Properties and Methodology of Earth Structures

GSD 6400: Energy and Environment
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Abstract

Earth construction offers benefits often under utilized in the developed world, and global energy concerns encourage the use of low-embodied materials such as earth. Understanding the material characteristics of soil can assist in the use of earth as an ecological on-site building material. Earth is modifiable using additives that can be added to obtain desirable properties, and earth construction is possible with a wide variety of building methods for potentially diverse architectural expression. The thermal storage properties and humidity balancing effects of earth can be an important component of passive design.

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Introduction

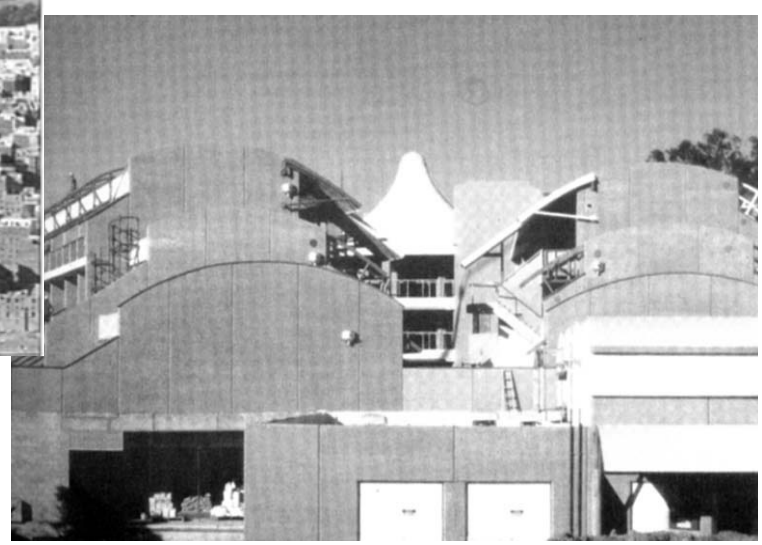
Earth is one of the oldest architectural materials, dating back 10,000 years, with archeological evidence of earth construction found in the earliest cradles of Middle Eastern and Asian civilizations. The Egyptians, Greeks and Romans all developed interesting methods of building with earth, not just for housing and storage, but also for grand monolithic structures. Earth is one of the most widely used construction materials in human history, and every continent has a heritage of building with earth. Today, it is estimated that more than two billion people live in buildings constructed of earth.

Above: Egyptian mud-brick storage rooms (3200 years old).

Why Earth?

Earth as a building material is available everywhere, existing in many different compositions that can be processed in a myriad of ways. In developing countries, earth construction is economically the most efficient means to house the greatest number of people with the least demand on resources. In developed countries, people are re-discovering the beneficial thermal comfort and healthy aspects of earth walls.

Above: Village in Yemen



Above: Modern Rammed Earth Buildings in Australia

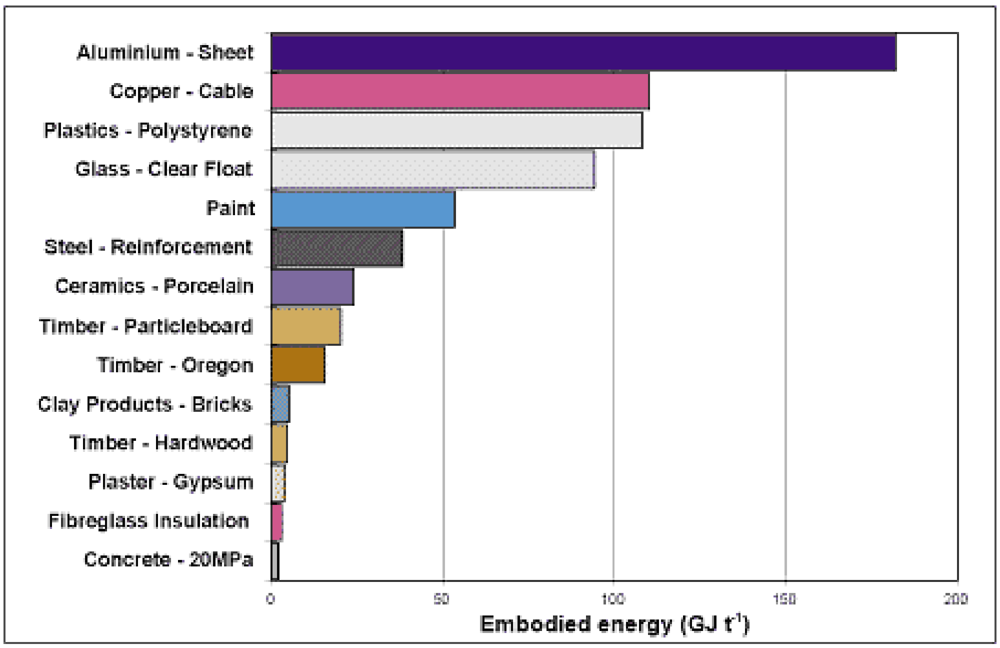
In addition, earth structures are completely recyclable with minimal resource requirements. All over the world, the awareness of the embodied energy of materials and the global impacts of carbon dioxide emissions encourages the use of low-embodied energy materials. It is clear that the use of earth for the built environment will continue to be a strong component in the future of humankind.

Energy Considerations

According to the Environmental Resource Guide, produced by the American Institute of Architects, more than 30% of the energy consumed in the United States goes to making and maintaining buildings. This includes both operating energy--the energy required for space heating and cooling, lighting, refrigeration, water heating and other building functions--and energy embodied in the physical structure. Earth construction can reduce both categories of energy requirements.

Embodied Energy

Although most earth construction methods are more labor intensive than other methods of construction, earth walls are significantly lower in embodied energy than other structural materials. Energy costs related to the transportation of building materials can be reduced with the use of materials found on or near the site. To prepare earth for building, only a fraction of the energy needed for the production, transport, and handling is required compared to timber or reinforced concrete.



Above: Embodied Energy of common building materials

Comparison of Masonry Materials

In 1984, Paul McHenry compared the embodied energy of common masonry materials, and found that even mechanically processed adobe bricks had significantly less embodied energy compared to bricks and concrete. In addition, the use of adobe avoids the localized atmospheric detriments of concrete production. For comparison:

PRODUCTION ENERGY COSTS OF MASONRY MATERIALS
Common Fired Brick: 218 Btu/in3
Concrete Block: 28.3 Btu/in3
Adobe Brick: 4.46 Btu/in3

Earth as Material

In order to understand the process of building with earth, it important to understand the mechanics of the material and how to make best make use of the soil on site. This requires a close look at the macro-structure of soil and an understanding of the properties that make it a viable building material. If necessary, on-site material can be modified appropriately by either refining or adding material brought to the site such as sand or lime. Even with a sizable proportion of the material is brought in from other sources, a considerable overall energy savings can be achieved. As in all architectural efforts, an in-depth knowledge of the material is essential for good design.

Properties of Soil

Soil is the result of erosion of rock. The characteristics of soil depend on the transformation from the parent rock, which involves physical, organic and chemical processes that take place over geologic time periods. Soils derived from a strong parent rock (e.g. granite) create a strong material for earth construction. The properties of soil vary depending on location, and different types of soil are more appropriate for different construction methods.

Composition

Soil is a mixture of aggregates, sand, silt, clay, water, and organic material. Organic material may consist of living flora and fauna, decomposing plants and animal waste, and colloids other than clay including humus and bacterial glues. Generally in earth construction it is advantageous to use soil without organic material, which gives a musty odor and may decompose, although pure peat houses are common in some parts of the world. Sub-soil dug at least 12” below the surface is generally free from significant organic material.

Component Size

Components in soil larger than 20mm in diameter (pebbles and stones) are generally not beneficial to the architectural properties of soil and can be sifted out prior to using soil as a building material. Gravel between 2mm and 20mm in diameter can act as a skeleton of the soil. Sand (particles between 0.06mm to 2mm in diameter), and silt (particles ranging from 0.002mm to 0.06mm) are particles of silica, quartz and other minerals, and are indistinguishable from a physical and chemical point of view, yet have different swell and shrinkage properties. Generally, the smaller the particle, the greater the swell in contact with water. Clay grains are the majority of particles smaller than 0.002mm. Particles smaller than 0.002mm also exist in soil, notably smaller quartz crystals silicates, and extremely fine crystals of limestone, magnesium, and iron oxides. A simple test to determine the ratios of each component can be made by adding water and soil in a jar, mixing thoroughly, and allowing to settle. The components will separate according to size with the largest on the bottom allowing a visual representation of the proportions.

2.2-1 Sedimentation test (CRATerre, 1979)

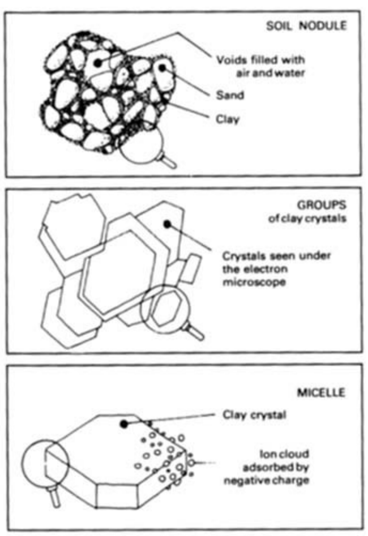
Water in Soil

There are several categories of water found in soil. Most water (free water) in soil will be removed by a normal drying process, which can cause the material to shrink. Pore water is water bound in the pores of the material and will evaporate at normal temperatures over a longer period of time. Absorbed water is water electrically bound to the grains of the soil and can only be removed if the soil is heated to at least 100 degrees Celsius. Water is also found as hydroxyl groups bound to the clay particles; this type of water is called the water of crystallization. The water of crystallization is beneficial to the binding forces in the clay and will only be removed from the soil if it is heated to 600 degrees Celsius.

Soil Binding Forces

Gravels, sand and silt enhance the compressive strength of the soil, but not significantly to the binding forces. Clay, the smallest component, acts as the primary binder in soil, just as cement acts as the primary binder in concrete. Other less influential binding forces in soil result from the friction among particles, cementation (the binding of particles as a result of chemical agents), capillary forces (attraction between particles and water molecules trapped in the pores of the soil), and Van der Walls' forces (the electromagnetic cohesive force).

Types of Clay



Clay minerals, in chemical terms, are hydrated alumino-silicates. Clays particles are elongated and platelike, and therefore have a much greater surface area than the other particles in soil, which are generally more spherical. The flat structure of clay allows it to bind strongly together, and while the larger particles in soil are electrically neutral, particles of clay are generally either negatively or positively charged, resulting in a strong electro-chemical bond. There are three main types of clay: kaolinites, illites, and montmorillonites. Each has a different swelling response to water: whereas kaolinites are generally stable in contact with water, illite and especially montmorillonite clays are less stable with water and swell considerably. In general, soil with between 15 and 30% clay makes for good building material.

Balanced Construction Soil

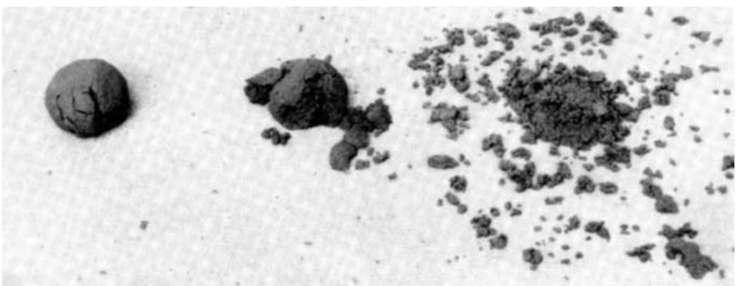
Suitable soils for construction purposes need to have a balanced amount of sand, silt, and clay. Soil with excessive sands and silts will tend to crumble when dried out, while soils rich in clays will shrink excessively and form cracks in the drying process. Suitable testing of the soil is required prior to construction, and additional clay or sand may need to be added to create a balanced natural building material.

Properties of Soil for Building

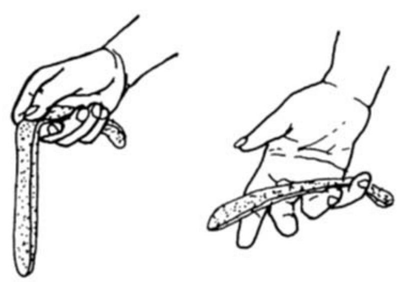
The main properties to consider when using soil as a building material are the potential for structural integrity related to density and strength, and the amount of shrinkage as the material dries out. Material with too high a clay content will shrink excessively when drying and cause cracking. Other advantageous factors of finished soil include moderate moisture absorption, high resistance to erosion and abrasion, and moderate thermal expansion/contraction characteristics.

General Indicators

Simple tests can determine a soil's properties and consistency. One can be performed by sampling soil that is as dry as possible (moisture content 15 to 30%) yet still able to be formed into a ball. Dropping the ball of soil from head height onto a hard surface will indicate general characteristics. If the ball of soil explodes, it is too sandy and cannot be used as a building material. If it flattens slightly and does not crack, it will probably have too much clay and must be thinned by adding sand. A good soil will retain its shape and crack only slightly after being dropped. Another conceptual indicator of the soil is given by a cohesion test. The cohesion of a soil can be measured roughly by first kneading moist soil and then rolling it into a thread about 1/4 inch in diameter. The thread is flattened and then pushed over an edge until it breaks. The length of the material at breakage indicates the amount of cohesion: if it breaks after a few inches, the material has little cohesion and will require additional binding agents (clay). If it breaks at more than 8", the material may have too much clay requiring additional sand. Prior to building, accurate testing of the soil properties of the site can be determined by digging a trench two meters deep and taking soil samples at varying layers in the trench. Composition of each layer can be determined by a geotechnical laboratory, or by additional tests made with specialized equipment. Often an optimal soil can be made by mixing various quantities of individual layers. Other factors such as color may also be modified by mixing soils found on site.



Soil Sampling. Right: too sandy. Left: good clay content.



Above: Cohesion test

Density

Density and strength in soil are generally proportionally related, and higher densities are preferred for thermal storage aspects. The density of freshly dug soil typically varies between 1000kg/m3 and 1500kg/m3. Compatibility of a soil is the measure of the soil's potential to reduce its porosity to a minimum, and is measured by the

Proctor compaction test. To achieve maximum compaction, the soil must have an optimal water content, which allows the particles to slide into a denser configuration without too much friction. It is also possible to over compact the soil so that the strength is compromised. Rammed earth after normal compaction will have a density between 1700kg/m3 and 2200kg/m3.

Strength

The strength of dry building elements varies depending on composition and processing method. The quality and type of clay, and the grain distribution of silt, sand, and larger aggregates affect the basic strength. Compressive strength of processed soil can vary from 300 to 700psi (for comparison, typical concrete varies from 2000 to 6000psi). Calculations on a five story rammed earth house built in 1828 and still standing, it was found that the maximum compressive force at the bottom of the building was only106psi.

Above: 1828 five-story rammed earth building in Weilburg, Germany.

Shrinkage

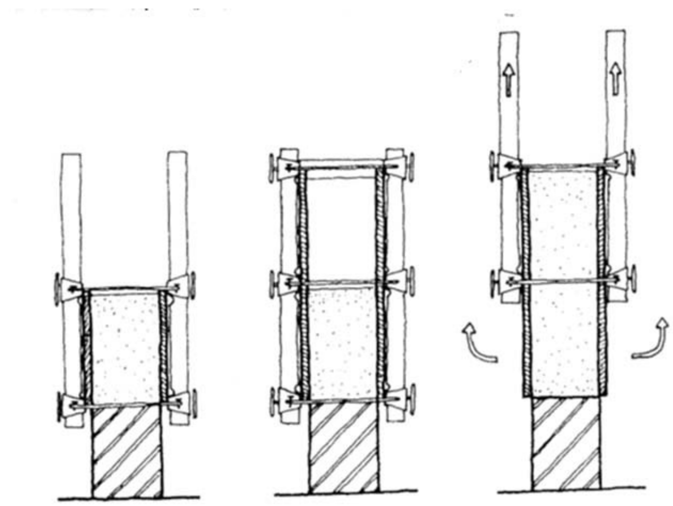
Controlling shrinkage can be a major challenge when building with earth. Shrinkage is related to the water content: soil swells when water is added and shrinks as the water dries out. Shrinkage is highly dependent on the type of clay, and on the grain distribution of silt and sand. Typical soil without additional additives will shrink between 3% and 12% with wet mixtures, and between 0.4% and 2% for drier mixtures (such as soil used for rammed earth or compressed adobe blocks). Generally, shrinkage can be controlled by increasing the percentage of sand to the soil, and by increasing the drying time. Other additives, including whey, straw and hair fibers, and gypsum, can also be incorporated into the soil mixture to control shrinkage. The effects of additives are not universal, and varying sources give contradictory information on the effects of individual additives, especially regarding gypsum (hydrous calcium suphate). This is likely attributable to the varying proportions of the types of clay found in earth, which respond differently to different additives. Clearly this is a promising future field of additional research.

Other Additives

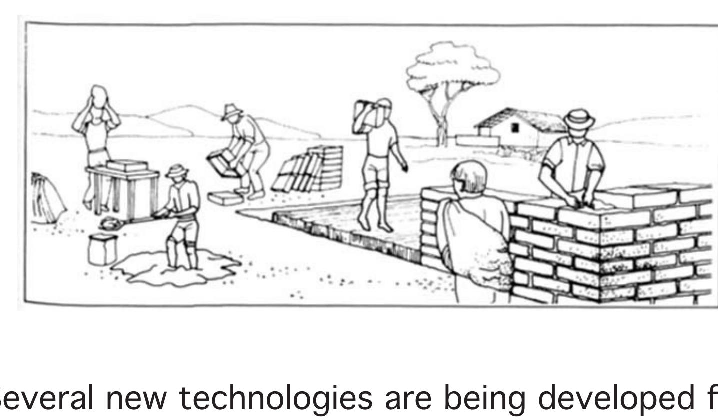
Lime, cement and bitumen are common additives to soil. Cement in proportions from 2 to 8% is used generally for sandy soils to increase stabilization, strength, and durability. A slow drying time is required for cement stabilized soil, otherwise the addition of the cement can result in detrimental effects. Non-hydraulic slaked lime $(CaOH)_2$ is often used with clayey soils in proportions from 2-5%. Slaked lime strengthens the binding action of the clay and limits the penetration of water into the fine particles, reducing shrinkage. Quicklime (CaO) is also used, but is more difficult to work with as it caustic and absorbs water quickly. Hydraulic and agricultural limes have little beneficial effect on soils. Bitumen (2-3%) is often used for soils with a low clay content to add to the weather resistance of processed soil. Here again, different sources cite widely varying results of additives, and specific testing is required on the local soils. Finally, other additives can be added to enhance the thermal properties of earth. Earth itself is not a good insulator. The use of a natural material like expanded perlite can enhance the insulating properties.

Part 3: Building Methods

There are many methods of building with earth, and the type of soil and the building method should be considered together. For example, a sandy soil may be more preferable for monolithic construction, while a clayey soil may be more appropriate for segmented construction. The main types of monolithic constructions include rammed earth (known as pise de terra in France), and poured earth. Monolithic formwork can either be removable or integrated into the structure (lost form methods). Segmented construction can include abobe (uncompressed dried bricks), compressed blocks, daub (shaping earth using a built framework), and various ways of stacking wet soil with balls of soil or extruded sections (cob, stranglehm, and direct forming). All methods offer unlimited possibilities for unique architectural expression and effective thermal design.



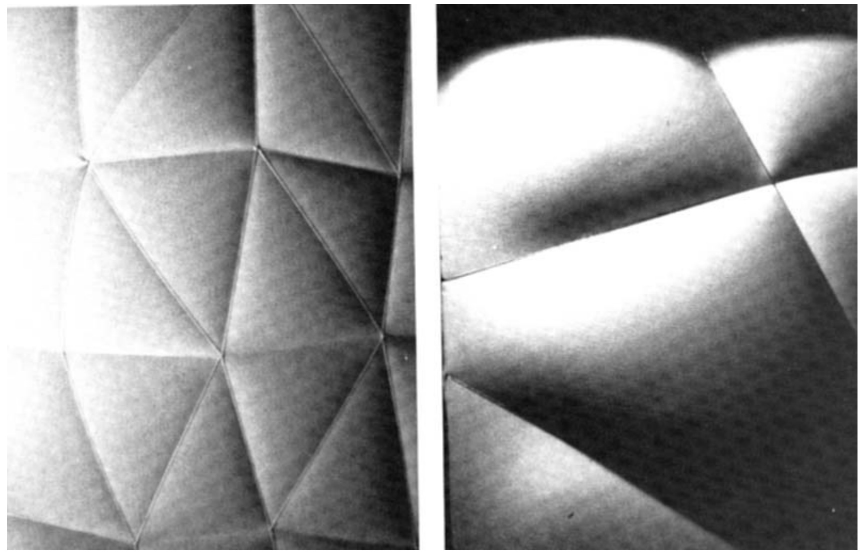
Above: Sliding Formwork for Rammed Earth



Left: Adobe Site Work. Right: Daub Techniques of laying earth on a framework.

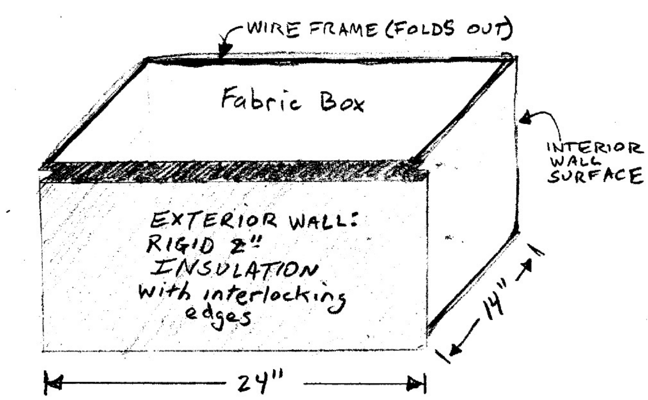
Several new technologies are being developed for earth construction. David Easton has developed methods for spraying earth using existing gunite (sprayed concrete) tools. The earth is mixed with concrete and walls of 16" thick can be produced by spraying the earth on a formwork panel.

Although pouring earth into formwork is an old technique, new interest is sparked by the economics and wide availability of concrete mixing equipment. In 1985, Ruhi Kafescioglu from the Technical University of Istanbul studied the effects of gypsum and found it to moderate shrinkage. Recently, Michael Frerking in Arizona has become a proponent of building with a poured earth/calcined gypsum mix. Additional retarders are added to manage the gypsum's set times. Using concrete technology, a large house with 24" walls can poured in a day. Poured earth using lost fabric formwork has been experimented with by Gernot Minke and the Research for Experimental Building (FEB) center at the University of Kassel, Germany, and the results offer an interesting surface textures. Further research will determine the longevity of poured earth in lost fabric construction the effects of the fabric on the humidity balancing factors of such construction.



Above: Lost fabric formwork for poured earth.

A method being investigated by the author is using a lost form method using a fabric box with one vertical surface made of rigid insulation for the external surface. The insulating surface would also give structure to the container which then can be filled with earth.



Above: Fabric box with one side of rigid insultion for building segmented earth wall.

Part 4: Thermal and Comfort Aspects of Earth Construction

"There is a certain magic to living in buildings with thick earth walls. It's hard to describe, but easy to notice. Just take a step inside one on some warm summer day and you'll feel it immediately. It's cool, of course—everyone knows adobe houses are "warm in winter and cool in summer" but there's something else, too, a little harder to put your finger on. "It's quiet, feels somehow incredibly solid and sturdy, very different from other houses, timeless even." I once had a happy homeowner tell me walking into her rammed earth house was like walking into her lover's outstretched arms.
--from The Rammed Earth House, David Easton.

Comfort

In addition to the lower energy requirements of using earth mass for structure due to its inherent thermal mass which can store the daytime heat for extended periods, there are also significant advantages in terms of human comfort. Additional reasons for why earth makes for comfortable interiors is seen is when you consider the 4 methods of how the body transfers energy form and to the environment:

- Conduction
- Convection
- Radiative
- Evaporative

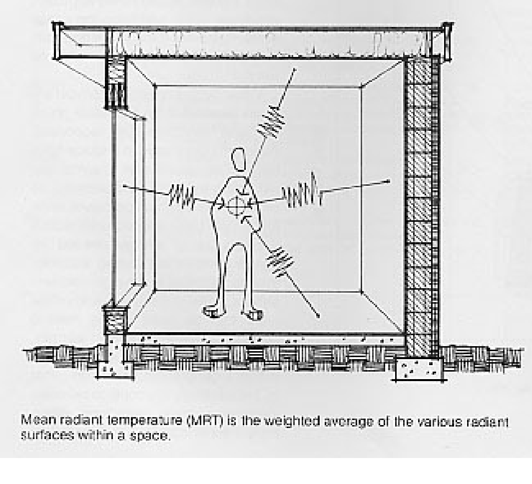
Of these, the last two (radiative and evaporative) play an important role in earth construction.

Radiative Heat Transfer

The benefits of a warm or cool wall contribute to human comfort significantly. For example, on a cold day, occupants of a room in a traditional insulated timber house with large windows can feel cold even if the air temperature in the room is 80 degree F. Similarly, people can feel hot in a room with a lot of hot surfaces even if the air temperature is less than 65 degrees F. The characteristics of earth walls to maintain average temperatures contribute to the radiative aspect of comfort.

Radiative Properties

Emissivity (e) and absorptivity (a) and are properties of a material which determine radiant exchange of a surface with its environment. Emissivity is the main factor which determines the heat exchange response of long wave (thermal) radiation. The emissivity is high (e = 0.9) for masonry surfaces. Radiation heat transfer is measured by Boltzman's equation which indicates that the heat transfer is dependent on the emissivity and the temperature to the fourth power. From the mathematics we can get an idea of the beneficial aspects regarding comfort in having moderate interior surface temperatures.



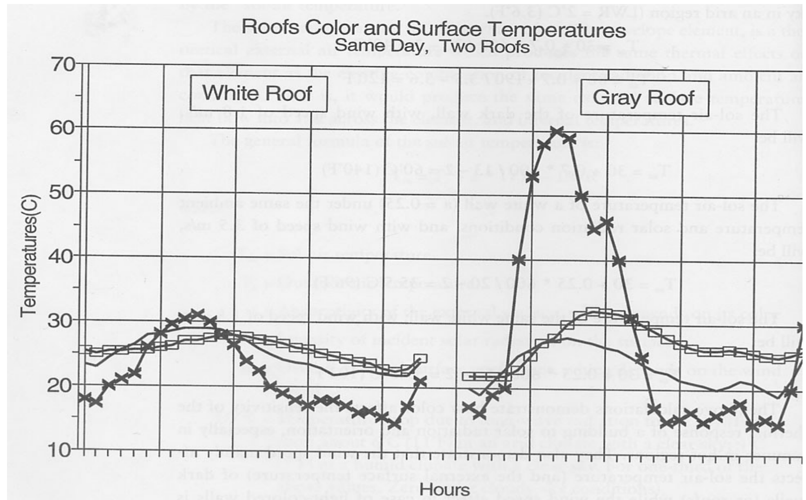
Mean radiant temperature (MRT) is the weighted average of the various radiant surfaces within a space.

Solar Absorptivity

Absorptivity, on the other hand, is the main factor in determining the temperature response to the absorption of short-wave (solar) radiation, and is dependent largely by color. The surface temperature can be measured by the ambient temperature and the amount of incoming solar radiation:

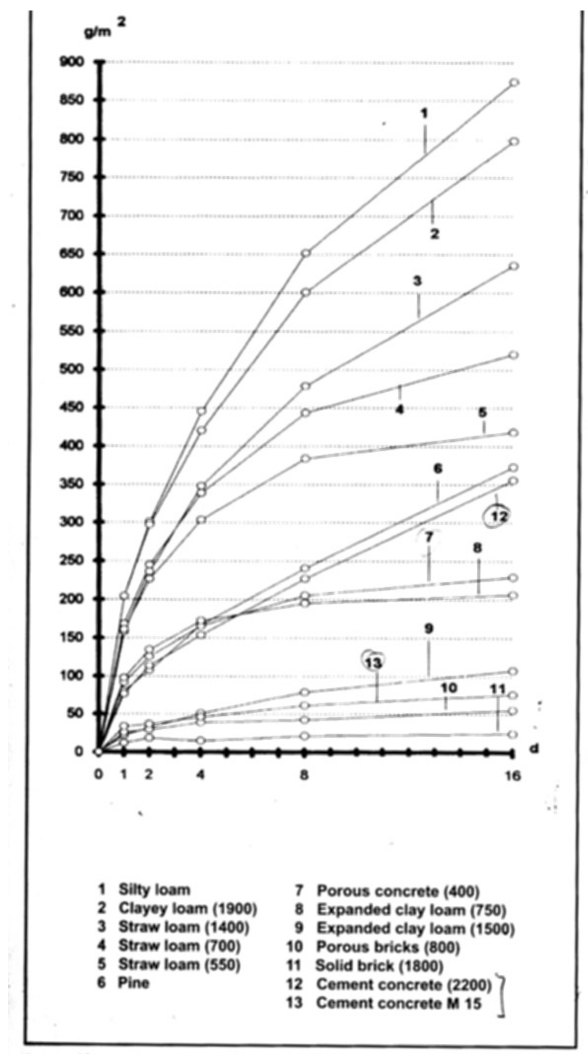
$$T_{sol\text{-}air} = T_o + (a*I/h_o) - LWR$$

where I is the incident solar radiation, h_o is the external surface coefficient, and LWR is a function of the long-wave radiation to the sky (~6º for clear sky, 0º for cloudy sky). The absorptivity for earth walls allows them to absorb and store the daytime energy.



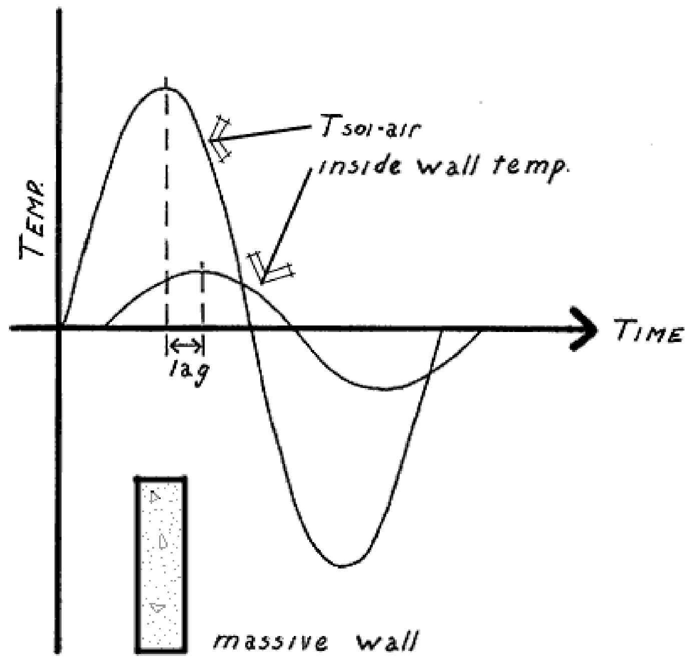
Porosity-the Miracle of Earth Walls

Humidity is another major factor in experiencing comfortable conditions. The ability of earth walls to balance the indoor climate by absorbing and releasing humidity and thus creating a healthy interior is unmatched by other materials. Recent research by the University of Kassel in Germany has shown that the first 1.5cm thick layer of an unfired mud brick wall is able to absorb about 300grams of water per square meter of wall surface in 48 hours if the humidity is increased from 50% to 80%. Comparison with other material are shown in the chart. In addition, recent research has shown that earth walls can actually absorb air pollutants. The choice of interior finish is critical if the absorption quality of earth walls is to be preserved. Gernot Minke recommends for aesthetics and ease of cleaning casein (pure or mixed with lime) or linseed oil as a interior finish.



1.4-4 Absorption curves of 11.5 cm thick interior walls with two sides exposed at a temperature of 21°C after a sudden rise in humidity from 50% to 80%

Thermal Mass Basics



Thermal mass refers to materials have the capacity to store thermal energy for extended periods. Thermal mass can be used effectively to absorb daytime heat gains (reducing cooling load) and release the heat during the night (reducing heat load). The use of thermal mass in shelter dates back to the dawn of humans, and until recently has been the prevailing strategy for building climate control in hot regions. Today, passive techniques such as thermal mass are ironically considered "alternative" methods to mechanical heating and cooling, yet the appropriate use of thermal mass offers an efficient integration of structure and thermal services.

Heat Storage and Diffusivity

The basic properties that indicate thermal behavior of materials are the density, specific heat, and conductivity. For earth and most masonry materials the specific heat ranges from 0.2 to 0.25Wh/kgC. The total heat storage capability is related to the density and volume of material (mass). Diffusivity is the measure of how fast heat travels through the material, and is a function of the conductivity divided by the product of the density and specific heat (units: area/time). The time lag between outside and inside peak temperatures is a function of the thickness of the material divided by the square root of the diffusivity. For solid masonry materials, conductivity can be approximated as a function of density, though precise values will vary according to moisture content :
k=0.072exp(1.35x(density/1000)).
Using these relations, we find that diffusivity has a non-linear relation to density. For example, the diffusivity of 2200kg/m^3 earth walls (k=1.3) is only 1.8 times the diffusivity of 600kg/m^3 (k=0.2) earth walls.

Thermal Time Constant

One of the more important mathematical constructs to imagine the behavior of thermal mass is the Thermal Time Constant of an building envelope, defined as the product of the heat capacity (Q) and the resistance (R) to heat transmission. The TTC is representative of the effective thermal capacity of a building.

To calculate the TTC of an area, the heat capacity per unit area (Q_A) is multiplied by the resistance to heat flow of that area (where Q_A=thickness*density*specific heat, R=thickness/conductivity). In calculating the TTC_A (TTC per area) of a composite wall, the Q_AR value of each layer, including the outside and inside air layers, is calculated in sequence. The Q_AR for each layer is calculated from the external wall to the center of the section in question, thus:

$$Q_{Ai}R_i = (c_m * l * p)_i * (R_0 + R_1 + \ldots + 0.5R_i)$$

For a composite surface of n layers, $TTC_A = Q_{A1}R_1 + Q_{A2}R_2 + \ldots Q_{An}R_n$.

The TTC_s for each surface is the product of the TTC_A multiplied by the area. Glazed areas are assumed to have a TTC of 0. The total TTC_{total} of the building envelope equals the sum of all TTC_s divided by the total envelope area, including the glazing areas. A high TTC indicates a high thermal inertia of the building and results in a strong suppression of the interior temperature swing.

Example TTC Calculations

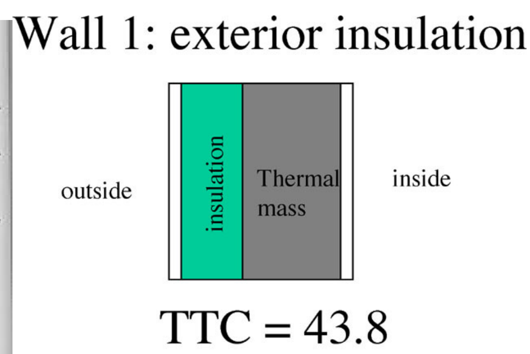
TABLE 3-8. CALCULATION OF THE THERMAL TIME CONSTANT OF 2 WALLS (METRIC)

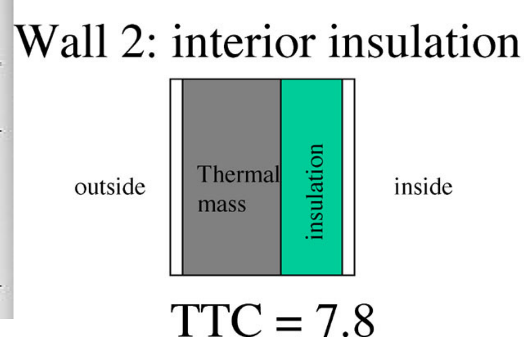
Wall #1

LAYER	THICK l_i(m)	DENSITY ρ_i(Kg/m³)	RESIST. r_i	CUMULAT. RESIST.	HC ρ*c	QR_i Hr
Ext. surface						0.03
Ext. plaster	0.02	1800	0.025	0.0425	414	0.35
Polystyrene	0.025	30	0.71	0.41	12	0.12
Concrete	0.10	2200	0.06	0.795	506	40.2
Int. plaster	0.01	1600	0.014	0.832	368	3.1
Wall's TTC						43.8

Wall #2

LAYER	THICK l_i(m)	DENSITY ρ_i(Kg/m³)	RESIST. r_i	CUMULAT. RESIST.	HC ρ*c	QR_i Hr
Ext. surface						0.03
Ext. plaster	0.02	1800	0.025	0.0425	414	0.35
Concrete	0.10	2200	0.06	0.085	506	4.3
Polystyrene	0.025	30	0.71	0.47	12	0.14
Int. plaster	0.01	1600	0.014	0.832	368	3.1
Wall's TTC						7.8





Diurnal Heat Capacity

The DHC is a measure of the building's capacity to absorb solar energy coming into the interior of the space, and to release the heat to the interior during the night hours. The DHC is of particular importance for buildings with direct solar gain.

The DHC of a material is a function of building material's density, specific heat, conductivity, and thickness. The total DHC of a building is calculated by summing the DHC values of each surface exposed to the interior air.

$DHC_{per\ area} = F_1 s$

From Balcomb, the temperature swing can be calculated from the DHC:
Delta T(swing)= $0.61Q_s/DHC_{total,}$, where Qs is the daily total solar energy absorbed.

Note that the DHC for a material increases initially with thickness, then falls off at around 5”. This behavior reflects the fact that after a certain thickness, some of the heat transferred to the surface will be contained in the mass rather than returned to the room during a 24 hour period.

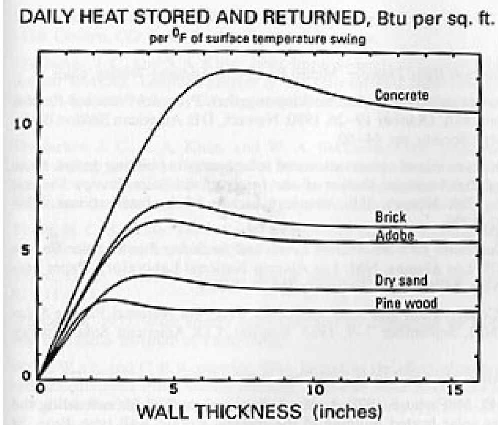


Figure 4.9
Diurnal heat capacity vs. thickness for various storage media. Source: Balcomb

$s = \sqrt{Pk\rho c/2\pi},$

$F_1 = \sqrt{(\cosh 2x - \cos 2x)/(\cosh 2x + \cos 2x)},$

$x = L\sqrt{\pi\rho c/Pk},$

TTC and DHC

Relative values of TTC indicate the thermal capacity of the building when a building is affected mostly by heat flow across the opaque parts of the envelope (i.e., when it is unventilated, and when solar gain is small relative to the total heat transfer through the building envelope). Relative values of DHC, on the other hand, indicate the thermal capacity for buildings where solar gain is considerable. The DHC also is a measure of how much “coolth” the building can store during the night in a night ventilated building. Both measures indicate the amount of interior temperature swing that can be expected based on outdoor temperatures (higher values indicate less swing).

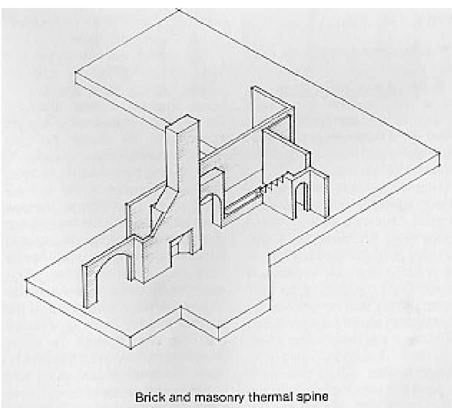
TTC and DHC Examples

Building which is externally insulated with internal exposed mass.
Here, both TTC and DHC are high. When the building is ventilated at night and closed during the day, it can absorb the heat in the mass with relatively small indoor temperature rise. Best for hot-dry regions.
Building with mass insulated internally.
Here, both the TTC is and DHC are low. The mass will store energy and release energy mostly to the exterior, and the thermal response is similar to a low mass building.
Building with high mass insulated externally and internally.
Here, the building has a high TTC, but a negligible DHC, as the interior insulation separates the mass from the interior. When the building is closed and the solar gain is minimized, the mass will dampen the temperature swing, but if the building is ventilated, the effect of the mass will be negated. With solar gain, the inside temperature will rise quickly, as the insulation prevents absorption of the energy by the mass.
Building with core insulation inside two layers of mass.
Here the TTC is a function of mostly the interior mass and the amount of insulation, and the DHC is a function on the interior mass. The external mass influences heat loss and gain by affecting the delta T across the insulation.

Design Strategies

It is clear that with the many ways of forming earth, a wide variety of architectural expression is possible. Depending on the consistency of the soil, variations in surface texture and color are also possible and modifiable. Good thermal design with earth follows the principles of passive solar design, where mass is used in areas which can absorb daytime heat gains. From the analysis of thermal mass, it is also evident that insulation can be used effectively on the exterior walls which are not exposed to considerable solar gain, whereas the south walls could be left uninsulated in moderate climates to optimize external solar gain. Interior mass can be optimized in areas exposed to direct sunlight though the fenestration. Courtyard and other architectural features may be considered.

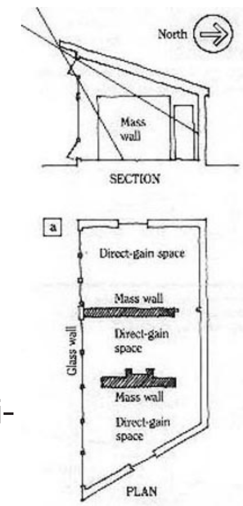
Adobe Dome with skylight.



Above: Interior thermal “spine”.

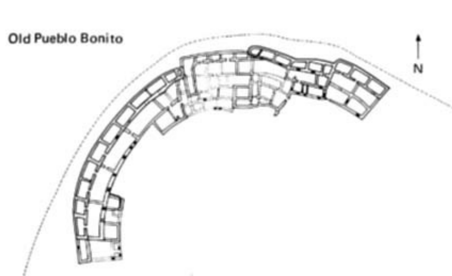
Prior to the architectural design of buildings with earth, it is important to outline the general thermal performance that is desired, for example, in a hot climate, the parameters may include:

- Slow rate of indoor heating in summer (minimize solar gain).
- Fast rate of indoor cooling and ventilation in summer evenings.
- Higher indoor temperatures during the day in winter.
- Slow release of stored heat during winter night.



Above: interior mass walls near south glass.

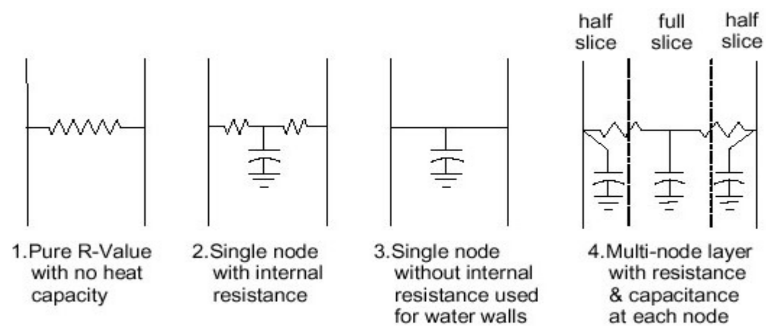
The outline of desired parameters can help integrate the design the ventilation and cooling systems, window size and locations, and radiant heat systems. Other factors to consider include acoustics, fire and earthquake resistance, and codes. Many examples of architecture have proved that passive thermal engineering can be integrated with the aesthetic design. Familiarity with the principles of the site specific thermal aspects can help with optimizing choices.



Left: The plan of the original Pueblo Bonito in New Mexico (built 900AD) has a southeastern orientation is aligned with great precision to the angle of the winter solstice sunrise. This orientation captures the maximum amount of winter sun when warmth is needed. Behind the site on the North side is a tall cliff which along with the orientation reduces the amount of summer morning and evening solar gains.

Appendix 1: Computer analysis programs that include contributions of thermal mass.

Sunrel (National Renewable Energy Laboratory)
A general-purpose thermal analysis program for residential buildings. The solution approach is a thermal network using a combination of forward finite differencing, Jacobian iteration, and constrained optimization. It was written to aid in the design of small energy efficient buildings, where the loads are dominated by the dynamic interaction of the building envelope, the environment, and the occupants. It is especially appropriate for buildings that incorporate energy efficient design features, such as: moveable insulation, control of interior shading, energy efficient windows, thermochromic switchable glazings, and thermal storage in Trombe walls, water walls, phase change materials and rockbins. Energy efficient buildings tend to be more free floating than buildings which are tightly controlled by large HVAC systems, therefore, proper design is essential for comfort and usability. The goal was to create a program that was simple to use with sophisticated thermal models and yet maintain flexibility to accommodate additional computational modules by researchers. Sunrel allows for the description of the wall as composed of one or more layers of material. Each of these layers may consist of either an R-value or a specified material described by its thickness, specific heat, density, and conductivity. In this way, walls of almost arbitrary complexity may be treated. Additionally, if the walls are part of an exterior surface and the user wishes to determine the effects of solar energy on the wall, the azimuth, absorptance, and parameters for shading can also be specified.



Solar 5 (University of California at Los Angeles)
Displays 3-D plots of hourly energy performance for the whole building. SOLAR-5 also plots heat flow into/out of thermal mass, and indoor air temperature, daylighting, HVAC system size, cost of electricity and heating fuel. Only four pieces of data initially required (floor area, number of stories, location, and building type), the expert system designs a basic building, filling in hundreds of items of data; user can make subsequent revisions.

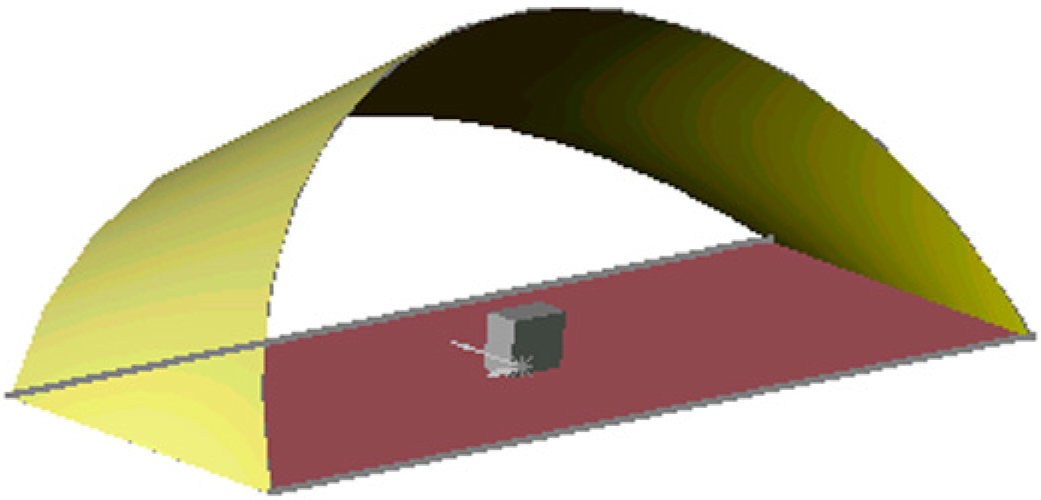
Energy 10 (Passive Solar Industries Council)
Design tool for smaller residential or commercial buildings that are less than 10,000 ft2 floor area, or buildings which can be treated as one or two-zone increments. Performs yearly whole-building energy analysis, including dynamic thermal and daylighting calculations. Passive Solar Industries Council.

BuilderGuide (National Renewable Energy Laboratory)
Design tool for residences that calculates annual heating and cooling estimates of loads based on simplified, but validated, algorithms; especially suitable for evaluating passive solar houses. Uses solar-load-ratio method (modified degree-day), diurnal heat capacity method, and simplified cooling load method.

Micropas4 (Enercomp, Inc.) Energy simulation program which performs hourly calculations to estimate annual energy usage for heating, cooling and water heating in residential buildings. Data is required describing each building thermal zone,opaque surfaces, fenestration, thermal mass. Used extensively for California code requirements. Calculates HVAC size and U-values.

Blast: (Building Systems Laboratory, University of Illinois)
Performs hourly simulations of buildings to provide accurate estimates of a building's energy needs. The zone models of BLAST (Building Loads Analysis and System Thermodynamics), which are based on the fundamental heat balance method.

Appendix 2: A method of visualizing annual solar paths for design.



Above: Annual Solar Paths in relation to a building site.

By analyzing the visual representation of the sun paths from the winter to the summer solstices, one can see how the building will experience solar gain throughout the year. Programming can color-code of the sun paths depending on when daytime gain is desired (winter), and when gain is undesired (summer). The color coded paths can then be linked to color coded surfaces and shadows on the building. With this visual information, architectural features can be modified to optimize thermal performance, as well as the size and location of shading devices.

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