Building Construction Department, Virginia Tech
Project Report
Peter Stephenson
Advisors: Dr. Annie Pearce, Prof. Michael O'Brien, Dr. James Jones

Background

Concrete and other masonry products have been used in passive solar heating/cooling systems for some time. Concrete has high thermal mass, meaning it can absorb and store a large amount of heat energy. Its heat capacity is 1000 J/kgC (http://edboyden.org/constants.html) (Heat Capacity = density x specific heat). Its application in buildings is to provide thermal lag for temperature swings and reduce the peaks of heating and cooling loads. Conceptually the concrete thermal mass will absorb the sun's energy and heat during a hot day, lowering the cooling load, and slowly release that energy at night lowering the heating load.

It is a simple model and assumes a predictable outdoor temperature cycle. It is most suited to a desert climate where very hot days and very cold nights are typical (diurnal extremes). Whatever the geographic region careful attention has to be paid to the specific site's climate; sun orientation, building use, etc. to determine the correct amount and placement of thermal mass for an effective passive heating/cooling system. Despite good planning thermal mass can become ineffective or even detrimental for comfortable indoor temperatures during unusual weather.

In the case of continuous hot, sunny days and moderate temperatures at night thermal mass can become saturated with heat energy. In this case excess heat given off at night is undesirable and the cooling effect during the day will be naught as the thermal mass is saturated and cannot absorb more heat. The result will be higher cooling loads and expenses compared to no thermal mass system at all. A permeable concrete system may fix this problem.

What is Permeable Concrete?

Permeable/Pervious/Porous Concrete is basically a mixture of concrete without smaller aggregates and less water. When it cures it contains cavities, 15%-25% (Farny 2004) voids where normal concrete would be solid. Traditional concrete can have air bubbles and its void ratio is variable on mixture, admixtures and conditions however for this study it was assumed that traditional concrete is monolithic. Pervious concrete's typical application so far has been in pavement and its ability to allow rainwater to seep through the voids and disperse into the ground naturally, rather than having to collect and process for normal storm water drainage and management. Some typical qualities of pervious concrete are listed in Figure 1.

Property	Typical Values
Slump	20 mm (3/4 in.)
Density (unit weight)	1600 to 2000 kg/m^3 (100 to 125 lb/ft^3)
Setting time	1 hour*
Porosity	15% to 25% by volume
Permeability (flow rate)	120 $L/m^2/min$ to 320 $L/m^2/min$** (3 $gal/ft^2/min$ to 8 $gal/ft^2/min$)
Compressive strength	3.5 MPa to 28 MPa (500 psi to 4000 psi)
Flexural strength	1 MPa to 3.8 MPa (150 psi to 550 psi)
Shrinkage	200×10^{-6}

* May be extended to as much as 2.5 hours with chemical admixtures.

** Laboratory mixtures with flow rates as high as 700 $L/m^2/min$ (17 $gal/ft^2/min$) have been prepared.

Figure 1 – Farny (2004) Basic characteristics of Permeable Concrete

Heat Islands and Permeable Concrete

There are three basic methods by which heat is transferred: conduction, radiation and convection. See figure 2.

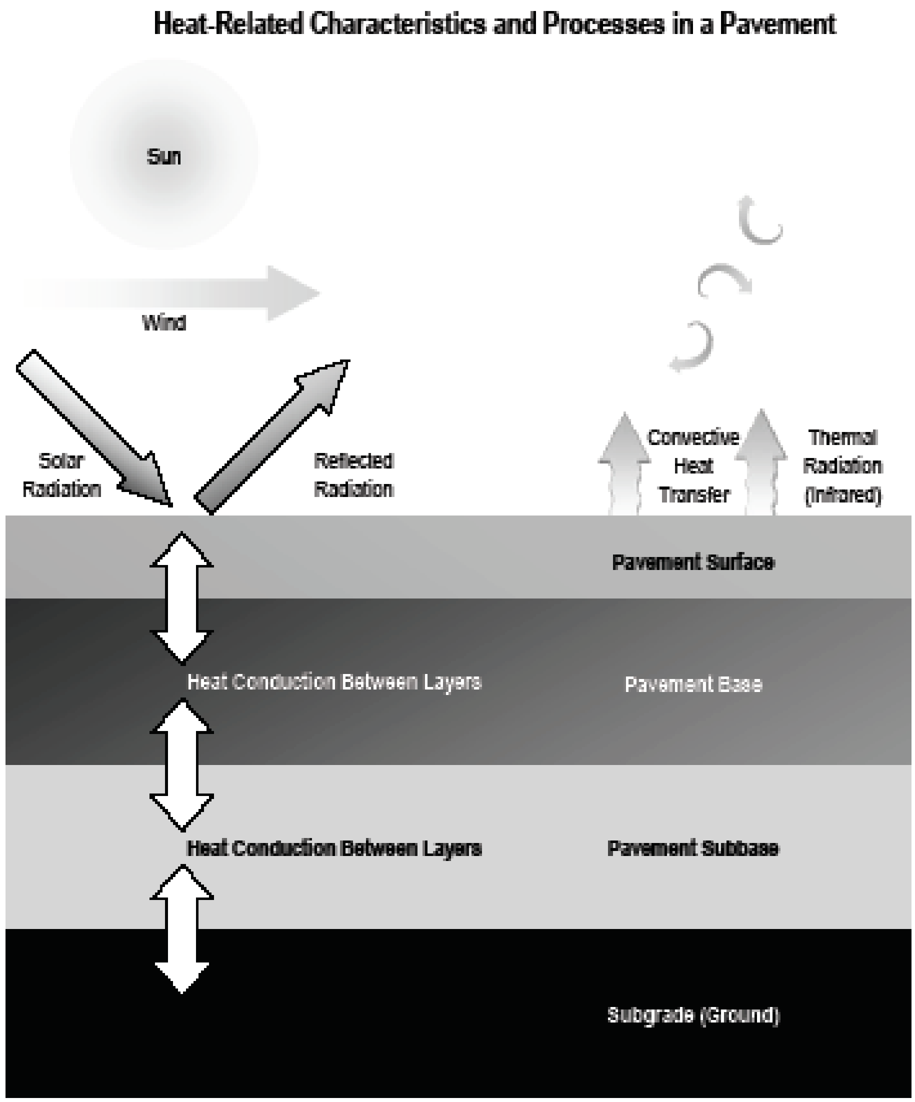


Figure 2 - Cambridge Systematics 2005

Permeable concrete's heat properties have been somewhat examined in helping with urban heat islands. Large amounts of square footage covered by asphalt and concrete can cause unusual hot zones especially in urban environments. The dark color of asphalt absorbs a lot of sun energy. With a large amount of thermal mass, flat surfaces with maximum exposure to sunlight and a dark color that absorbs radiation readily can easily become saturated with heat and make the outside environment uncomfortably hot.

There have been other solutions to help with the heat island effect. One solution has been use of concretes and pavements with a higher albedo. Albedo refers to a surfac's reflectance of radiation. A white surface that reflects heat readiation has a high albdeo and a black surface that absorbs heat radiation has a low albedo. (Snow 2007)

Permeable concrete has advantages for the heat island effect. Because of the voids within permeable concrete there is less mass to absorb heat and according to the study the moisture trapped within the voids will cool the pavement through evaporation. This way the storage capacity of heat for the surface can be restored and will make the outdoor environment more comfortable. (Snow 2007)

Surface Area and Thermal Mass

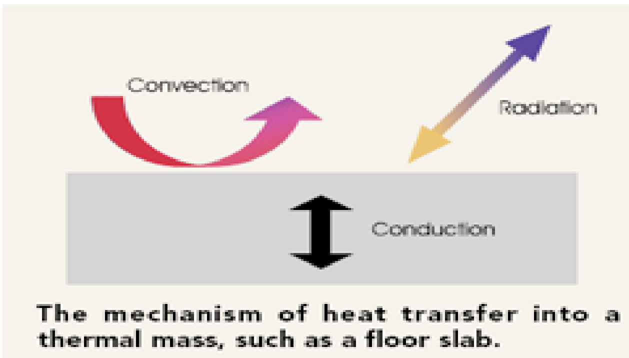
The amount of surface area is a factor for heat transfer for any system. The same concept is utilized in conventional heating and cooling systems. In a conventional forced air system an air-handling unit will blow air through heating coils that carry hot water or some other media and will heat the air passing over it. If a single large diameter tube was used to carry the water there would be little contact surface between the air and the tube to make effective heat transfer. If there were many smaller tubes carrying the same amount of water there would be a larger contact surface to the heat source and the air would get hotter faster.

The idea of maximizing surface area is somewhat taken advantage of in some thermal mass systems. (Figure 3)

Increased surface area of a profiled composite slab, right, compared to that of a flat slab, lab.

Figure 3 - Gorgolewski 2007

The author is suggesting this same concept can be applied to permeable concrete and the improvement of some thermal mass systems by replacement of solid concrete with permeable concrete. In theory if permeable concrete can be penetrated by water it should also allow air to move through its voids. With extra air to the interior of the mass in its voids Permeable concrete should promote heat transfer through convection (assuming voids are interconnected)(Figure 5). In comparison a solid concrete mass would only have contact area on its volumetric limits (Figure 4). With its increased surface area permeable concrete may act as a 'concrete heat coil'.



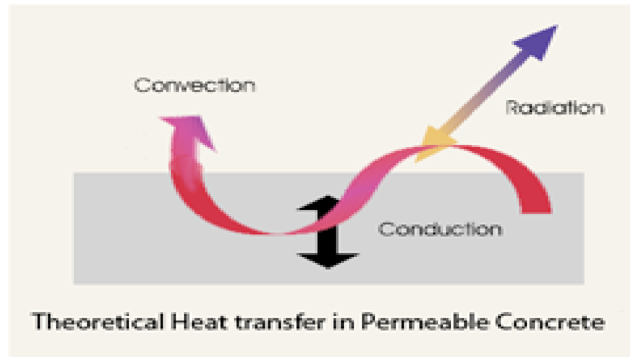


Figure 4 - Gorgolewski 2007

Figure 5 - Stephenson

Applications of Permeable Concrete in Passive heating/cooling

Assuming the Permeable concrete will act as predicted its application in thermal mass systems is limited only by imagination. The author expects it will be best used in situations where the inhabitant of the space can control airflow. Under these circumstances the system can greatly help the situation mentioned earlier where there is a prolonged period of hot days. Since the permeable concrete mass will release its heat energy faster during the night it has a greater chance of becoming an empty reservoir for the hotter period during the day. Giving the interior air an escape route to the outside will keep the interior room from becoming hot, as natural convection currents will circulate cooler air in. For the purposes of this study the author will use a suitable example to demonstrate the type of contribution it could make.

Example: House in Essen, Italy

In this example there is a concrete floor storage system with variable air flow access to the room and the attic that can be controlled by the inhabitant. (Figure 6 Hastings, 1994). If the room needs to be heated air can be directly funneled to the space (Mode 1). If the room is warm enough and it is still hot outside air is directed to the concrete through piping and heat is stored in the concrete (Mode 2). On a cool night the path from the concrete base can be opened to release heat stored there (Mode 3). It is a scenario the author believes would be ideal for permeable concrete. Permeable concrete would allow more air to surface contact than the piping would, speeding up the heat transfer. But because the user controls the airflow and speed of the airflow the user can control the rate of heat transfer from reservoir to the space.

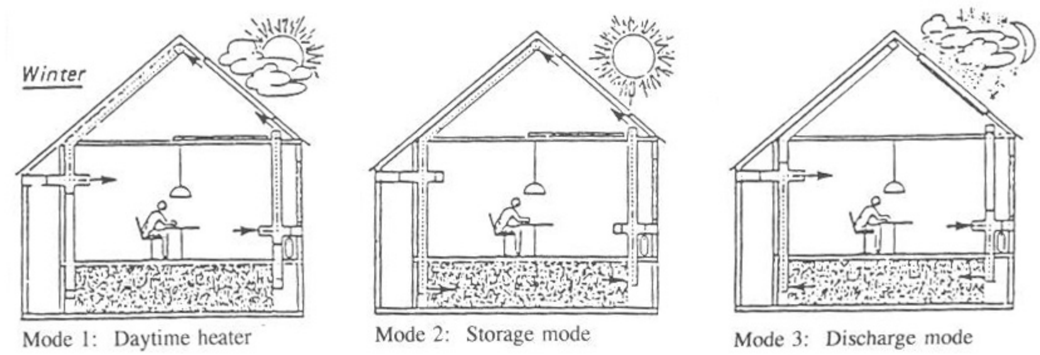


Figure 6 - Hastings 1994

Experiment:

- Description

The experiment will involve testing two subjects. A solid concrete block 1'8"x1'8"x5.5" which will give a block 1.378 cubic feet and roughly 200 lbs (density 2242 kg/mcubed http://edboyden.org/constants.html) and one of permeable concrete the same dimensions and approximately 175 lbs (density 80 kg/mcubed http://www.nrmca.org/aboutconcrete/cips/38p.pdf). A block of this size will allow the author to have a reasonably sized sample yet it was important to be able to handle and maneuver it for this experiment and for any follow ups. The experiment will take place at the Research and Demonstration Facility (RDF) at Virginia Tech (Figure 7).

Figure 7 - RDF facility

Measurements for temperature of the blocks will be taken at locations shown (Figure 8 and 8-a) as well as indoor and outdoor air temperature. The Materials list (Table 1) and initial schedule (Table 2) is shown below.

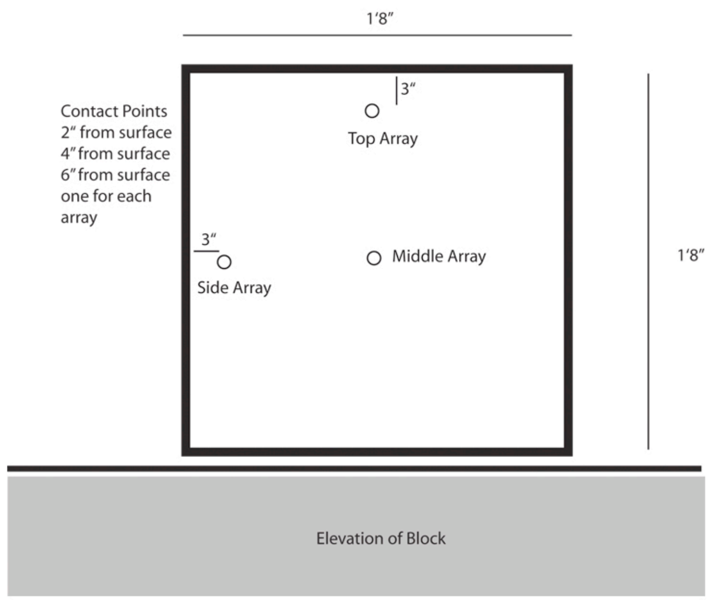


Figure 8 – Elevation of a block

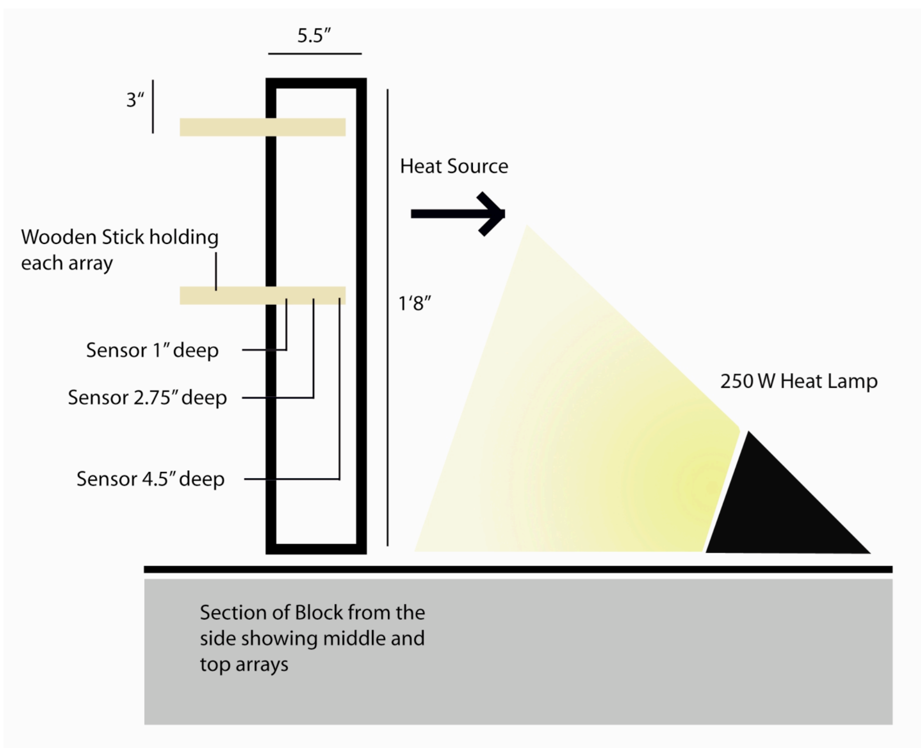


Figure 8-a- Section of Block from side

Materials List – Table 1	
ITEM	COST
PR-T-24 Thermcouple wire	160.00
Quikrete Mix (2 80lb bags)	30.00
Permeable Concrete (Aggregate and cement to be mixed)	30.00
Formwork material	35.00
Vegetable Oil	3.00
Heat Lamps 250 Watt (2)	30.00
Data Collector	Jones
Concrete Mixer	Available at RDF
Total amount requested from CAUS	**458.00**

Tentative Schedule – Table 2	
Dates	Task
Week of March 12	Construct Formwork
Week of March 19	Pour Blocks
Week of March 26	Conduct Experiment
Week of April 2	Analyze Results
Week of April 19	Compose Paper
Week of April 16	Float
Week of April 23	Float
Week of April 30	Float

The mix ratios used on the project were taken from Figure 9.

Cementitious materials	270 to 415 kg/m³ (450 to 700 lb/yd³)
Aggregate	1190 to 1480 kg/m³ (2000 to 2500 lb/yd³)
Water-cement ratio (by mass)	0.27 to 0.30***
Aggregate-cement ratio (by mass)	4 to 4.5:1***
Fine-coarse aggregate ratio (by mass)	0 to 1:1****

Figure 9 - Farny 2004

Exact recipe used for 1.38 cubic foot block (0.05139 cubic yards):

- 115.63 lbs aggregate
- 29.5 lbs cement
- 8.865 lbs or 17 cups water
- no fine aggregate

- Lab set up

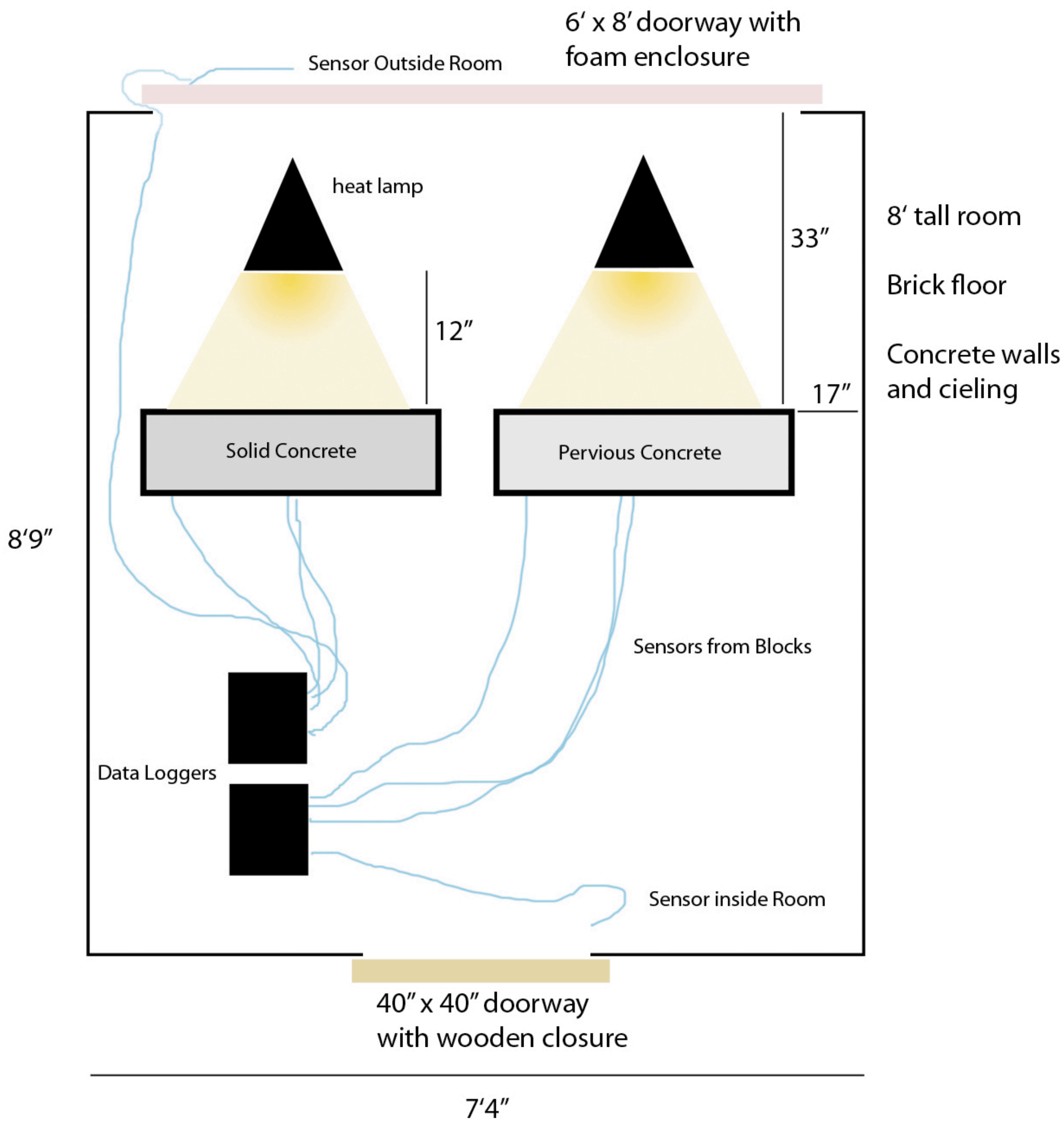


Figure 10 - Lab Set-up

- Procedure
  - Creating Thermocouple Sensors and Arrays (See Appendix A for pictures)
    - Remove an inch of the insulation from the ends of the wire
    - Wrap Constantine end around the Copper to form a ball

- Use blow torch to melt the Copper and form a welded bead at the point of the ball
- Mark wooden stick (or whatever material used to hold the array) at desired depths. In this case the depths were 1", 2.75" and 4.5".
- Tape thermocouple sensors to stick and be sure to keep exposed wire free from the tape and each wire separate from one another except at the point of contact

- Create Formwork
  - Cut formwork material to length (material was half inch OSB in this case).
  - Screw or nail sides and bottom boards together
  - During pouring a ratchet strap around the form was used for extra support
- Mix Permeable Concrete (See Appendix B for pictures)
  - Wash Stone (Standard mixed gravel was used)
  - Let Dry
  - Place in Mixer and turn on
  - Add cement in amounts that it will not blow away (Federal White Cement used)
  - Let Dry ingredients mix
  - Add measured amount of water and allow to mix
  - Pour/place/scoop mix into the form
  - Use a trowel or tool to spread mix
  - Use rebar or other tool to dig a temporary hole for array
  - Place array and tamp permeable mix back into place
  - Secure array to 2x4's to stay in place
- Mix Traditional Concrete
  - Clean mixer
  - Add Quikrete (Mix 1101) mix to mixer
  - Turn on and add water as appropriate (the author has a lot of practical experience with Quikrete)
  - Pour concrete in form
  - Place arrays in mix
  - Tap sides of form to remove air bubbles
  - Secure array to 2x4's to stay in place
- Experiment Set up
  - Allow blocks to cure (Sat for about a week and a half with plastic cover over the top)

- Set up blocks in experiment as shown in Figures 8, 8-a and 10. Also See Appendix B for more pictures
- Blocks were placed directly on the brick floor
- Turn on heat lamps (250) Watt in the morning and off at night. Exact times are shown in table 3.

On/Off times for 250 Watt Heat Lamp – Table 3

Date	On/Off	Time
4/4/07	On	0745
	Off	2100
4/5/07	On	0900
	Off	2200
4/6/07	On	0745
	Off	1800
4/7/07	On	0745
	Off	1830
4/8/07	On	0745
	Off	1930
4/9/07	On	1212
	Off	2050
4/10/07	On	0930
	Off	2045

- Expectations

It's expected that the permeable concrete block will see temperatures that rise and fall faster than the solid concrete block. The temperature will also be more equally spread in the permeable concrete block, where as the solid concrete block's higher temperatures will be localized at the surface facing the heat lamps (4.5" marked nodes). It's expected that the free movement of air within the permeable concrete will distribute the heat energy from the lamps more readily to the rest of the block than will conduction in the traditional block.

The biggest difference between the two blocks should be in the top array. The top array should experience the greatest impact from convective heat transfer since heat rises. Heat received by the permeable concrete block below will heat air in the adjacent voids that will rise and transfer heat energy to the top of the block and the top array. The solid block will not have this quick energy transfer and the top array is the farthest from the heat lamps (5.2 inches further from source), suggesting it will likely be the coolest in the traditional block.

If the temperature data for the permeable block plateaus before the concrete block then we can determine it has reached its thermal equilibrium point faster.

- Temperature curves in Pervious Block will be steeper
- Pervious block will reach thermal equilibrium sooner
- Biggest difference between blocks should be in the top array. The top array should have much higher temperatures in the pervious block (at least before thermal equilibrium is reached)

It has been suggested to the author that the pervious concrete's voids may act like trapped air pockets. In that case the voids would act as an insulator slowing heat transfer. The author proposes that because a fluid such as water can flow through some if not all voids in porous concrete, the voids must be interconnected (See further research section for more).

Observations During Construction: Mixing, Placement, Procurement

As expected the Permeable concrete was difficult to work with and had some added difficulties being a homemade batch. The mixer was underpowered for the job and could not mix adequately. There was a tendency for deposits of dry cement to form at the bottom of the mixture. I had to stop the mixer and manually break up and mix by hand periodically. The mixer also had a harder time turning than with the regular concrete mix. I had to help push the mixer by hand to get it to turn (the mix was about 2 cubic feet and the mixer's capacity is 3 cubic feet).

The Pervious concrete would not readily take the form of the box I made for it. The mix had to be scooped into place and pushed and compressed to form a box. If poured like traditional concrete the pervious mix would settle into a mound rather than into the block.

The average do it yourself homeowner would also find it more difficult to collect materials for pervious than for traditional concrete. Getting supplies for a batch of ready mix concrete is simple. Home Depot and Lowe's have commercial ready mixed bags of Quikrete that you just add water and mix to prepare. There is no commercial ready mix bag of pervious concrete mix. Cement can be found easily enough, however there isn't the ideal set of aggregate available. No. 8 stone is called for in the mixture. However bags of specific aggregate are unavailable. To get a specific stone mix it would have to be ordered from a provider similar to ordering a concrete truck for concrete. The next best thing is bags of gravel that needed to be washed before mixing.

It is the author's opinion that pervious concrete will not become truly mainstream until it is available in ready mixed bags like Quikrete. The added hassle and required planning to buy ingredients separately and mix in the correct proportions is an obstacle that will deter many homeowners and small contractors from choosing it as an option.

Observations During Construction: Final Product

The Final block products were mostly satisfactory. Something unexpected that is worth noting is the texture of the Permeable concrete block on its backside. (Backside: the side facing the ground when being poured and left to set) Seen in Figure 11 the backside is smooth and not permeable around the center of the square, very different from the rough top surface in Figure 12.

Figure 11 - Backside of Pervious Block

The main concern here is that the block is not permeable in this area. On site a water test was performed and water could enter and escape through all sides of the block. It appears that this surface area might be solid and smooth but the block taken in its entirety still has the voids and the permeability within that this experiment is looking for.

Figure 12 - Rough Surface Permeable Concrete

It appears that any excess water in the pervious mix sinks to the bottom. When placing for pavement purposes the water can escape into the sub base just as it is intended for rainwater. This is a problem with a closed solid form. The water cement excess made its way to the bottom of the form where it gathered to produce an impervious area. This effect would become more critical if it were to be used in a system such as a wall (non load bearing) where there will be greater potential and greater impact for water to pool at the bottom of a solid form. Some clever formwork will have to be designed for this purpose or a very controlled mixture ratio.

Temperature Data Analysis

Note:

- Indoor air temperature sensor was faulty and gave readings of -6999 F. Those results were thrown out and are not shown in the graphs
- The room could not be made air tight with the author's resources as such outdoor air temperature may have been very close to the indoor air temperature

Data results did not meet expectations (See Appendix C for temperature graphs). Results were nearly identical for both blocks. It appears that the biggest difference between the readings is that the permeable temperatures were slightly more volatile.

While the permeable readings followed the same general trend its progression was less smooth than the solid blocks. The same unpredictable small magnitude spikes are seen in the readings for the outdoor temperature however (Figure 13).

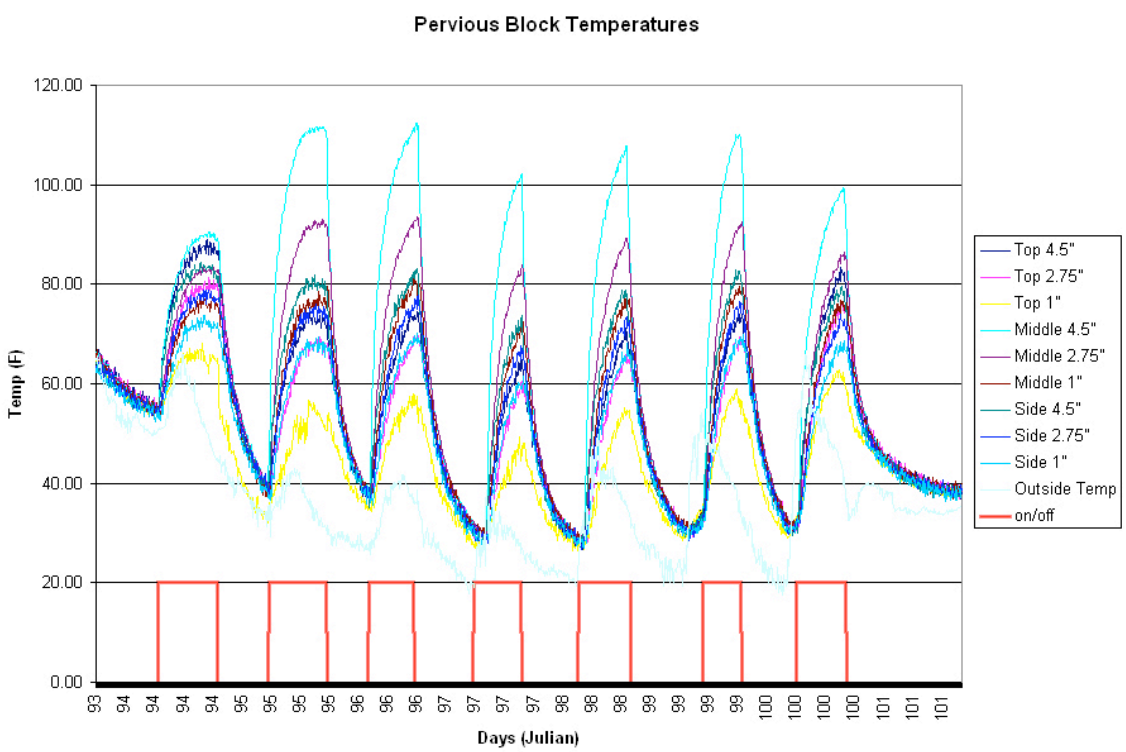


Figure 13

This indicates that the permeable block is more susceptible to the exterior air temperature. The unpredictable spikes in the permeable concrete may be caused by small changes in air temperature since the air temperature will be able to mix and exchange with the air in the voids. It has also been suggested that the spikes may be the result of a poor connection with the thermocouple sensors.

If outdoor air temperature was the cause it is expected that the average and peak temperatures for every node in the permeable block to be lower than the traditional block but that is not the case. It seems clear that the dominating factor in the experiment was the heat lamps. The closer a node was to the heat lamp the faster the heat absorption and the higher the temperature (Figure 14). The middle array was 15.6" from the heat source, the side was 17.11" and the top was 20.8". Again the hypothesis was incorrect. It was expected that the top array would be hotter than the side, however as seen in Figure 14 the side array shows higher temperatures throughout.

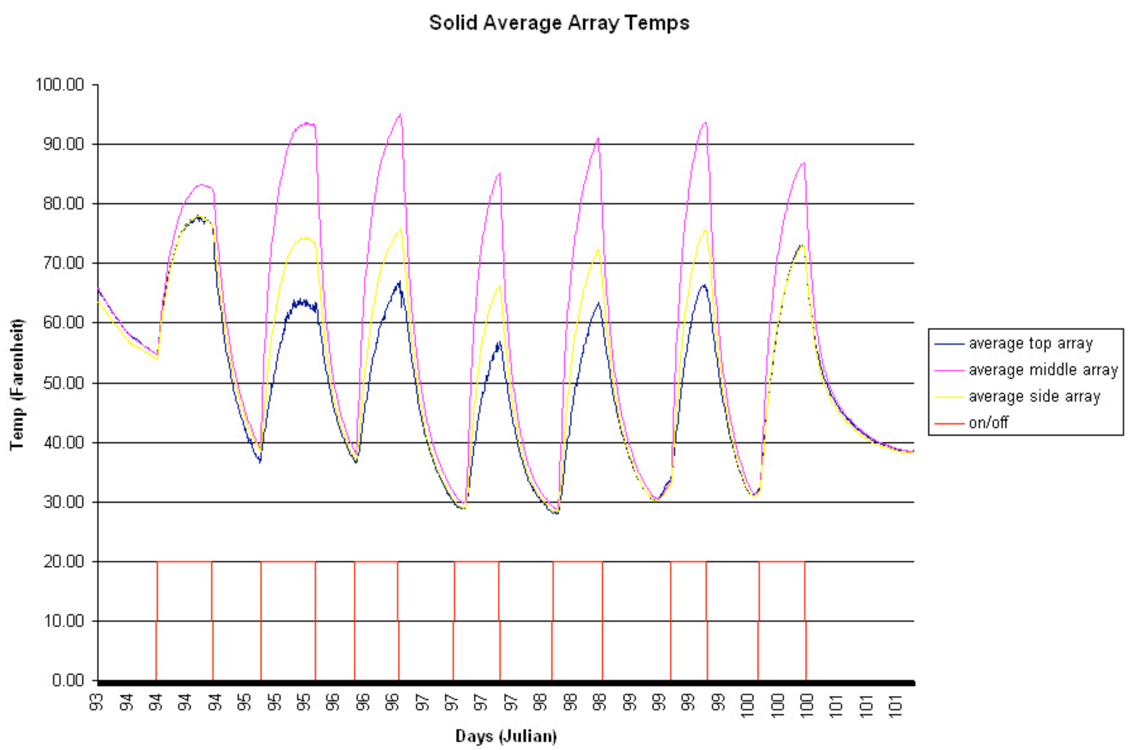


Figure 14

There did not seem to be any difference in the top array between the two blocks as expected. The pervious block and traditional block had nearly identical curves for the top array. In this experiment it appears that convection played little if any role in thermal characteristics of the concrete blocks.

Conclusions

The experiment suggests that permeable concrete does not add significant benefits to thermal mass systems in an open environment of a room. However there may be applications in closed systems.

The author does not feel this experiment rules out the importance that convection can play in permeable concrete and thermal mass systems. This experiment did not support the expectations however the author would suggest two main improvements to the lab. The blocks should be poured using professionally made and ordered permeable concrete from a local provider and the lab set up should be changed to enclose the blocks.

In the example given earlier regarding the house in Italy the concrete was enclosed trapping the air within the system. Convection and distributing heat energy by convection may play a bigger role if the concrete has its own housing. In the author's set up the convective cycle was that of the entire room. In an enclosed setting the block will be a part of the entire convective loop. It is also suggested that the heat source be changed to hot air blown into the enclosed cavity instead of direct application by a heat lamp. This experiment will be more directly related to the example in Italy. If it is proven that convection does play a significant role permeable concrete could fill a niche in particular thermal mass systems rather than a replacement.

It is also recommended that the permeable blocks be poured from a commercial provider better able to meet mix standards. The author is suspicious about the level of porosity in the permeable block because of the complications involved with procurement and mixing in at home batch mixing. The water test indicated that the block was porous however there may still be significant clumps of solid throughout preventing the expected convective flow.

Future Research Ideas from this Project and Report

- Same experiment but with modified housing for concrete and blown hot air as heat source. Also include more sensors and arrays. Take readings at surface conditions as well. Also develop a way to test the air temperature within the concrete and the concrete itself.
- Determine CFM air flow rate given controlled air pressures
- Experiment with different formwork types and liners to solve the 'pooling' problem experienced in this project. Perforated plastic for example.
- Determine thermal characteristics with differing albedos and color of concrete blocks
- Dissect or determine in a non intrusive way the actual permeability of the block used in this experiment and the nature of the clumps inside of it
- A non destructive way to determine void characteristics that could be used to test pervious pavements or structures put in place
- New batch mixing procedure: mix and place dry ingredients and pour measured volume of water over the top

References:

Cambridge Systematics, Inc. (2005) "Cool Pavement Report." Prepared for Heat Island Reduction Initiative, U.S. Environmental Protection Agency.

Crosbie, M.M. (1998). The Passive Solar Design and Construction Handbook. John Wiley & Sons, West Sussex, England.

Crouch, L.K., Smith, N., Walker, A., Dunn, T., (2004) "Pervious PCC: Effective Voids, Permeability and Compressive Strength." Tennessee Concrete, Vol. 18, No. 3

Farny, J. (2004). "Aging Gracefully." Concrete Technology Today. Vol. 25, No. 3.

Gorgolewski, M. (2007), "Framing Systems and Thermal Mass." Modern Steel Construction.

Gui, J., Carlson, J., Phelan, E.K., Golden, J. "Impact of pavement thickness on surface diurnal temperatures." Department of Civil and Environmental Engineering, Arizona State University.

Hastings, S.R. (1994). Passive Solar Commercial and Institutional Buildings: A Sourcebook of Examples and Design Insights. Wiley, West Sussex, England.

Ruppersberger, J.S. (1995), "Concrete Blocks' adverse effects on Indoor Air and Recommended Solutions." Journal of Environmental Engineering Vol. 21, #4, 348 – 356

Shaviv, E., Yezioro, A., Capeluto, I., (2001) "Thermal Mass and Night Ventilation as Passive Cooling Design Strategy."
http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V4S-439VBJM-G&_user=513551&_coverDate=11%2F30%2F2001&_rdoc=1&_fmt=&_orig=search&_sort=d&view=c&_acct=C000025338&_version=1&_urlVersion=0&_userid=513551&md5=3d75be7e5b8b17efe533b66288a75109#toc4

Snow, K. (2007). "Pervious Concrete Feature Helps Reduce Urban Heat Island Effect." ASU Foundation. http://www.asufoundation.org/news/stories/0130-concrete.asp

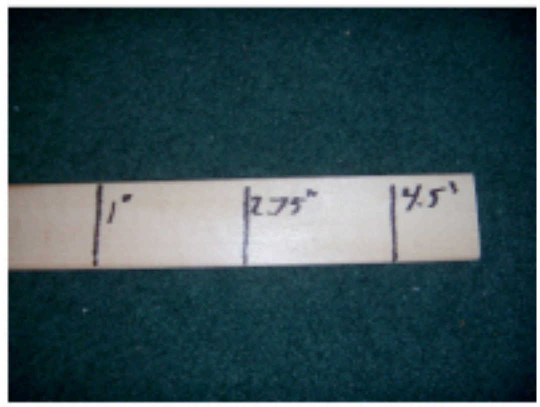
Tsibin, P., Litovskii, E., Fedina, G. (2005). "Effective thermal conductivity of a refractory concrete." Refractories and Industrial Ceramics. Vol. 29, No. 3-4

Appendix A: Making Thermocouples

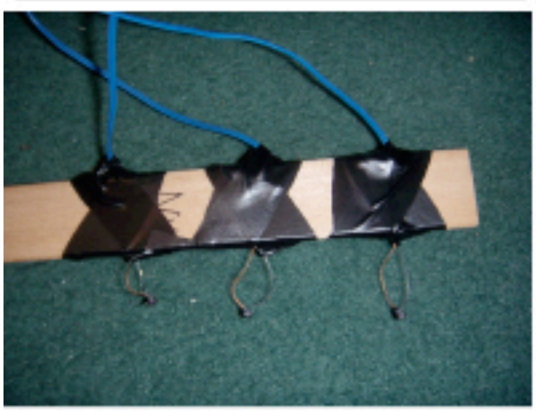
Thermocouple Equipment

Thermocouple wire

Twist and melt to a bead



Depth measuring stick



Completed array

Appendix B: Construction and Lab Pictures

Mixing Site and Formwork

Quikrete, Stone and Cement Material

Mix and Pour on the Ground

Measured water for Pervious Block

Working the Pervious Material into a block

Mixing Traditional Concrete

Appendix B: Construction and Lab Pictures

Tap bubbles out of Concrete

Blocks covered and left to set

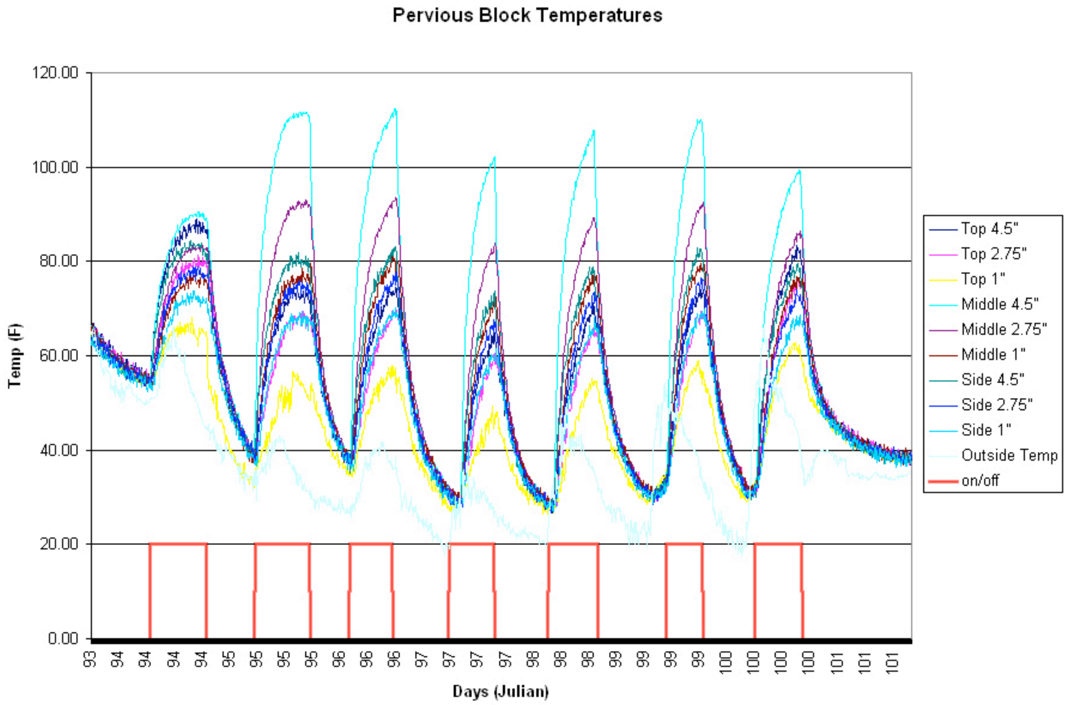
Setting up the Data Logger

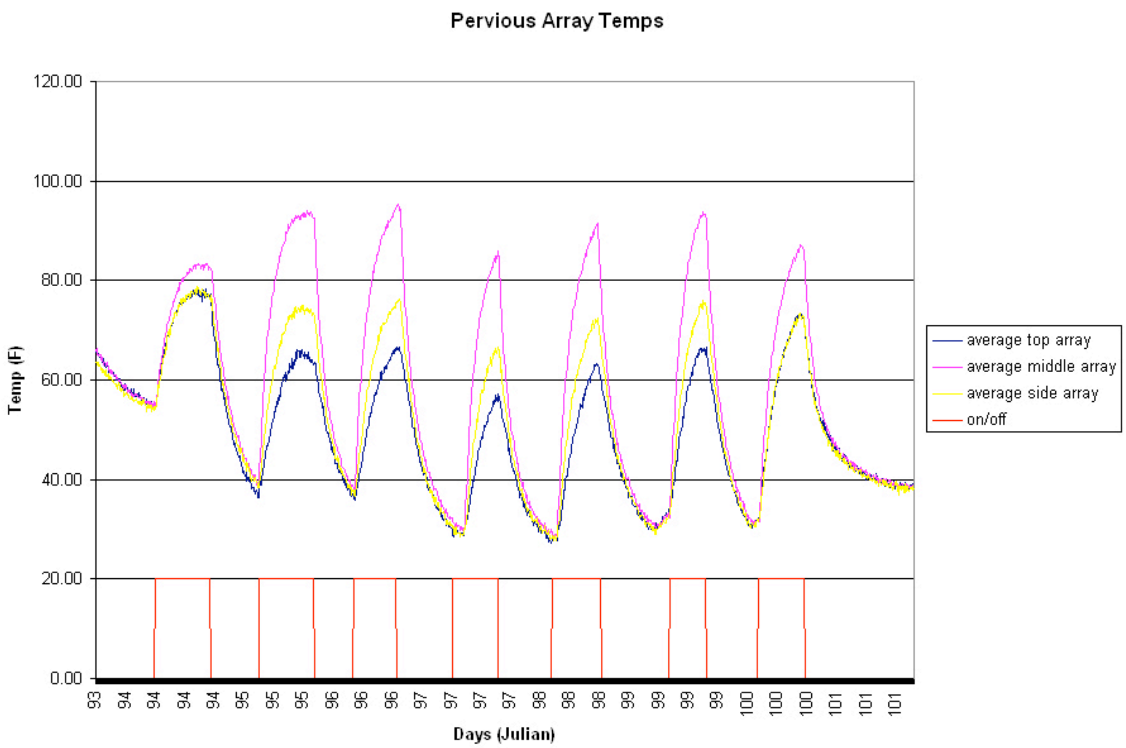
Completed Lab Set-up

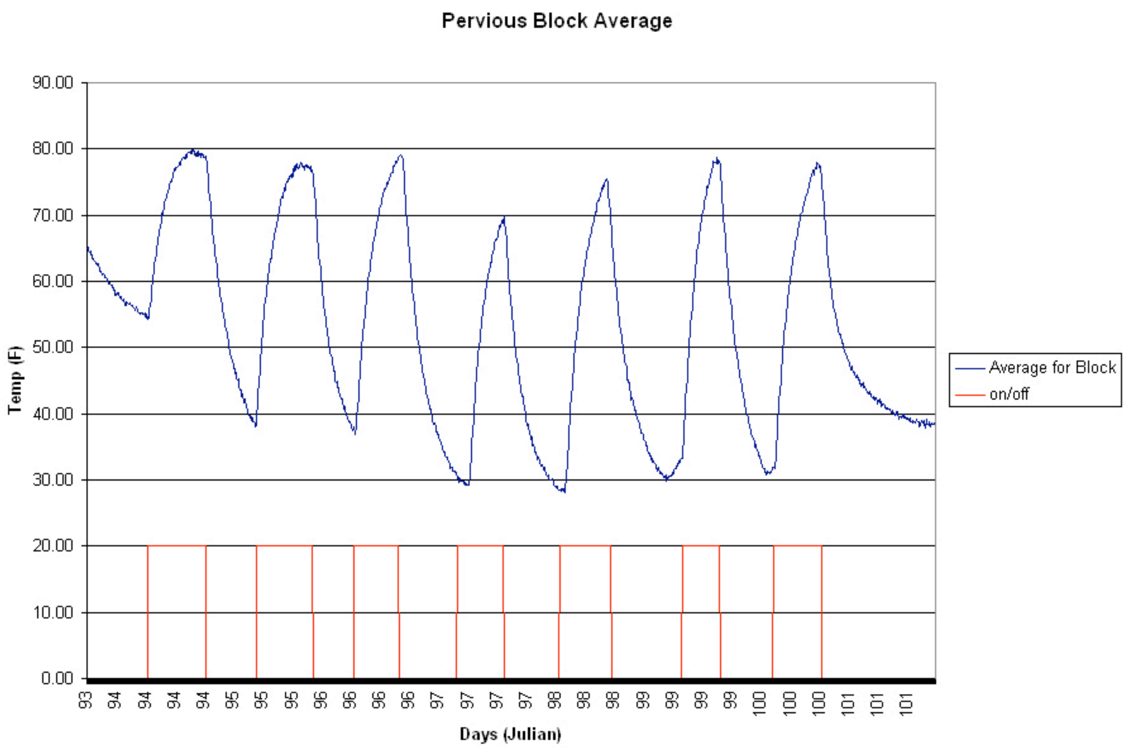
Front Opening covered up with Foam panel

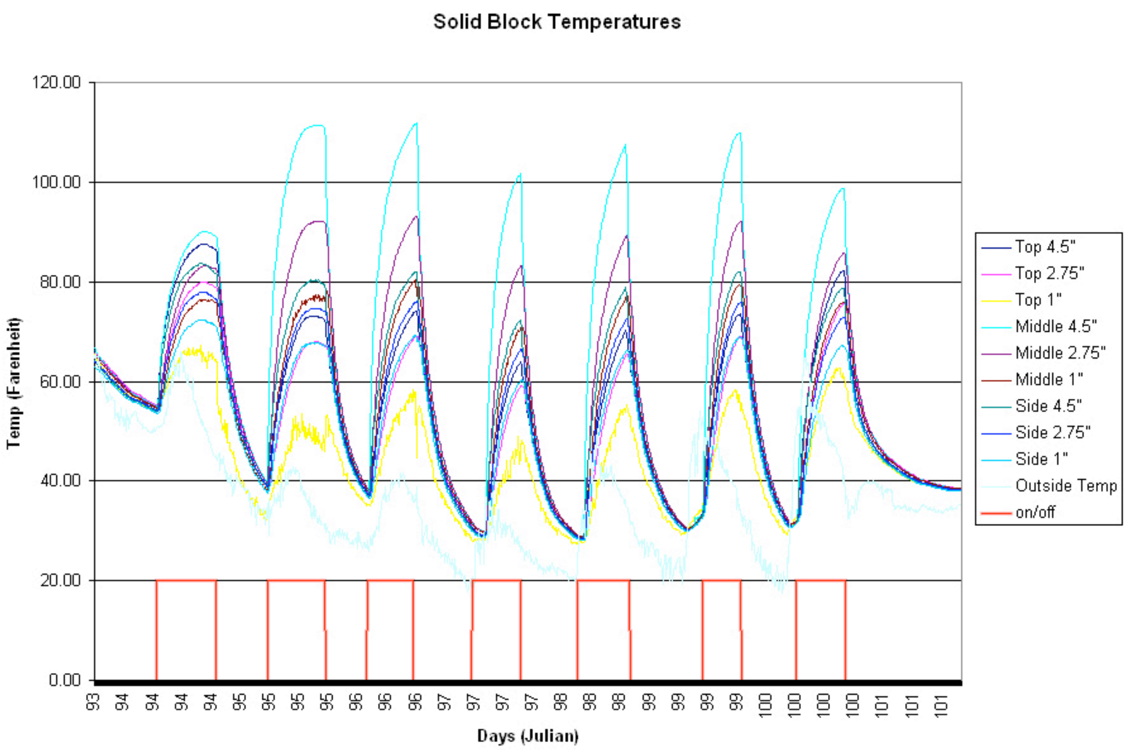
Back entrance covered with Wood hatch

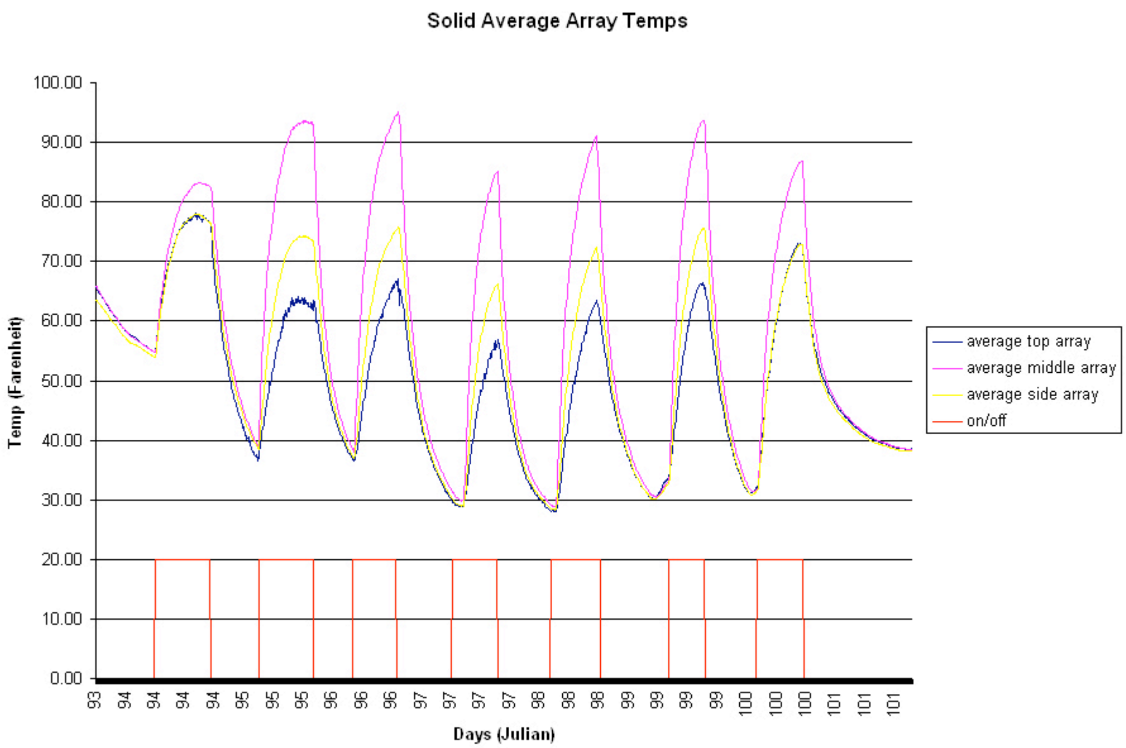
Appendix C: Temperature Charts

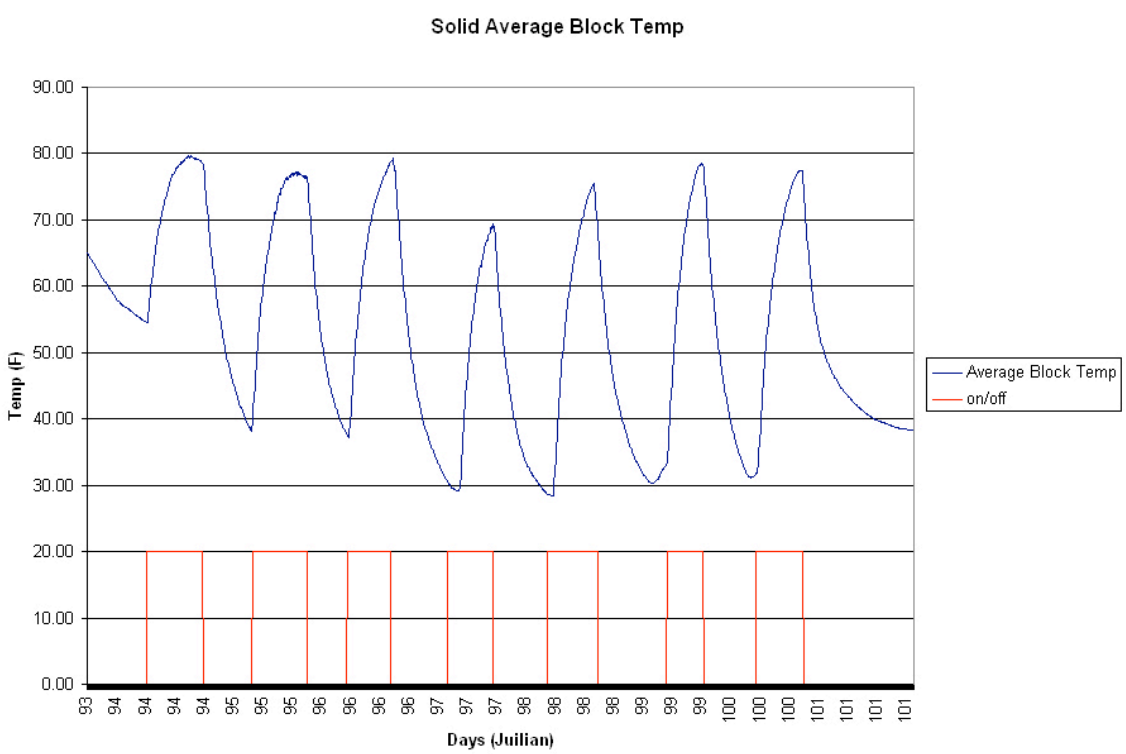





Pervious Block Average
Temp (F)
Days (Julian)
Average for Block
on/off


Solid Block Temperatures
Temp (Farenheit)
Days (Julian)
Top 4.5"
Top 2.75"
Top 1"
Middle 4.5"
Middle 2.75"
Middle 1"
Side 4.5"
Side 2.75"
Side 1"
Outside Temp
on/off


Solid Average Array Temps
Temp (Farenheit)
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Days (Julian)
average top array
average middle array
average side array
on/off


Solid Average Block Temp
Temp (F)
90.00
80.00
70.00
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40.00
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Days (Juilian)
Average Block Temp
on/off