built using one of the oldest construction techniques - traditionally called **Gya-pak**. The ground floor is residential (day and night use), and the first floor (office – day use) is made of strawclay bricks manufactured at HIAL campus.

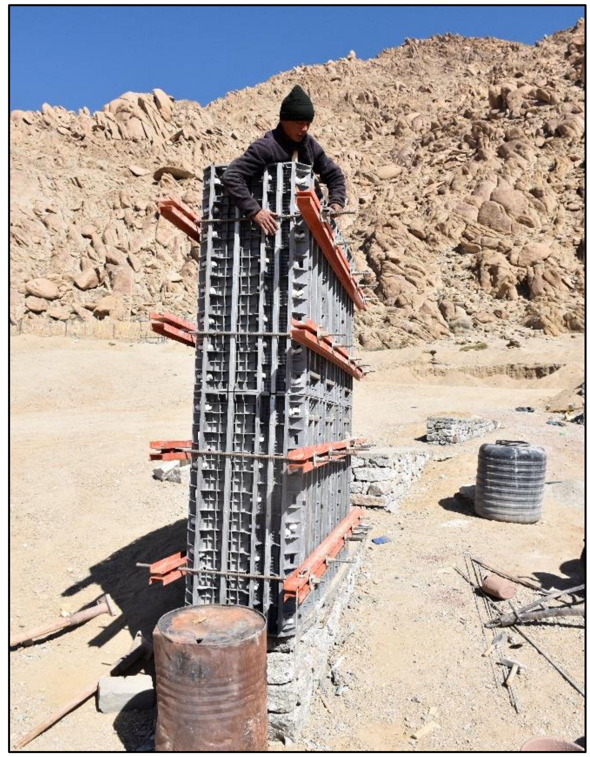

Figure 84: Rammed Earth Shutter Set Up

Rammed Earth is compacted earth made up of gravel, sand, silt and clay. **Gravel** gives compressive strength to the wall, while **sand** & **silt** fill the voids and make an interlocking matrix. The **clay** is an adhesive and binds the material together. Rammed Earth has high thermal mass making it ideal for solar passive design. However, for extra cold climates the insulation can be improved with the construction of a double wall filled with straw or other natural insulation. (validate)

Figure 85: Rammed Earth Shutter Set Up

Figure 86: Process of Ramming Earth

This building was built at HIAL in 2019.

The exterior walls are double walls with 600mm thickness and 100mm thick thermocol insulation sandwiched between the two layers of wall.

Photo/illustration here of the walls

The roof uses Pashmina waste for insulation between the wooden planks. The raw material for the rammed earth has been sourced locally, making it one of the most sustainable techniques.

Figure 87: Rammed Earth building at HIAL

Figure 88: First floor construction using Straw Clay Bricks

Farma 8ft.

Floor straw clay insulation

Silt is not good for walls but Ladakh has silt that's why we need more clay

13.5. Ex-fill

It is a framed structure with an envelope of straw-clay blocks for insulation.

Figure 89: Enveloping the column with Straw Clay bricks

This construction technique is specially devised to comply with the National building code followed by most Government bodies, by replacing the partition walls of framed structure with an envelope of straw-clay blocks' walls, while the actual load is taken by concrete beams and columns.

Figure 90: Ex-Fill level G construction

The technique has been given the name of "ex-fill" by HIAL.

The floors use thermal pipes to create a thermal storage bank (thermal mass).

The building was started in 2020 and is under construction, designed as a three floor structure.

Figure 91: Ex-Fill level G+1 construction

For glazing, instead of glass, polycarbonate has been used, which is easy to install, is cost effective, and is also easy to transport (double UV layer – 20 years life)

Figure 92: Polycarbonate for glazing

Figure 93: Roof Insulation with Straw Clay Bricks

Appendix

14. Techniques to find Solar South

There is a giant magnet inside the Earth. This big magnet rotates along with the Earth. However, its axis is not aligned exactly with the Earth's axis of rotation, although they are pretty close to each other. **The declination is approx. 14 degree**. (Figure 17)

For better understanding -

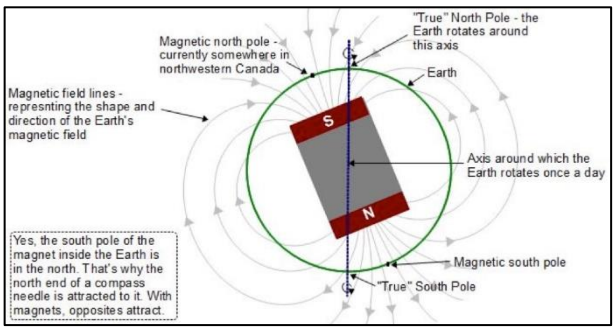

Figure 94: Magnetic Poles vs. Earth's True Poles [17] (color scheme)

When the compass needle points at the South, it is actually aligning with the Magnetic South Pole and not the True South Pole (Figure 18).

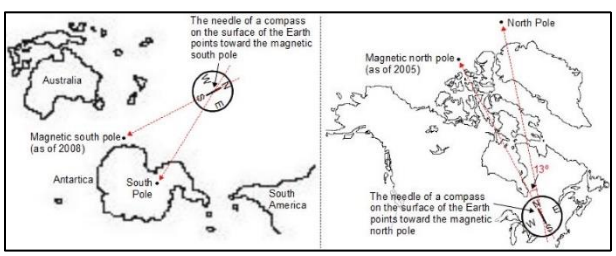

Figure 95: Compass pointing towards magnetic South [17] (higher quality, color scheme)

We often refer to the direction of the Earth's South Pole as the True South or the true solar South, while the direction of the magnetic south pole is referred to as the Magnetic South.

14.1. Shortest Shadow Method

The shadow of an object will be shortest when the Sun is highest at noon, and at this moment, the direction of the shadow line is the true solar South.

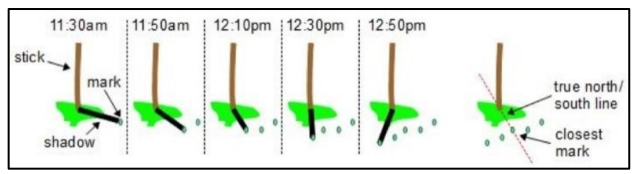

Figure 96: Shortest Shadow Method [17] (color scheme)

Simple steps:

1. **Set a straight stick on flat ground** before noon – the straight stick must be perpendicular to the horizontal. The ground should be as flat as possible because a tilt-mounted stick or uneven ground will produce a faulty result of the shortest shadow. (TIPS: A PLUMB BOB COULD EFFICIENTLY HELP YOU PUT UP THE STICK VERTICALLY ON THE GROUND)
2. **Mark the shadow end on the ground every few minutes** – as time passes by, the shadow cast by the stick will move. You need to leave a mark at the end of the shadow on the ground every 10 – 20 minutes, and these marks will finally form

a curve. (TIPS: THE INTERVAL NEED NOT NECESSARILY BE THE SAME, AS LONG AS WE CAN GET THE MOMENT WHEN THE SHADOW STARTS BECOMING LONGER INSTEAD OF SHORTER.)

3. **Find out the shortest shadow line** – draw a line to connect those marks to the point where the stick touches the ground. By now, the shortest line is evident.
4. **Reveal the true solar South** – now that we have marked that special line we concluded in the third step, the direction of the Solar South has been revealed.

14.2. Shadow at Solar Noon

This could be the simplest way – it takes far less time than Shortest Shadow Method. Let us start with the question: what is solar noon?

Solar noon is the **local time when the Sun rises to its highest point at your location**, and at this time, the Sun is crossing your local meridian. (Fig. 22)

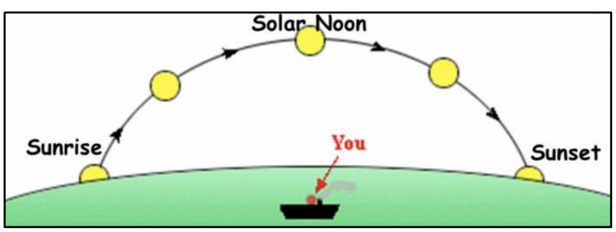

Figure 97: Solar noon [18] (color scheme, show person in the center)

Instead of spending several hours standing outside and measuring the shortest shadow, in this method, all you have to do is –

1. **Find out your local solar noon**
2. Go out **at that time** to **check the direction of the shadow** of an upright object on the ground.

Two feasible ways to calculate your local solar noon -

http://www.spot-on-sundials.co.uk/calculator.html

http://suncalc.net/

(You can use the compass app on your phone to know the latitude and longitude for use in the above links)

14.3. Magnetic Declination

The magnetic South that a compass points to slightly deviates from the **true South** – the direction **along a meridian towards the South Pole**. The deviation angle between them is called magnetic declination.

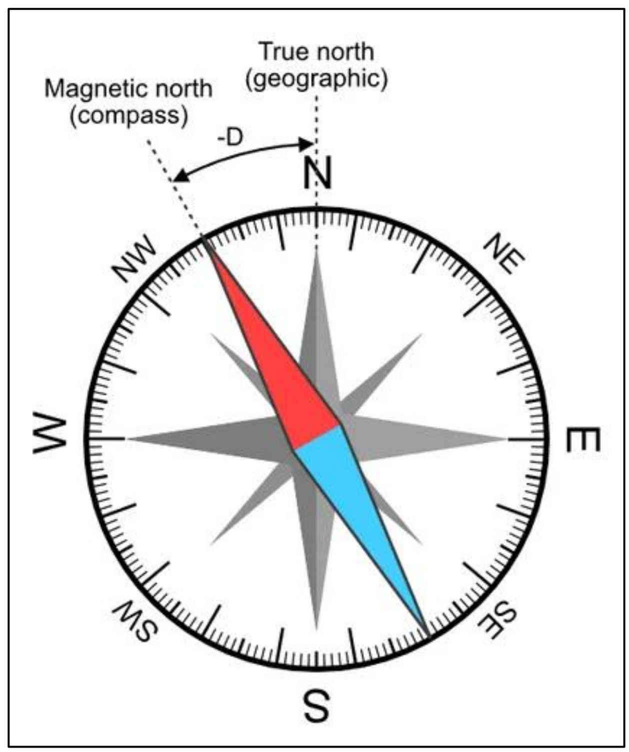

Figure 98: Negative Magnetic Declination [19]

The magnetic declination changes every year because magnetic poles are shifting each year. However, the Earth's pole is not moving.

Hence, we should visit the authority's online database to obtain up-to-date data on declination.

Let us go through the **simple steps**:

1. Visit the authority site NOAA (https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml) and fill in the required data – (Alternate - https://www.omnicalculator.com/physics/magnetic-declination)
2. Your magnetic declination would be displayed.
3. **Prepare the compass** – we need a compass with degree scales. Place it on a horizontal surface, and adjust the needle to align with the south-north scale as usual. Its black hand will point to the magnetic South.
4. Rotate the compass horizontally according to the declination. **Now, the 'S' on the scales will point to the true solar South.**

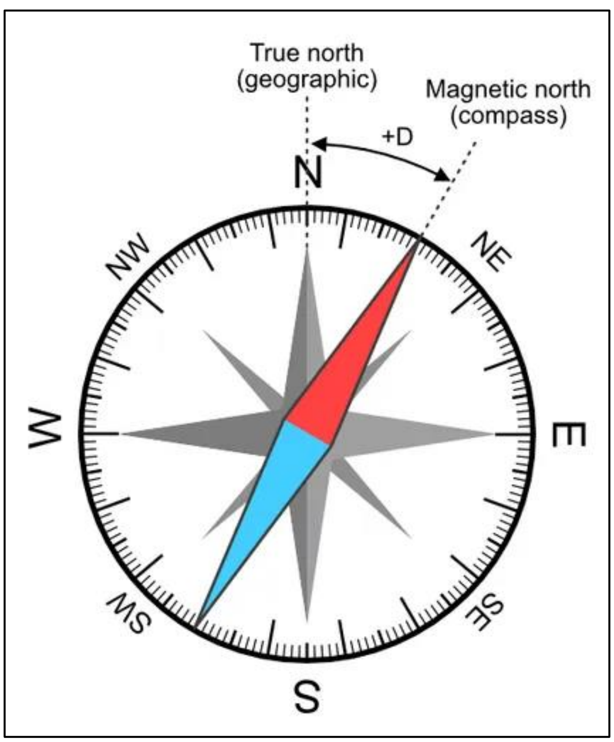

Figure 99: Positive Magnetic Declination [19]

14.4. The Polaris Method

In the **northern hemisphere**, you can also use the Polaris to locate the true north or South.

The Earth's imaginary rotation axis always passes through the Polaris. It does not move in the sky. The direction towards the Polaris is always the true north.

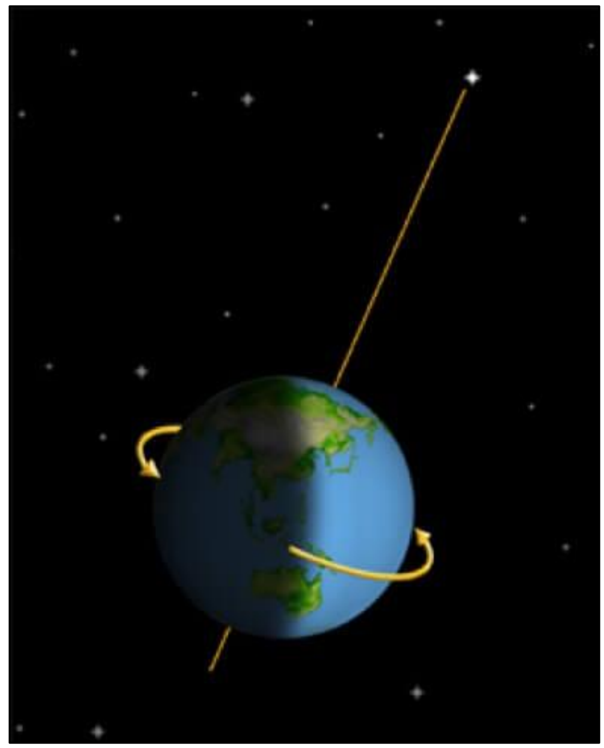

Figure 100: Polaris lies along Earth's axis of rotation [17]

2. **Identify the Polaris** – Commonly, finding the Polaris requires the help of "The Big Dipper" and "Little Dipper" in the northern sky. Below are three helpful clues –
   - The Polaris belongs to "Little Dipper," together with six other stars
   - The Polaris does not move
   - The "Big Dipper" constellation revolves around the Polaris all year round.

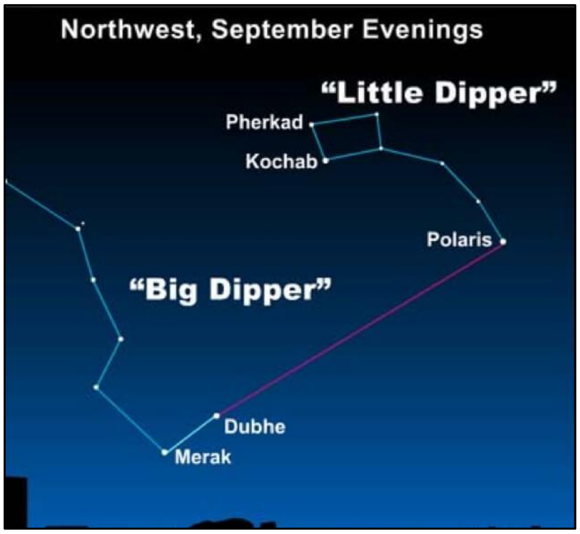

Figure 101: Position of Polaris in the sky [17]

3. **Set up a rectangular object** – Line up the seam between 2 sheets of paper/cardboard/rectangular object with the Polaris as instructed in the following picture. The object will be facing the true South.

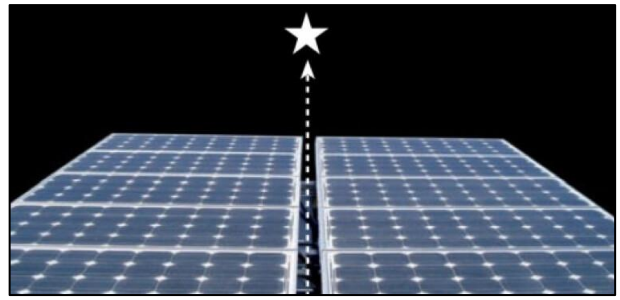

Figure 102: Lining up the seam with Polaris [17]

15. Foundation & Flooring

Foundation has a single purpose – when you put something on the ground it should not move. While building foundation, we should keep in mind that a foundation has the following jobs -

- Distribute downward force of a structure over a large enough area to reduce the bearing pressure and avoid shear failures or excessive settlement.
- Structural loads don't just come from gravity. Wind can exert tremendous and rapidly fluctuating pressure on a large structure pushing it horizonally and even creating uplift like the wing of an airpane. Earthquakes also create loads on structures, shifting and shaking them with very little warning. Just like the normal weght of a structure, these loads must also be resisted by a foundation to prevent it from lifting or sliding along the ground
- To resist the effects of long term degradation and decay that come from our tiny biological neighours.
- To reach a deep enough layer that can't freeze or that doesn't experience major fluctuations in moisture content to avoid problems that come with water in the subgrade below a structure.
- Foundtions have to be cost effective as per the lifetime of the building. No need for unnecessarily strong foundation. [23]

Flooring – When properly insulated, floors instead of losing heat through conduction, can act as thermal masses, i.e., they can store the thermal heat gained from solar radiation, during the day and radiate it back at night.

Steps for flooring:

1. **Levelling** - Ground level between the wall footings are levelled and checked for bigger stones.

Figure 103: Levelling

2. **Stone Soling** - Soling is the process of hand packing rubble stones one adjacent to another, to provide a stable base to the foundation and footing, before concreting work. It is done to enhance the bearing capacity of the soil.

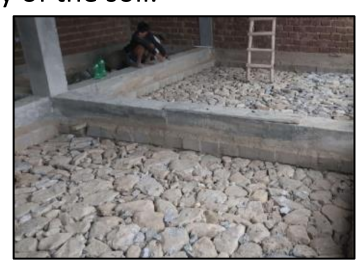

Figure 104: Stone Soling

3. **Laying Straw Clay Blocks** - Strawclay blocks along with aggregate is laid for insulation.

Figure 105: Laying Straw Clay Bricks

4. **Laying Aggregates** - 10 mm of aggregates are laid before concreting the floor.

Figure 106: Laying Aggregates

After completing these four steps, we have **3 different options** to complete the flooring -

Option 1: Layering Plain Floor

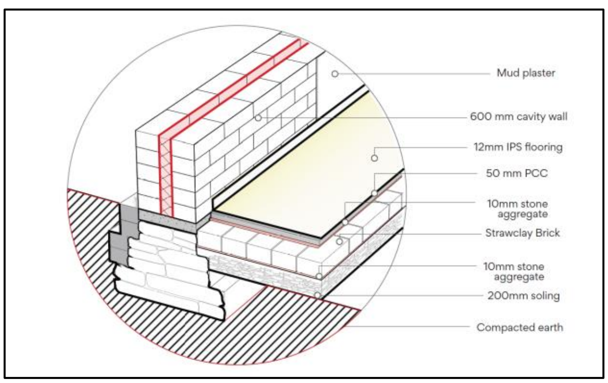

Figure 107: Layering Plain Floor [24]

In this option, PCC is laid on top of strawclay bricks, and the floor is finished with IPS flooring. The floor does not act as a thermal mass and hence the entire floor can be carpeted.

Figure 108: 50 mm PCC is laid on top of straw clay brick

Figure 109: IPS Flooring

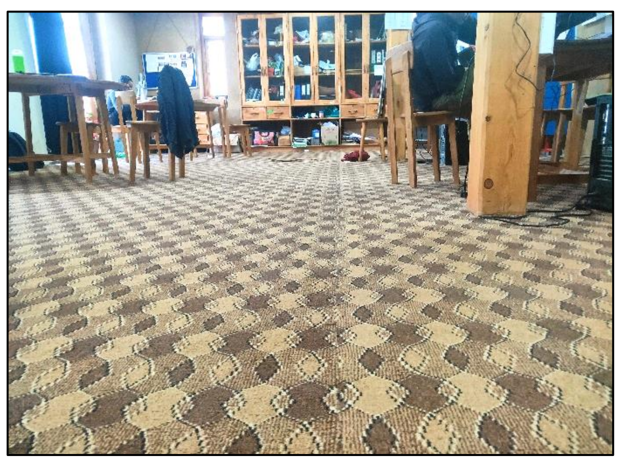

Figure 110: Carpet can be laid on top of flooring for additional thermal comfort

Option 2: Layering Floor with thermal pipes

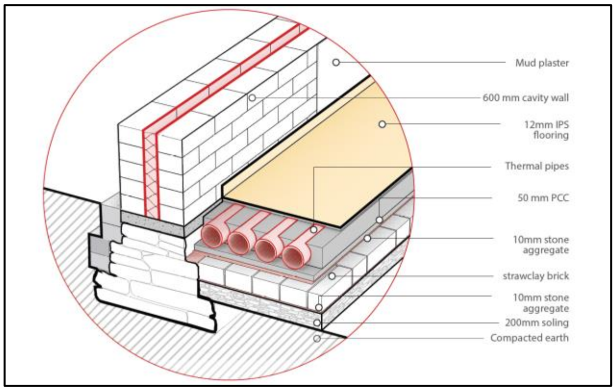

Figure 111: Floor with Thermal Pipes [24]

In this option, plastic pipes of 8’’ diameter, filled with saline water is laid on top of PCC. Concrete is poured on top of the pipes, and the flooring is finished with IPS flooring.

In this technique, the floor acts as a thermal mass and hence the entire floor should not be covered with carpet for an efficient solar gain.

Figure 112: 50 mm PCC is laid on top of the strawclay bricks

Figure 113: Thermal Pipes

Figure 114: IPS Flooring

Option 3: Layering Floor with water filled plastic bottles

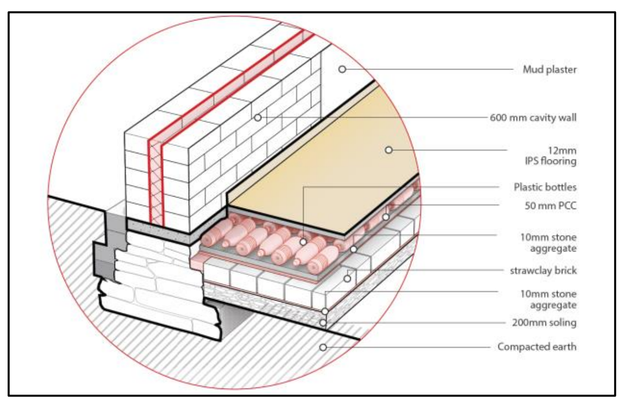

Figure 115: Floor with water bottles [24]

In this option, plastic bottles , filled with saline water is laid horizontally on top of PCC.

Concrete is poured on top of the bottles and the floor is finished with IPS flooring.

In this technique, the floor acts as a thermal mass and hence the entire floor should not be covered with carpet for an efficient solar gain.

Figure 116: 50 mm PCC is laid on top of strawclay bricks

Figure 117: Plastic bottles with saline water are laid on top of PCC flooring

Figure 118: IPS Flooring

16. What is Temperature?

The concept of temperature, like that of force, originated in man's sense perceptions. Just as a **force** is something we can correlate with **muscular effort** and describe as a **push** or a **pull**, so temperature can be correlated with the sensations of relative hotness or coldness.

But man's **temperature sense**, like his force sense, is **unreliable** and restricted in range.

Out of the primitive concepts of relative hotness and coldness, there has developed an objective science of thermometry, just as an objective method of defining and measuring forces has grown out of the naïve concept of a force as a push or a pull. [1]

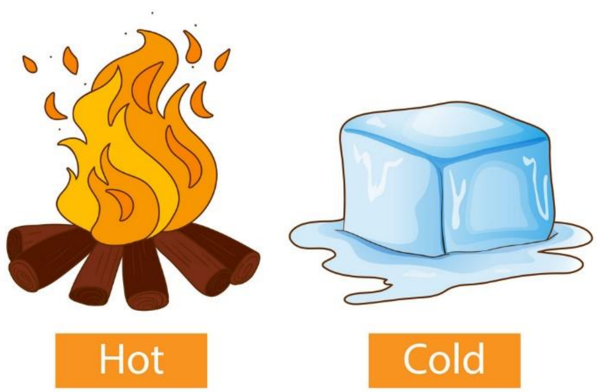

Figure 119: Primitive Temperature Sense

Temperature is related to the **average kinetic energy** of the **constituent particles** of a substance.

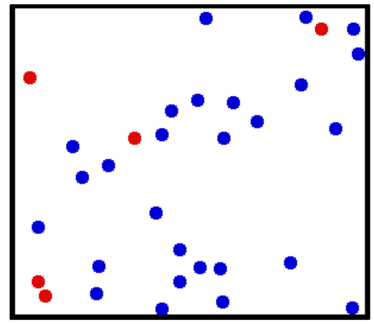

Figure 120: Kinetic Energy of Molecules [2]

Temperature is measured with a thermometer. The **SI unit** for temperature is **Kelvin (K)** and is predominantly used for scientific purposes.

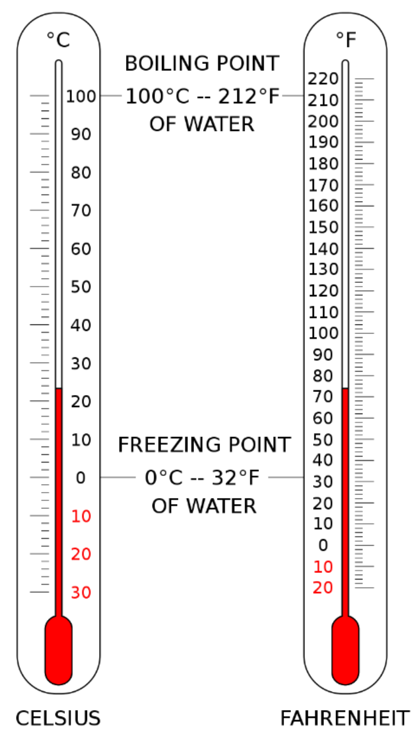

Figure 121: Fahrenheit & Celsius Temperature Scales [3]

Commonly used scales for temperature measurement are **Celsius (°C)** and **Fahrenheit (°F)**.

The equation for conversion b/w Celsius and Fahrenheit –

- Celsius to Fahrenheit: $(°C \times 9/5) + 32 = °F$
- Fahrenheit to Celsius: $(°F - 32) \times 5/9 = °C$

17. Mechanisms of Heat Transfer

4.1 Volumetric Heat capacity

To know if a material can be efficiently used as thermal mass, we can calculate its volumetric heat capacity, which depends directly on its thermo-physical properties.

Volumetric heat capacity (symbol: ρC_p; unit: $kJ/(m^3\text{-}K)$) represents the capacity of a material to store heat. **The higher the volumetric heat capacity of a material is, the more the material can store heat. (**Easier explanation with list of materias that have good Vol heat capacity.**)**

$$\textit{Volumetric Heat Capacity} = (\rho) \cdot (C_p)$$

With:

- Volumetric heat capacity in [kJ/(m3.°C)];
- ρ: density of the material in [kg/m3];
- Cp: Specific heat capacity of the material in [kJ/(kg.°C)]

18. Thermal Conductivity

EXAMPLE 1: *Walking barefoot on a bathroom tile in Winter is annoying since it feels colder than the carpet.*

This is interesting since the carpet and tile are usually both at the same temperature (i.e., the temperature of the house's interior).

The different sensations we feel are explained by how different materials transfer heat at different rates. [9]

Figure 122: Walking on tiles vs. carpet

Tile and stone conduct heat more rapidly than carpet and fabrics, so tile and stone feel colder in Winter since they transfer heat out of your foot faster than the carpet does.

EXAMPLE 2: *Why do metals feel colder in the Winter, and hotter in the summer?*

Materials with a high thermal conductivity constant (like metals and stones) will conduct heat well both ways - into or out of the material. So, suppose your skin comes into contact with metal that is colder than your skin temperature. In that case, the metal can rapidly transfer heat energy out of your hand, making the metal feel particularly cold.

Similarly, suppose the metal is hotter than your skin temperature. In that case, the metal can rapidly transfer heat energy into your hand, making the metal feel particularly hot.

This is why concrete will feel especially cold to our bare feet in Winter (the concrete transfers heat out of our feet rapidly), and especially hot to our bare feet in summer (the concrete transfers heat into our feet rapidly).

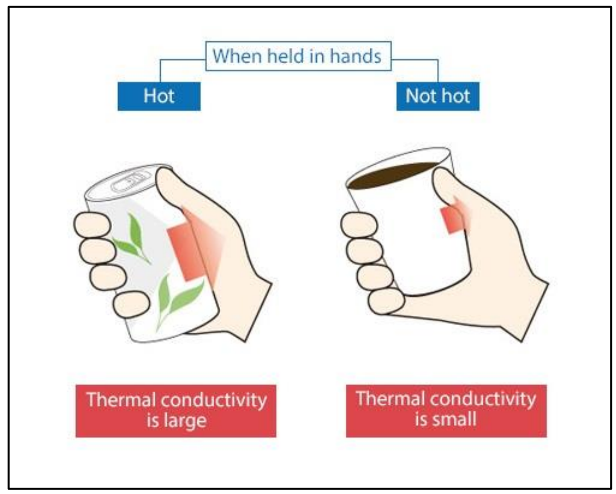

Figure 123: Holding a cup with high thermal conductivity feels hot [10]

Thermal conductivity - The rate at which heat is transferred by conduction through a unit cross-section area of a material when a temperature gradient exists perpendicular to the area.

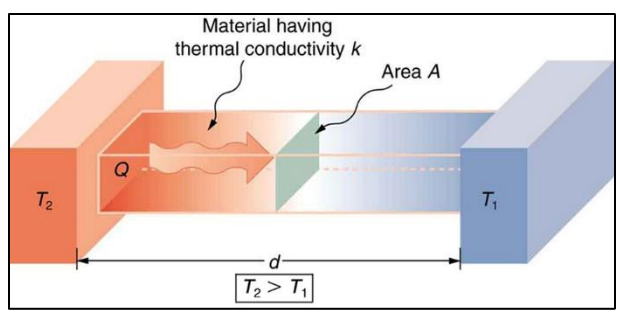

Figure 124: Thermal Conductivity Definition [9]

There are four factors (k, A, ΔT, d) that affect the rate at which heat is conducted through a material.

Formula

$$K = \frac{Qd}{A\Delta T}$$

K = thermal conductivity

Q = amount of heat transferred

d = distance between the two isothermal planes

A = area of the surface

ΔT = difference in temperature

19. Thermal Resistance (R-value)

Thermal resistance is the property of a material by which an object resists the flow of heat flow when a temperature gradient exists through it.

The **R-value** can be defined as the resistance that any specific material offers to the heat flow**. Good insulation material will have a high R-value**. [11]

Thermal resistance (R) and thermal conductance (C) of the materials are reciprocals of one another. They can be derived from thermal conductivity (k) and the thickness of the materials.

The value of the thermal resistance can be determined by dividing the thickness by the thermal conductivity of the specimen.

$$R = \frac{\Delta T}{q} = \frac{L}{k}$$

Thermal Resistance

20. Thermal Transmittance (U-Value)

The use of U-values allows for the comparison of different build-ups for applications, so the insulating properties of a solid wall could be compared to that of a cavity wall, for example. U-value also allows the comparison of two different types of insulation at different thicknesses.

Without knowing the U-value of a wall, floor, or roof, we will not know how energy efficient the whole building will be.

Before starting any building work, we should calculate the U-value as part of the design process.

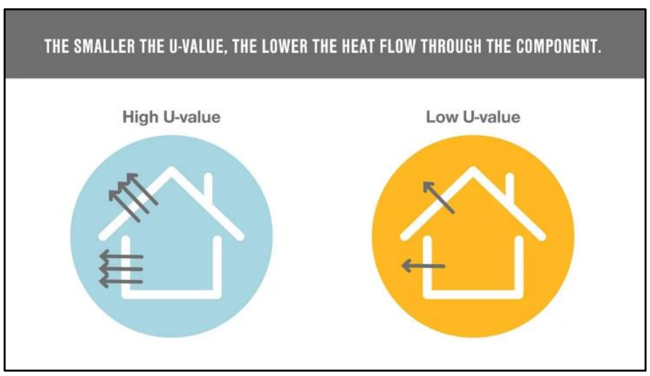

Figure 125: U-value comparison [12]

Thermal transmittance, also known as U-value, is the **rate of heat transfer through a structure** (which can be a single material or a composite), **divided by the difference in temperature across that structure**. The units of measurement are **W/m²K**. **The better insulated a structure is, the lower the U-value will be.**

U-Value is the reciprocal of all resistances of the materials found in the building element. To calculate the U-Value of the building element, the R-Value of all the different components that make up that element need to be considered. [13]

- U-Value = 1/(Sum of all R-Value)
- U-Value (of building element) = 1 / (R_{so} + R_{si} + R_1 + R_2 ...)

where R_{so} is the fixed external resistance, R_{si} is the fixed internal resistance, and R_1, R_2 etc., are the resistivity of all elements within the application, including that of cavities within the construction.

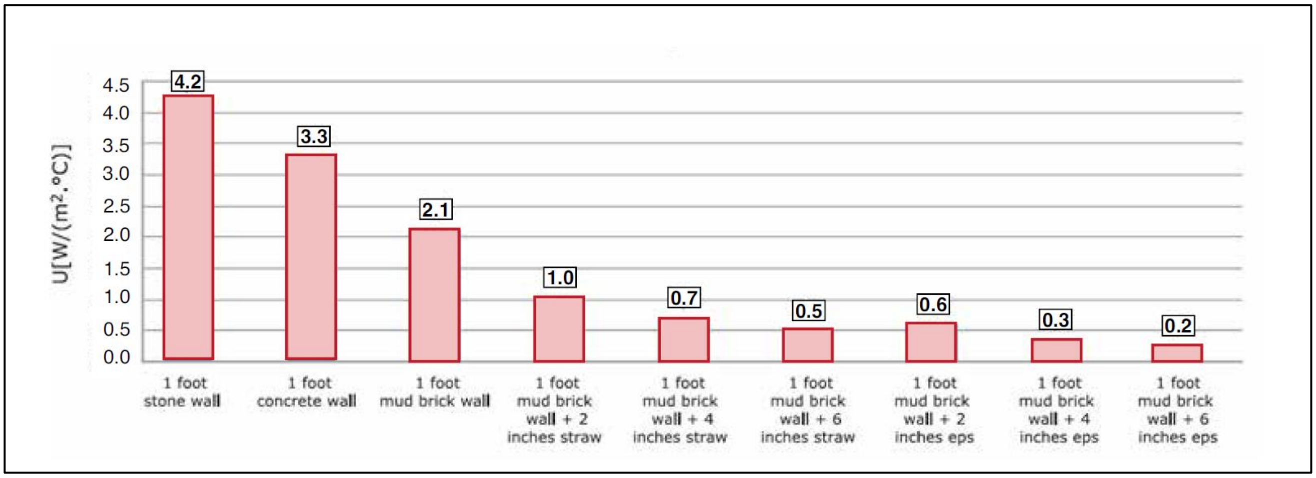

Figure 126: U-value comparison for different types of walls [8]

21. Bibliography

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