EXPERIMENTAL STUDY OF SOIL AS POROUS MEDIUM FOR EVAPORATIVE COOLING

LAGUNESVARY A/P GANESAN

UNIVERSITI SAINS MALAYSIA

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EXPERIMENTAL STUDY OF SOIL AS POROUS MEDIUM FOR EVAPORATIVE COOLING

by

LAGUNESVARY A/P GANESAN

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LIST OF ABBREVIATIONS

		Units
NASA	The National Aeronautics and Space Administration	
WBT	Wet Bulb Temperature	^{o}C
DBT	Dry Bulb Temperature	^{o}C
RH	Relative Humidity	%
EAHE	Earth To Air Heat Exchanger	
ISSS	International Society of Soil Science	
IMAD	Isothermal Membrane-Based Air Dehumidification	
MVC	Mechanical Vapor Compression	
MIC	Meter Industrial Company	
USB	Universal Serial Bus	
TC	Thermocouple	
Min.	Minimum	
Avg.	Average	

LIST OF SYMBOLS

		Units
V	Total Volume	ml
V_v	Volume of Void	ml
V_a	Volume of Air	ml
V_w	Volume of Water	ml
V_s	Volume of Soil Particles	ml
n	Porosity	%
k	Thermal Conductivity	W/mK
Q	Power Supply	$Watt$
A	Cross Section Area	cm^2
$\frac{dT}{dx}$	Variation of Temperature Over the Travel Distance	$^{\circ}C/m$
D	Diameter	m
m_w	Mass of Water	kg
p_w	Absolute Humidity	g/m^3
p_{ws}	Saturation pressure of air	Pa
$\emptyset$	Relative Humidity	%
P	Pressure	Pa

MENKAJI TANAH SEBAGAI MEDIUM BERLIANG DALAM PENYEJATAN PENYEJUKAN

ABSTRAK

Penyejukan amat dititikberatkan mutakhir ini disebabkan oleh kenaikan suhu ambien. Tanah banyak digunakan dalam sistem penyejatan pasif dan separa pasif. Penyejukan bumbung, paip haba, periuk Zeer dan banyak lagi aplikasi telah dibina supaya menggunakan tanah sebagai medium berliang untuk mendorong dan mengekalkan penyejukan. Namun, tiada banyak rujukan kajian yang boleh dijustifikasi terhadap pengaruhan ciri fizikal tanah dalam penyejukan sejatan. Penyejukan sejatan dipengaruhi oleh kelembapan udara, kadar pengaliran udara, kehadiran air, ketersediaan tenaga haba dan sifat fizikal medium berliang. Tanah loam, pasir, batu kelikir dan batu kecil telah dikaji sebagai medium berliang dalam satu sistem penyejukan sejatan. Didapati bahawa perubahan saiz zarah mempengaruhi keliangan dan kebolehtelapan. Tanah loam, pasir, batu kelikir dan batu kecil menghasilkan 23.8%, 34.7%, 51.3% dan 64.8% keliangan, manakala ketelapan adalah 0.02 ml/s, 0.43 ml/s, 9.77 ml/s dan 12.37 ml/s masing-masing. Kehadiran keliangan dan ketelapan mengubah kadar pengaliran udara dan air dalam sesuatu medium berliang. Selaras itu, medium berliang yang padat sesuai untuk mengekalkan kesejukan yang dihasilkan untuk suatu tempoh masa. Penyelidikan diteruskan dengan udara termampat 1 bar ke 5 bar untuk mengkaji pengaruhuan tanah loam, pasir, batu kelikir dan batu kecil pada penyejatan. Penyelidikan dengan udara termampat 5 bar mencapai keputusan yang lebih baik disebabkan kelembapan relatifnya rendah dan ketumpatan volumetriknya tinggi. Hasil kajian ini membuktikan tanah loam dan pasir berfungsi dengan efisien ketika kandungan kelembapan 30%, sebaliknya batu kelikir dan batu kecil boleh berfungsi dengan baik dalam keadaan kandungan air 5% disebabkan ciri-ciri fizikalnya. Dalam kajian perbandingan dengan 10kg tanah dan 30% kandungan kelembapan, didapati bahawa tanah loam mancatatkan suhu yang paling rendah iaitu 16.43°C manakala pasir, batu kelikir dan batu kecil masing-masing mencatatkan suhu 17.06°C, 17.40°C, dan 18.26°C. Berikutan itu, jumlah kehilangan air dalam masa 2 jam proses penyejatan untuk tanah loam, pasir, batu kelikir dan batu kecil adalah 0.3 kg, 0.35 kg, 0.45 kg, dan 0.45 kg. Sekiranya diteliti, kehilangan air yang banyak dalam proses penyejatan secara langsung mengakibatkan kehilangan haba yang tinggi. Kadar penyejukan berkurangan dari 0.103°C/min, 0.098°C/min, 0.098°C/min, 0.096°C/min dan 0.084°C/min untuk kelikir, air, batu kecil, tanah loam dan pasir. Kesimpulanya, pemilihan jenis tanah untuk sistem penyejukkan sejatan bergantung kepada keperluan aplikasi. Tanah loam dan pasir adalah pilihan terbaik untuk aplikasi yang memerlukan kesan penyejukan, kemampanan haba dan kestabilan. Sementara itu, batu kerikil dan batu kecil sesuai untuk aplikasi yang memerlukan kadar penyejatan yang tinggi.

EXPERIMENTAL STUDY OF SOIL AS POROUS MEDIUM FOR EVAPORATIVE COOLING

ABSTRACT

Cooling is becoming a major concern nowadays due to the increment of ambient temperature. Soil is vastly used in passive and partially passive evaporative cooling systems. Roof cooling, heat pipe, Zeer pot and more applications were built to use soil as porous medium in inducing and preserving cooling. However, there are no many literatures to justify the influence of physical property of soil on evaporative cooling. Evaporative cooling influenced by the air humidity, air flow rate, presence of water, heat energy availability and the physical properties of porous medium. Loam soil, sand, gravel and small rocks were studied as a porous medium in an evaporative cooling system. Variation in particle size influences soil porosity and permeability. The loam soil, sand, gravel and small rocks provided 23.8%, 34.7%, 51.3% and 64.8% porosity, while 0.02 ml/s, 0.43 ml/s, 9.77 ml/s and 12.37 ml/s permeability respectively. Porosity and permeability influences air and water flow inside the porous medium. A compact porous medium feasible to sustain coldness generated for period of time. The research was continued with 1 bar to 5 bar compressed air to study the influence of loam soil, sand, gravel and small rocks on evaporative cooling. The setup with 5 bar compressed air performed better due to its low relative humidity and high volumetric density. Loam soil and sand were worked greatly in 30% moisture content while gravels and small rocks were able to work with 5% water content due to its physical characteristics. In a comparative experiment with 10 kg soil and 30% moisture content, the loam soil archived minimum temperatures of 16.43°C while sand, gravel, and small rocks were 17.06°C, 17.40°C, and 18.26°C respectively. The water lost from 2 hours of evaporation in loam soil, sand, gravel and small rocks are 0.3 kg, 0.35 kg, 0.45 kg and 0.45 kg respectively. Higher water lost through evaporation results higher heat lost. While the cooling rates reduces from 0.103°C/min, 0.098°C/min, 0.098°C/min, 0.096°C/min and 0.084°C/min for gravels, water, small rocks, loam soil and sand. However, selection of the type of soil for an evaporation cooling system is based on the requirement of the application. Loam soil and sand are the great selection for an application that required cooling effect, thermal sustainability, and stability. While gravels and small rocks are good for an application that required a high rate of evaporation.

CHAPTER ONE

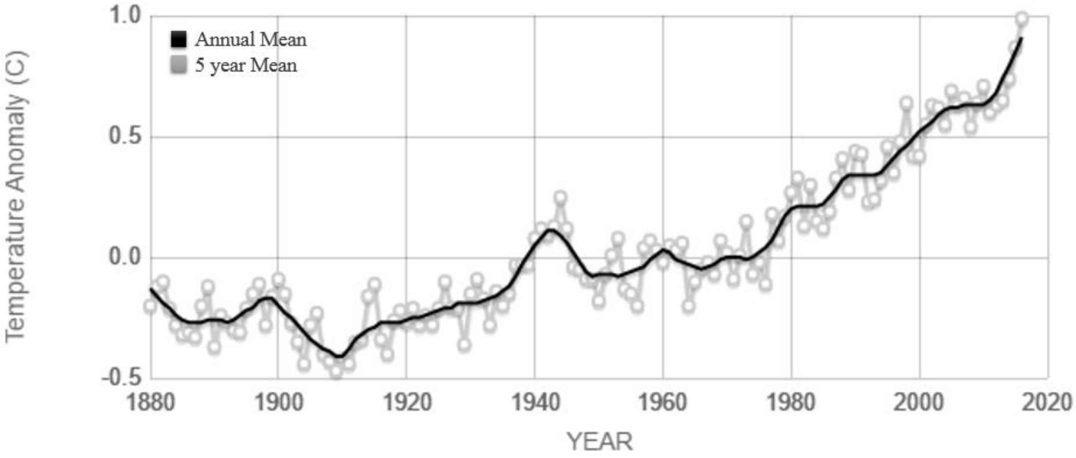
INTRODUCTION

1.1 Introduction

Cooling is an effect of comfort for both human and environment. As the era of industrial development at its maximum speed, the existence of cooling in nature is fading. In contrast, the warm and hot radiation is taking over the world. The main source of heat is sun. The absence of sun reduces heat energy in atmosphere and fills with chillness. As every sunset leading to sunrise, the fading of heat is taking over by chillness. Though the presence of heat is essential for environment and human survival; as huge amount of energy transforms into heat brings discomfort as it exceeds relaxation level.

The comfort and discomfort of a weather and an ambient condition is based on a person`s health and the past experiences in the brain. Working towards comfort is what human made of. However, working towards re-generating chillness is harming globally as the regeneration work itself releasing heat energy, using chemicals and adding trashes.

Figure 1.1 shows the global land-ocean temperature index. In past 20 years, the global temperature has increased around 1°C. The temperature value of 1°C is huge as comparing to the mass of earth with amount of heat emitted. Based on NASA climate forecast, the global temperature is steadily increasing and now at 2018, the temperature is at peak.



Source: climate.nasa.gov

Figure 1.1: The global land-ocean temperature index (Global Temperature: Vital Signs of the Planet)

In late centuries, the globe was not as hot as these days. Yet, in late centuries the environment was manipulated to induce chillness. The method of generation cooling can be divided into active, passive and partial passive cooling systems.

1.2 Types of cooling

The active cooling system uses energy to produce cooling effect. An active system made of fan, pump and motor components to operate. Besides, it operates with chemicals to be an efficient cooler. Partial passive cooling system uses powered ventilation in passive method. The usage of force ventilation is crucial in location with least wind flow.

Passive cooling operates through natural momentum. The surrounding being rearranged in a beneficial way without causing any harm to nature. Therefore, in passive cooling system the potentiality of a method is varied around the world based on the climate and environmental condition.

1.3 Passive Cooling Methods

Ventilation, radiative, soil beneath and evaporative cooling are among the vastly used passive cooling methods (Abram, 1986). Designs, heat gain control and climate plays a huge role in selecting an effective passive cooling method for a location (Givoni, 1991).

The old underground buildings, insulated space and storages, and massive exterior building walls with white stucco are the notable examples of heat gain cancelations methods. This prevention cooling is even being used to these days with shutter, draper and sun reflective paint, glaze and stickers. Blocking heat gain is the outmost crucial step in passive cooling (Givoni, 1991).

Wind properties, sun direction, and the construction materials are principal factors in designing ventilation cooling system. Ventilation cooling highly effective in a location with continues high wind speed. Ventilation cooling removes infinite amount of heat with no man power required.

Sky works as heat sink in radiative cooling (Givoni, 1991). Heat transfers in the form of electromagnetic wave. As radiation travel in a straight line, cooling only happens on water surface that is parallel to the clear sky with no external disturbance. Radiative cooling highly effective in arid counties such as North Africa. In North Africa, radiative cooling is used for ice production (Abrams, 1986).

Soil beneath is thermally stable throughout the year (Derradji and Aiche, 2014). The soil in depth is feasible to act as heat sink during hot days and as heater on chilly days. The earth usage has evolved from underground building construction to heat pump. There are direct and indirect earth cooling. Underground building construction is a direct cooling system while heat pump is an indirect cooling system. Evaporation is an essential process in stabilizing earth temperature, climate, environment, and even human body.

1.4 Evaporation Cooling

Evaporation cooling is an adiabatic process where the energy changes phase while the total energy remains constant. Evaporation is generally the conversion of sensible heat to latent heat (Givoni, 1991). This leads to reduction in temperature with the increment in relative humidity. Evaporation process happens in both cold and hot liquid, though evaporation in warmer liquid are vastly studied.

Sensible heat is associate with temperature variation while latent heat is associate with physical state of the liquid. Liquid molecules draw sensible heat from surrounding to break its molecular bonds. Once gathered sufficient amount of heat energy, it leaves the liquid phase and vaporised with latent heat. This transaction of heat energy leads to reduction in temperature and increment in relative humidity (Givoni, 1991; Liberty et al., 2013). The rate of evaporation directly influences the cooling rate to the fraction of the total 2mass of the system (Yeu and Vakhguelt, 2011).

1.5 Problem Statement

There are many researchers studied on soil as porous medium in evaporative cooling system. Roof cooling, heat pipe, Zeer pot and more applications were built to use soil as porous medium in inducing and preserving cooling. Though soil is vastly used in passive and partially passive evaporative cooling systems. There are no many literatures to justify the influences of physical property of soil on evaporative cooling. The correlation between moisture content, air flow and the physical properties of soil is important to select a suitable type of soil for an application. Therefore, this experimental study was conducted to investigate influence of soil physical property in evaporative cooling and find a better performing soil type.

1.6 Objective

- To investigate the performance of loam soil, sand, gravels and small rocks as a porous medium in evaporative cooling system using compressed air flow.
- To study the influence of porosity, permeability, moisture content and the air flow distance on evaporation cooling.
- To investigate the influence of sand and gravels as a porous medium in an evaporative cooling cold storage setup.

1.7 Contribution

The first contribution of this research is defining the relationship between soil and vaporization. The investigation on feasibility of soil to function as porous medium in evaporative cooling system was studied. There are past literatures on porous medium in evaporation cooling system and the feasibility of soil to function as heat sink. However, there are no clear experimental study on property of soil to function as porous medium in evaporative cooling system. Therefore, in this research the influences of physical property of soil and other basic parameters of evaporation cooling were studied.

The second important contribution is the usage of compressed air to enhance the evaporation cooling. Due to condensation in the pressurized air and the high volumetric density, the compressed air greatly enhances the rate of vaporization. The feasibility of experimenting and using evaporative cooling in humid regions is essential for future development and innovations.

This research presents the relationship between soil types, compressed air pressure, rate of evaporation and temperature depletions.

1.8 Scope

The research is limited to experiments on four types of soil; loam soil, sand, gravels and small rocks. The soil was collected from less contaminated location. Loam soil was used to experiment the influence of moisture content and air flow distance inside the porous medium. The optimum setup was used to test the influence of soil type on evaporation. The temperature variation due to evaporation inside the wet soil and the outlet air was measured and analysed. The rate of evaporation was calculated by measuring the weight of whole setup for every 15 minutes throughout the experiment. The moisture content and soil were setup, measured and analysed in weight scale, except in porosity and permeability test. The compressed air (1 bar to 5 bar) through mist filter was used to enhance evaporation process due to the high relative humidity in Malaysia. The experiment was conducted in self-built containers in the laboratory.

As an addition to the study, sand and gravels were used to test as an evaporative cooling porous medium in a cold storage setup. The setup was built based on Zeer pot concept. Instead of using clay pots, the inner clay pot was substitute with Aluminium box while the outer clay pot was substitute with polystyrene box. The space in between Aluminium and polystyrene box was filled with wet soil. The temperature variation inside the cold storage space and wet soil was measured and analysed. The influence of moisture content and soil type on cooling inside the storage space were studied, and a comparative analysis was conducted. To keep the experimental setup in control, the water was added through the air outlet valve at the top of the polystyrene box. In this setup, compressed air through mist filter in the range of 2 bar to 4 bar pressure was used. Compressed air at 5 bar was not able to use due to the inevitability to seal the top cover of the polystyrene box during highly pressured air flow.

The experiment was conducted inside the laboratory where it was assumed that the sun radiation does not influenced the evaporation inside the experimental setup. All the fans in the laboratory was shut during the experiment to avoid accelerated air flow around the experimental setup. Therefore, it was assumed the no air flow from surrounding was influenced the evaporative cooling inside the porous medium.

1.9 Outline

This thesis is divided into five chapters which are introduction, literature review, methodology, results and discussions and conclusions. Chapter one presents basic idea of this research. A brief introduction on cooling methods and evaporative cooling are introduced. Problem statements, objectives, contributions, scope and outline are stated. Chapter two examines further into the literature on parameters that influences evaporation, evaporative cooling application and past studies on soil cooling. Chapter three reports the methodology for various experiments conducted to study soil properties, basic characteristics of soil and evaporation cooling. Chapter four presented findings on soil to function as porous medium in an evaporative cooling system. Finally, chapter five concludes all the findings from this research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Cooling has become mainstream discussion. The demand of cooling increases with the awareness towards hot and sweaty environment. Researches and inventions on cooling sector has increased dramatically with the rise of cooling demand.

There are diverse types of cooling operational system. Whilst evaporative cooling is the oldest and most economical cooling system. Many studied on active and passive evaporative cooling system for industrial and basic daily uses. In this chapter, a brief past researches and knowledges on evaporative cooling systems, applications, and the parameters that influences its efficiencies are presented.

2.2 Parameters that influences evaporative cooling

Wet bulb temperature (WBT), dry bulb temperature (DBT), relative humidity (RH) are the important parameters in a cooling system. WBT is the cooling limit of an evaporative cooling air in a system (Givoni, 1991). Cooling limit is the coldest temperature viable to archive at the given atmospheric temperature and relative humidity (Abrams, 1986; Liberty et al,. 2013). In an evaporative cooling, WBT is archived when the RH of the air is 100%.

Relative humidity is the percentage of vapor being carried by the air molecules comparing to its saturation level (Liberty et al., 2013). RH is playing a vital role in vaporization as the whole system depends on the balance percentage that is available for future vaporization process (Yeu and Vakhguelt, 2011). Vaporization will be zero when the RH of the air is 100%. Air flow with low RH provides highly efficient vaporization. Theoretically, psychrometric chart is used to check the feasibility of air to produce efficient evaporation based on the RH, dry bulb temperature (DBT) or pressure (Abrams, 1986).

Temperature difference is crucial in heat transferring process. The intensity of work to bring temperature to equilibrium will be higher when the differences are greater (Çengel and Ghajar, 2011; Yeu and Vakhguelt, 2011). Synonymously the rate of evaporation ranges with differences between DBT and WBT (Velasco Gómez et al., 2010; Yeu and Vakhguelt, 2011; Givoni, 1994; Givoni, 1991; Abrams, 1986; Liberty et al., 2013). Vast difference between DBT and WBT leads to higher rate of evaporation. DBT is an ambient temperature that measured with casual mercury thermometer. Based on studies conducted by Givoni, the evaporative cooling is beneficial when the DBT and WBT are ranges from 42°C to 44°C and 22°C to 24°C respectively (Givoni, 1991). While the average DBT and WBT in Malaysia is 33.3°C and 27.7°C.

Air flow is essential in evaporative cooling (Givoni, 1991). The thermal conductance increases with the air flow rate (Velasco Gómez et al., 2010). With no wind flow, the evaporated air would stay near the water surface and reaches its saturation limit (Yeu and Vakhguelt, 2011). This scenario reduces rate of vaporization because of the least vapor pressure different (Givoni, 2007). To maintain the efficiency of evaporation the saturated air is needed to be replaced rapidly. Figure 2.1 shows the relationship between cooling capacity over the air flow rate.

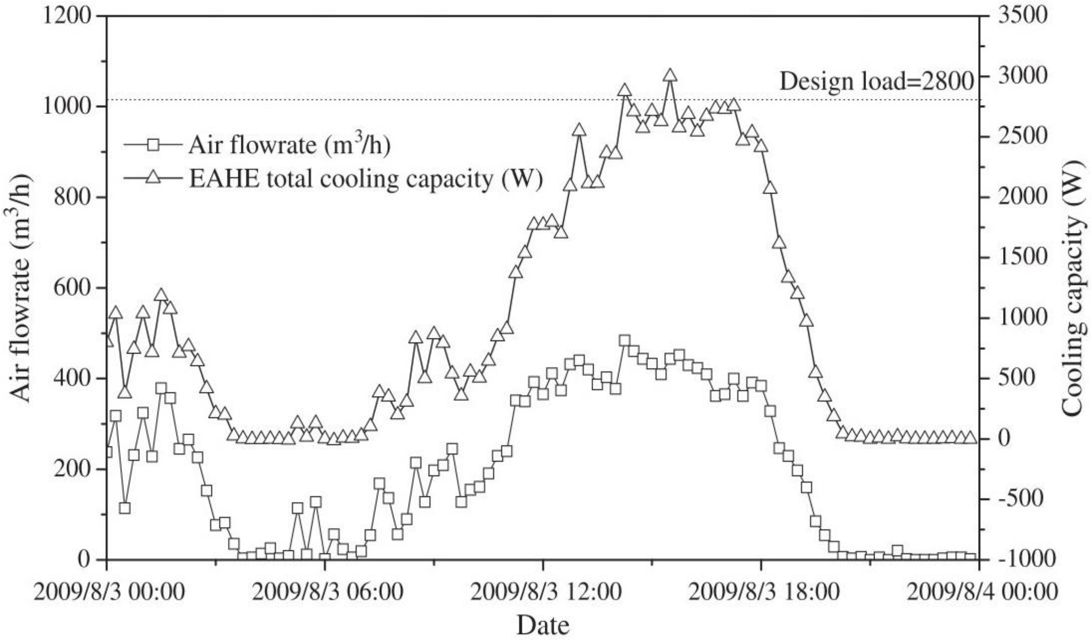


Figure 2.1: Airflow rate vs EAHE total cooling capacity (Yu et al.)

Maintaining air flow is important to maintain the optimum cooling effect. The cooling load increases with the rate of air flow. Air flow can be induced either through active or passive method. The forceful air flow through fan, pump or any mechanical powered devices can be easily controlled and maintained. However, it needed power supply to function. In passive air flow system, the nature is being used through manipulative designs to generate wind flow automatically without any power supply. The only disadvantage of this system is that its highly fluctuated with surrounding weather. Therefore, it`s hard to control and maintain at a fixed flow rate unless the environment itself is being less fluctuated.

2.3 Types of evaporative cooling

Vaporization is a process where the water molecules in liquid form converts into vapor. During this process, the molecular bond of water liquid is broken with the help of heat energy which leads to cooling effect on its surrounding.

There are two types in evaporative cooling system, indirect and direct system (Liberty et al., 2013). Indirect evaporative system is a closed cooling circuit (Abrams, 1986). Heat exchanger is used to keep the fluid apart and create space for heat transfer (Liberty et al., 2013). Indirect evaporative cooling is beneficial in a location with DBT is not more than 46°C and WBT is 25°C (Givoni, 1991). Figure 2.2 shows the workflow inside an indirect evaporative cooling. There is no direct interaction between working fluid and indoor air. The prime purpose of this system is to control the relative humidity of the indoor air. This system is highly appreciable in a high sensitivity RH control space (Guan et al., 2015).

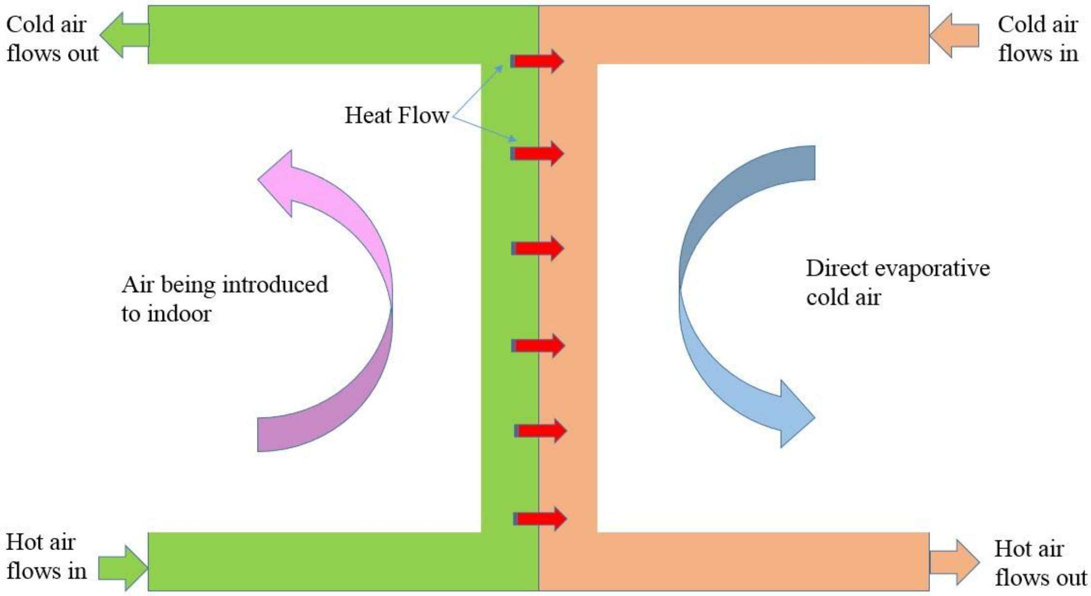


Figure 2.2: Schematic diagram of indirect evaporative cooling system

While in a direct evaporative cooling system, the cold humid air is directly introduced to the occupants or space. Building design and the purpose of the usage are the deciding factors on selecting direct or indirect evaporative cooling system (Guan et al., 2015).

2.3.1 Direct evaporative cooling

Direct evaporative cooling system is simple, energy efficient, environment friendly and provides excellent quality air (Mehere et al., 2014). Figure 2.3 shows the work process of direct evaporative cooling.

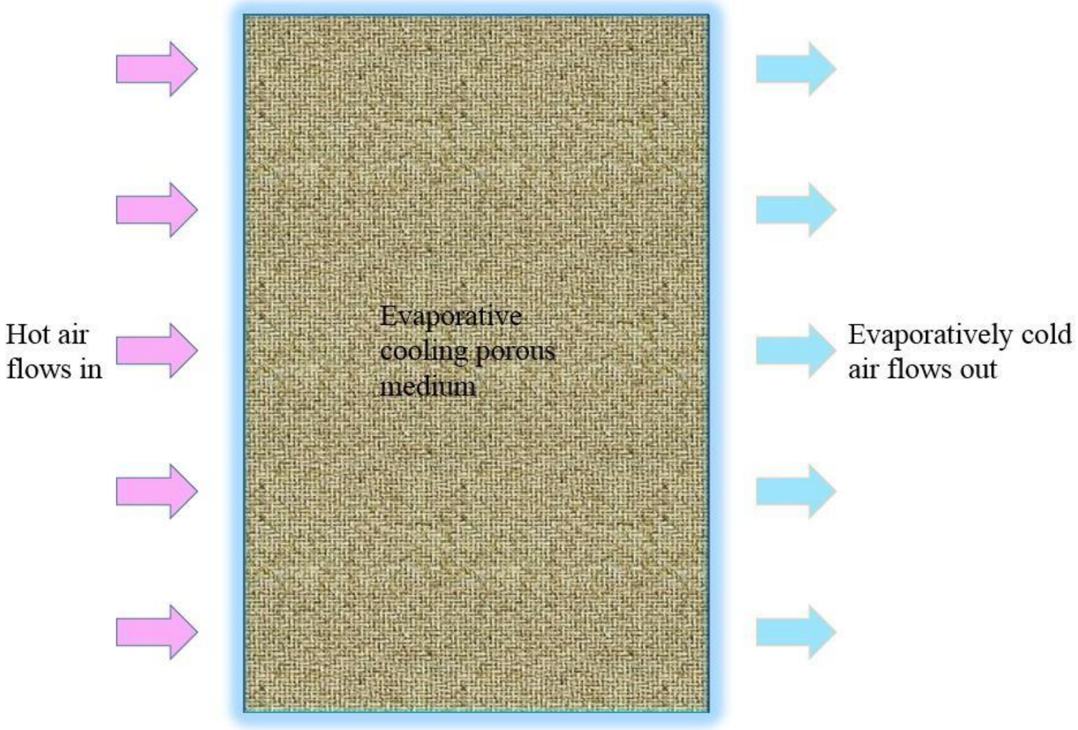


Figure 2.3: Schematic diagram of the direct evaporative cooling

The high RH air could create discomfort to occupant due to lack of evaporation on body. However, with good ventilation and in open space direct evaporative cooling is incomparably comfortable and energy efficient.

2.4 Applications of direct evaporative cooling

Direct evaporative cooling is an economical method to produce cooling effect with least maintenance. Many researches to utilise this concept to produce an effective cooling design. Though the system uses huge amount of water, it does not pollute nor bring negative impact to the environment.

A typical direct evaporative cooler made of a wet porous medium with dry air supply (Liberty et al., 2013; Givoni, 1991). The porous medium enhances surface area for the evaporation process. Besides it gives flexibility for the water to flow and spread through due to its porosity and permeability.

2.5 Evaporative cooling in porous medium

Porosity is the empty space in a medium and it increases with particle size (Shokri et al., 2010). Porosity directly effects the hydraulic conductivity, layer thickness and thermal resistance of a medium. Wet porous medium boosts evaporative cooling as compare to only through water (Yeu and Vakhguelt, 2011). Porosity enhances the surface area in contact between water and dry air. Figure 2.4 shows the relationship between specific surface area and particle sizes of soil. The surface area of soil reduces with the increment of particle size. Fine soil particles are the best selection for evaporation unless it traps air bubbles.

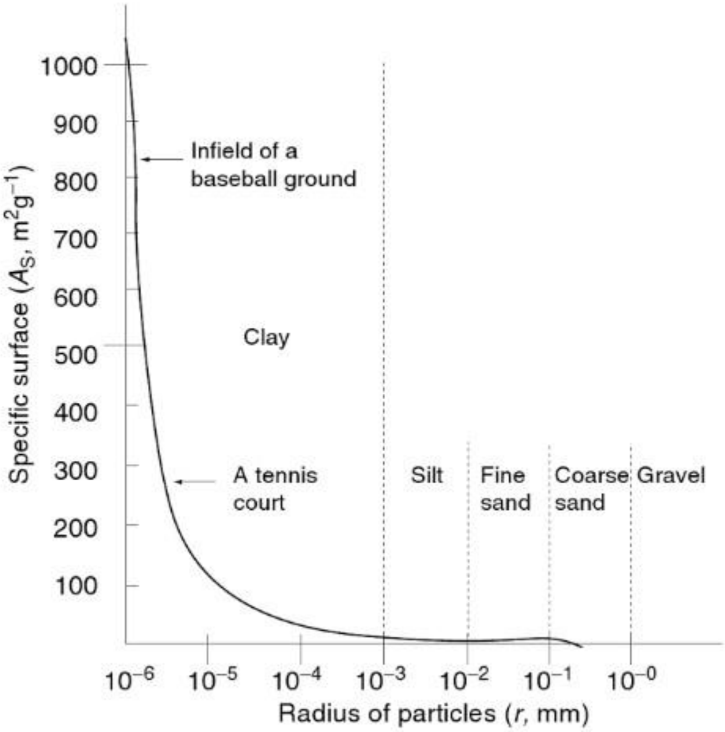


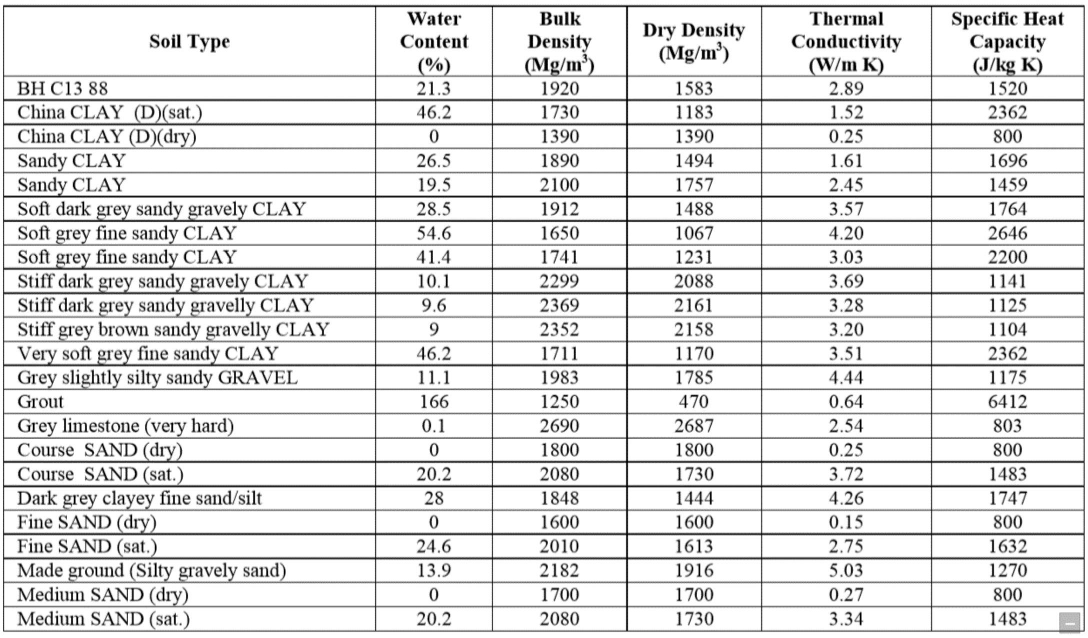
Figure 2.4: Specific surface versus equivalent radius of sphere particles (Miyazaki)

The porous medium layering characteristics are important factor for evaporative cooling (Shokri et al., 2010). Water in thin wet porous layer reaches minimum temperature sooner compare to massive wet porous medium (Yeu and Vakhguelt, 2011). However, the cooling effect on outlet air at a thin wet porous layer is smaller and the moisture in porous medium would dry out soon. Besides, the thermal sustainability in thin layered porous medium will be low unless the whole setup is insulated. While massive porous medium takes extensive time to archive minimum temperature and thermal stability throughout the porous medium. However, it possessed high thermal sustainability and thick layered porous medium viable to provide effective evaporation.

Porous medium layer thickness possessed less significant effect on the rate of evaporation as compare to its porosity (Yeu and Vakhguelt, 2011). The rate of evaporation increases coherently with porosity as long the air gets sufficient time for evaporation process. Big porosity with thin layered porous medium provides less hydraulic resistances which limits the time of air inside the porous medium. Therefore, the air would not have sufficient period to archive RH at 100% while leaving the porous medium. However, small porosity with thin layered porous medium provides high hydraulic resistance, which lengthen the period of air inside the porous medium. Therefore, the air would have sufficient time to induce, convert heat energies and carry more vapor molecules. The porous medium layer thickness only important when the outlet air does not leave with RH of 100%. However, the selection of porosity and its characteristics are depending on the requirement of the applications.

The thermal properties of porous medium materials influence the rate of evaporation. Table 2.1 presenting thermal conductivity of various soil types in various moisture content. The thermal conductivity of soil increases with the water content due to the creation of internal bonding between the soil particles and the high thermal conductivity of soil.

Table 2.1: Thermal conductivity and specific heat capacity of various soils (Hamdhan and Clarke)



Soil Type	Water Content (%)	Bulk Density (Mg/m^3)	Dry Density (Mg/m^3)	Thermal Conductivity (W/m K)	Specific Heat Capacity (J/kg K)
BH C13 88	21.3	1920	1583	2.89	1520
China CLAY (D)(sat.)	46.2	1730	1183	1.52	2362
China CLAY (D)(dry)	0	1390	1390	0.25	800
Sandy CLAY	26.5	1890	1494	1.61	1696
Sandy CLAY	19.5	2100	1757	2.45	1459
Soft dark grey sandy gravely CLAY	28.5	1912	1488	3.57	1764
Soft grey fine sandy CLAY	54.6	1650	1067	4.20	2646
Soft grey fine sandy CLAY	41.4	1741	1231	3.03	2200
Stiff dark grey sandy gravely CLAY	10.1	2299	2088	3.69	1141
Stiff dark grey sandy gravelly CLAY	9.6	2369	2161	3.28	1125
Stiff grey brown sandy gravelly CLAY	9	2352	2158	3.20	1104
Very soft grey fine sandy CLAY	46.2	1711	1170	3.51	2362
Grey slightly silty sandy GRAVEL	11.1	1983	1785	4.44	1175
Grout	166	1250	470	0.64	6412
Grey limestone (very hard)	0.1	2690	2687	2.54	803
Course SAND (dry)	0	1800	1800	0.25	800
Course SAND (sat.)	20.2	2080	1730	3.72	1483
Dark grey clayey fine sand/silt	28	1848	1444	4.26	1747
Fine SAND (dry)	0	1600	1600	0.15	800
Fine SAND (sat.)	24.6	2010	1613	2.75	1632
Made ground (Silty gravely sand)	13.9	2182	1916	5.03	1270
Medium SAND (dry)	0	1700	1700	0.27	800
Medium SAND (sat.)	20.2	2080	1730	3.34	1483

Porous medium with higher thermal conductivity enhances the rate of evaporation (Farouki, 1981; Yeu and Vakhguelt, 2011). Yeu and Vakhguelt (2011) conducted an experiment with metal ball and non-metallic material as porous medium. The material with high thermal conductivity, metal balls provides high cooling rate than non-metallic material. Porous medium with high thermal conductivity archives thermal stability throughout the porous medium in short period. Due to the good thermal conductance of metal balls, the water molecules viable to retain heat rapidly and converts its phase from liquid to vapor.

2.6 Earth as cooling source

Sun is the biggest and the main heat source for earth. However, the soil beneath possessed great potential of blocking the sun rays. The soil beneath archives thermal stability as moving in depth (Givoni, 1991; Givoni, 2007; Givoni, 2011; Sanusi et al., 2013; Costa, 2006; Derradji and Aiche, 2014; Mustafa Omer, 2012; Yuejun Liu et al., 2011). The seasonal temperature variation does not affect the soil temperature as it reaches four meters beneath (Derradji and Aiche, 2014). This facilitates earth to act as cooling source during summer and heating source on winter (Costa, 2006; Mustafa Omer, 2012). This thermal stability of earth enables it to produce stable cooling effect throughout the year in hot countries.

2.7 Soil as porous medium in an evaporative cooling system

Soil is a vastly available porous medium. Soil made of organic and inorganic particle in various shapes and sizes. International Society of Soil Science (ISSS) classify soil in five categories based on its particle sizes as in Table 2.2.

Table 2.2: Soil classification based on particle size. (Miyazaki)

Soil Classes	Range of particle size
Gravel	> 2.0 mm
Coarse sand	2.0 mm – 0.2 mm
Fine sand	0.2 mm – 0.02 mm
Silt	0.02 mm – 0.002 mm
Clay	< 0.002 mm

Characteristics of soil influenced by its physical properties. Rate of evaporation in soil akin with the variation of hydraulic capability, porosity, and permeability of soil. Penetration of fine particles among the larger particle pores leads to formation of aggregates as shows in Figure 2.5. Aggregation makes the soil a be loose and a dense porous medium.

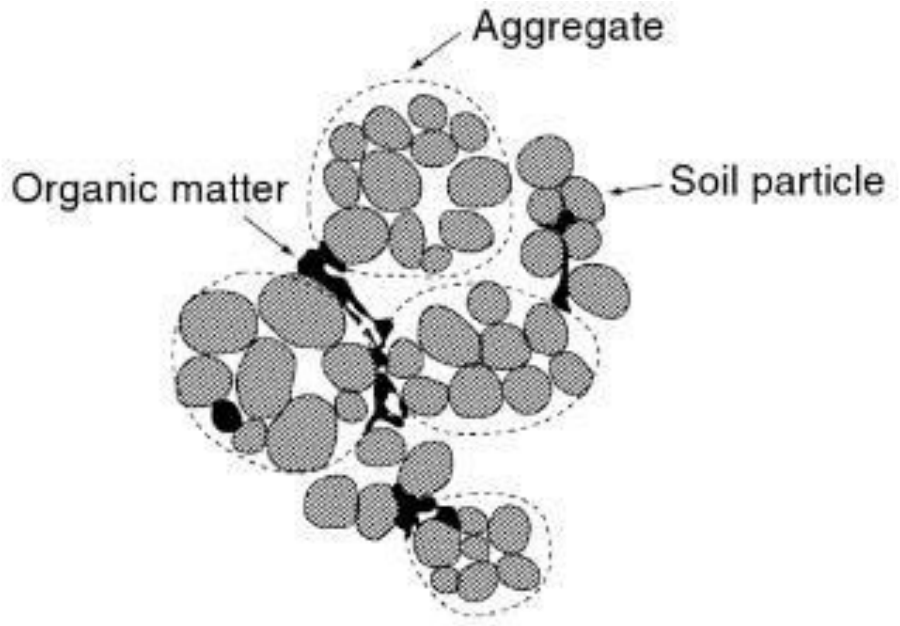


Figure 2.5: Structure of soil aggregate (Miyazaki)

Shokri (2010) studied soil to use as cooling medium in evaporative cooling system. Naturally the voids in the porous material are filled by air. The thermal conductivity of air is poorer than water. Therefore, wet soil possessed better thermal conductivity than dry soil. Thermal conductivity of dry soil to wet soil varies from 0.25 W/m/K to 2.5 W/m/K (Mustafa Omer, 2012). The heat transfer in wet soil depends on the moisture content and the temperature differences (Barrio, 1998).

Permeability increases with moisture content in soil (Farouki, 1981). As water being introduced to dry soil, a water film is built around the particles. This film is infeasible to drain by the gravitational force. The additional water is which fills the void in soil. The thermal conductivity of wet soil increases with moisture content as long the thermal conductivity of soil is less than water (Yu et al., 2007; Farouki, 1981). The thermal conductivity of wet soil increases only until the voids are being sealed completely (Mustafa Omer, 2012). Adding water exceeding the saturation level of soil will not influence the thermal conductivity of the wet soil.

Specific heat is the amount of heat energy required to raise 1°C temperature of 1 gram of water. The specific heat increases with the moisture content in soil (AbuHamdeh, 2003). Every gram of water required around 0.66 Kcalory heat energy from surrounding to vaporize (Givoni, 1994). The latent heat of vaporization of water is 2260 kJ/kg. Greater amount of water needs huge amount of heat energy to reduce 1°C temperature. The volumetric heat capacity of the wet soil increases with the soil density and moisture content (Abu-Hamdeh, 2003). The heat capacity of water is comparably bigger than soil. Therefore, amount of water presence in soil highly influences the total heat capacity of the wet soil.

Thermal diffusivity is the degree of thermal inertia. Thermal inertia is the resistance of heat energy transfer from hot medium to cold. In soil, the thermal diffusivity effected by the moisture content, density and soil`s texture. Rate of heat transfer and evaporation in soil effected by moisture content, density and soil`s texture (Shokri et al., 2010). With the small thermal diffusivity, the whole wet soil reaches thermal equilibrium in short period. Thermal equilibrium is important to stabilize and sustain the evaporation rate and temperature inside the wet soil. Thermal diffusivity increases with the decrement of the particle sizes. However, the arrangement of the porous medium controls the thermal resistance.

Shokri (2010) experimented the influences of sequent layering and thickness with coarse and fine sand. The capillary pressure in fine and compact soil leads to an effective vaporization and reduces evaporative loses. Providing more space and time is important to have an effective evaporation setup. However, having loose soil section is equally important to give path for the air flow. Air flow is the essence of evaporation process. Therefore, finding a balance between compactness and capillary pressure of the porous medium is essential. Shokri (2010) concluded that sequent layering between two different capillary pleasured materials provides high and sustainable evaporation.

2.8 Past researches on earth as cooling source

The soil beneath feasible to work as heat sink (Sanusi et al., 2013). Earth cooling is efficient at location with great ambient and ground temperature differences (Givoni, 1991). Earth as cooling source with heat pipe is among the famous cooling construction system (Mustafa Omer, 2012; Sanusi et al., 2013). Though the installation cost is high, the running and maintenance cost are cheap. Besides, the system is environmentally friendly and possessed long term sustainability (Mustafa Omer, 2012).

The wet soil properties are an important aspect in deciding the efficiency of the earth cooling system. Moisture content of soil influences the rate of cooling and WBT. Figure 2.6 displaying the outcome of the experiment conducted by Yu, Ma, and Li (2007). The temperature reduction varied from 9.1°C, 8.4°C and 8.0°C to the moisture content of 15%, 25% and 35% respectively. The temperature reduction declines with the increment of the moisture content due to the increment of the heat capacity in wet soil.

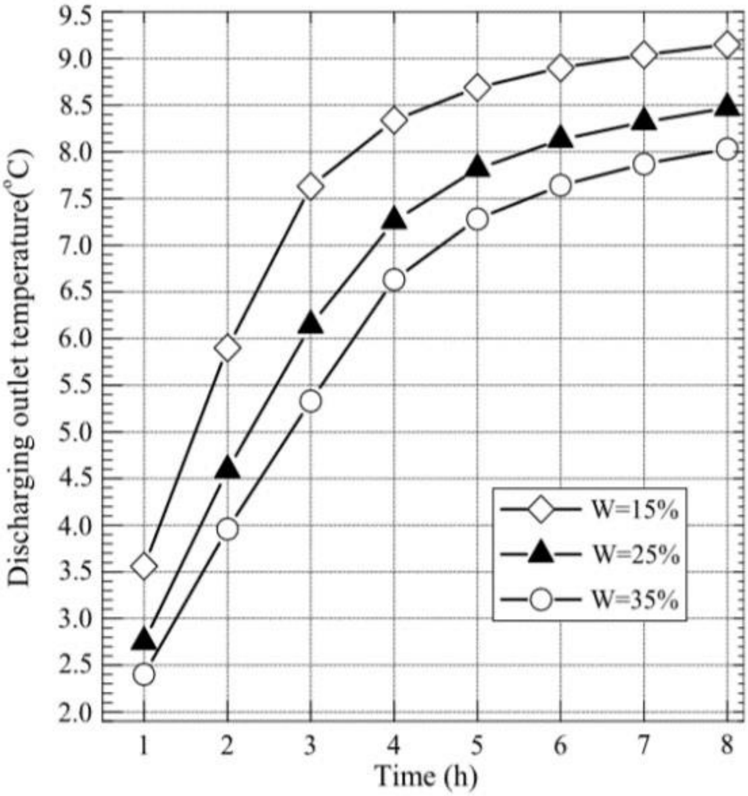


Figure 2.6: Effect of soil moisture content on discharging outlet temperature (Yu et al.)

Givoni has been researching soil cooling for over 20 years. As going deep into the earth, the effect of sun fades. Many researchers studied the influence of soil depth towards cooling efficiency (Givoni, 2011; Sanusi et al., 2013; Mustafa Omer, 2012; Derradji and Aiche, 2014; Givoni, 1991; Liu et al., 2011). The effectiveness of temperature reduction increases with the depth due to the limited influence of the sun (Mustafa Omer, 2012).

The porosity and weak thermal conductivity of the soil increases the thermal diffusivity. Figure 2.7 shows the relationship between 2 meters, 3 meters and 5 meters of soil depth with the temperature throughout the year.

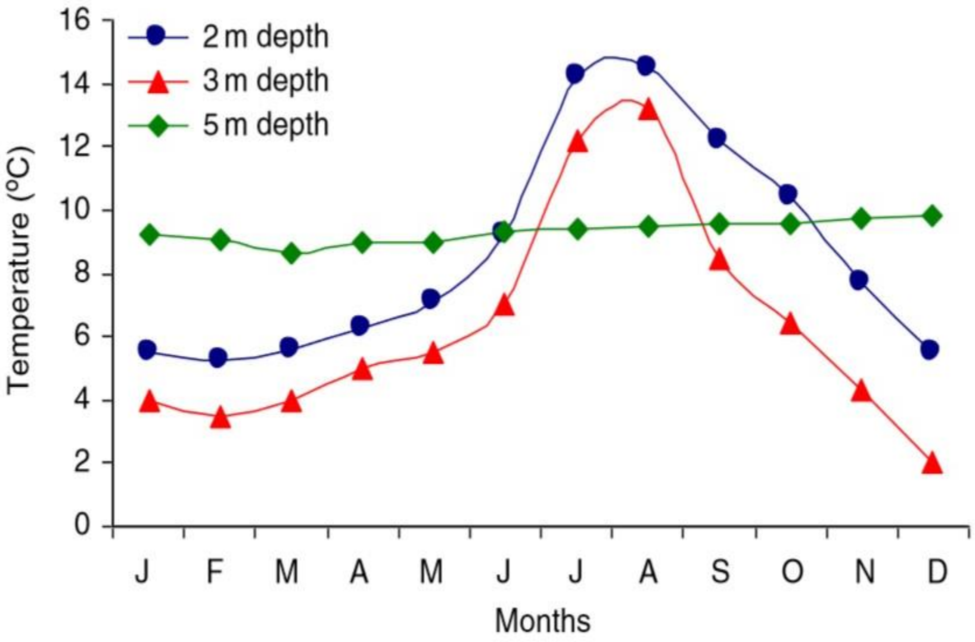


Figure 2.7: Ground temperatures throughout the year (Mustafa Omer)

Mustafa Omer (2012) conducted an experiment at United Kingdom to find the feasibility of using soil beneath for cooling application. The effect of heat from sun fades as going deep into the soil.

The soil temperature at 5 meters depth is almost constant regardless seasonal effects. Mustafa Omer (2012) stated that the average mean temperature around the world will be constant at the depth of 7 meters to 7.5 meters. While Givoni (1991) stated that soil beneath 2 meters to 3 meters able to serve as heat sink at temperate regions.

In the research conducted by Sanusi et al. (2013) at Malaysia, the temperature reduction was 6.4°C to 6.9°C at 1 meter depth. The experiment was conducted on bare soil without any irrigation. Soil filters the effect of sun and blocks the heat penetration.

However, the presence of moisture in soil uses the heat energy for evaporation which indirectly reduces the soil temperature. Derradji and Aiche (2014) studied on soil cooling at Biskra. Based on the study conducted by Derradji and Aiche (2014), the irrigated soil temperature varies from 21.11°C to 22.86°C at 1 meter depth when the outdoor temperature was 40°C.

Even at winter season, soil at depth of 2 meters to 3 meters is feasible to function as heater while on summer as cooling source (Givoni, 2011). Adding shading layers on top of soil and the early morning irrigation facilitates the soil in depth to maintain its minimum temperature. Givoni (2011) experimented soil at 0.6 meters depth at Tallahassee, Florida, 34°C ambient temperature with gravels shading and early morning irrigation. The non-irrigated soil temperature was 29°C, while irrigated at 8 am temperature was 22°C. The temperature fluctuation of dry and wet soils is 2°C and 1°C respectively (Givoni, 2011).

Blocking the direct contact of sunlight is an important alternative to preserve the chillness in soil. The shading technics has been studied by many research to increases the efficiency of the cooling method (Derradji and Aiche, 2014; Givoni, 1991; Givoni, 2007; Givoni, 2011). Shading minimizes the heat gain of the soil from sun. This creates thermal resistance for heat convection and preserves moisture in soil for longer period. Therefore, the soil temperature viable to maintain a steady state from early morning to sunset.

Figure 2.8 shows the schematic diagram of experimental setup of soil shading that Givoni conducted on 2007. The gravel blocks sun light and preserve moisture in soil with controlled evaporation. However, this method fails on rainy days (Givoni, 2007). The hot water from surrounding flows into the control space and rise the temperature to average.

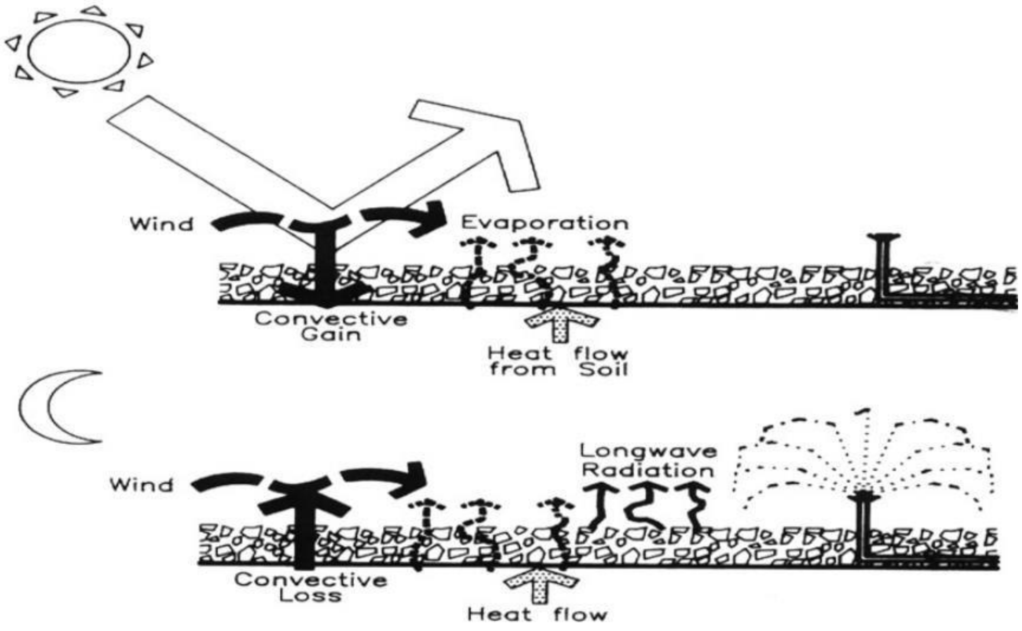


Figure 2.8: A layer of gravel blocks solar radiation away from the soil surface and reduces convective exchange (Givoni)

The porosity, particle size and type of shading material are highly influence the efficiency of the chillness preservation in soil. Shokri et al. (2010) experimented effectiveness of coarse and fine sand; while Givoni (2007) and Yuan et al. (2009) on gravel mulches and Pearlmutter and Rosenfelf (2008) on mesh and layer of lightweight gravel as a shading layer over the soil. The size of gravels, layer arrangements and the thickness of the soil influences the rate of evaporation and temperature stability of soil in depth (Shokri et al., 2010). Figure 2.9 shows the relationship between gravel size and the rate of evaporation based on Yuan et al. (2009) study.

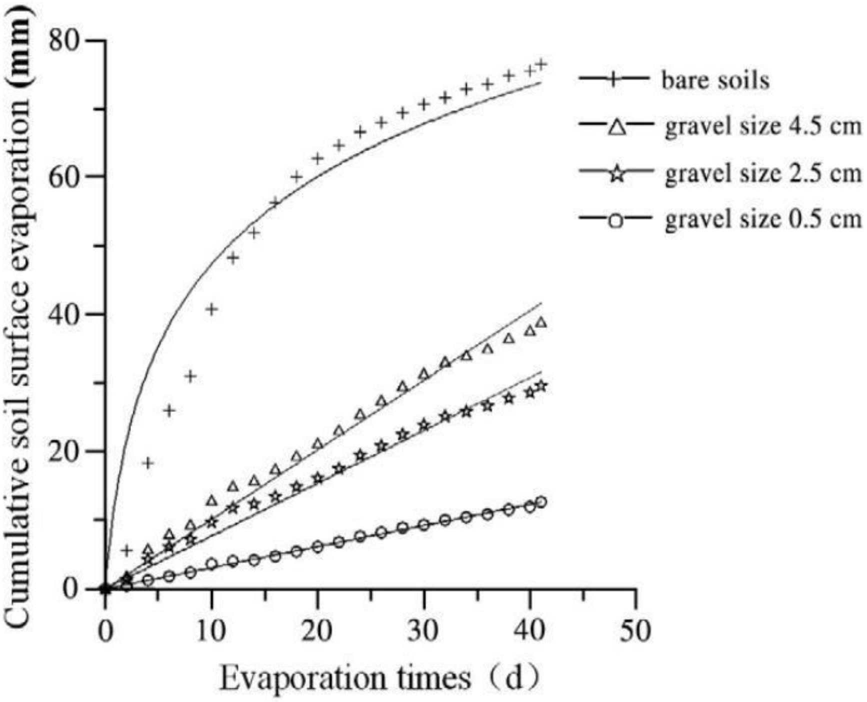


Figure 2.9: Cumulative soil surface evaporation under different gravel mulches (Yuan et al.)

Yuan et al. (2009) experimented gravel size of 0.5 cm to 4.5 cm with 5 cm layer thickness for shading material. The rate of vaporization increases with the diameter size of the gravels (Yuan et al., 2009; Shokri et al., 2010). Porosity and permeability of porous medium increases with the particle size. Therefore, the hydraulic resistance for the hot ambient air to flow through the shading material reduces. Besides, the chillness preservation under the shading decreases with the increment of particle size of the shading material. Selection of particle size and the layer thickness depends on the need of the application and ambient condition of the region. The necessity of evaporation may vary for different climate and application.

2.9 Roof cooling with soil

Roof cooling with soil was famous on past centuries. The thermal stability of soil beneath facilitates it to work as heat sink and insulator. Many researchers studied on using soil for roof and building cooling (Pearlmutter and Rosenfeld, 2008; Barrio,