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Experimental Investigation on Porous Materials for Enhancing the Soil Cooling in Hot and Humid Regions

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Abstract. Soil has been proven as a promising cooling source in arid region, yet it has underperformed in hot-humid tropical countries. This paper aims to investigate the cooling performance (soil temperature) in hot and humid regions under the enhancement of different porous materials such as gravel and woodchips. Two experiments were conducted to evaluate the materials. First, the materials were tested outdoor under open condition. The performance of the surface covered by these materials was compared with other surface conditions such as the empty uncovered surface and the surface covered by a building model. The soil temperatures at the depth of 0.25 m and 1.00 m below the surface covered by wood chips are the lowest compared to other samples. Even at noontime, the soil temperatures at these depths are 0.8°C and 0.4°C lower compared to the soil temperature at the same depths below the uncovered surface. In the second experiment, the porous materials were examined under the desired radiation intensity (1000 Wm^{-2}) from a halogen lamp. The soil surface covered by 2cm-thick and 5cm-thick wood chips is 3°C and 4°C lower than the soil surface covered by gravel. Meanwhile, the soil temperatures at the bottom of the container covered by 2cm-thick and 5cm-thick wood chips are 0.5°C and 0.8°C lower than the soil covered by gravel. Furthermore, soil with empty surface experienced the highest weight loss amongst the samples and the sample covered by gravel has the least weight loss though it has the highest temperature. In conclusion, wood chips performed better in enhancing the cooling effect of soil as they have lower thermal conductivity and better ability to absorb water compared to gravel. The absorbed water may evaporate when solar radiation falls on the wood chips. As evaporation happens, the heat within soil is extracted and the soil is cooled down.

Keywords: Soil cooling, Porous materials, Cooling source, Hot and humid regions, Tropical countries

1. Introduction

The energy used by air conditioning systems constitute the major domestic use in the US and China, and is rapidly increasing in Malaysia. In a report presented by Chan [2], energy consumed by the refrigerator and the air conditioner in a residential terrace house is 4.1 MWh, which is 59% of the total annual energy consumption. Meanwhile, 64% of the total annual energy consumption in a single storey office, or 148.4 MWh is used for air conditioning [2]. The air conditioning has become an important element in life as the living standards rise. Its demand across the globe is expected to increase exponentially in the next hundred years [3,4]. Therefore, an alternative air conditioning system that operates without compressor and refrigerant not only can reduce the energy load of the grid, but also reduce the carbon footprint of buildings.

The alternative cooling source that is being considered in this paper is soil [5–8]. From a report presented by Climatetemp [9], the maximum and minimum ambient temperatures in Kuala Lumpur are 33°C and 22°C, respectively. Givoni [10,11] found that the maximum temperature of the dry bare soil at 60 cm under the ground is 29°C while the maximum ambient temperature above the ground is 34°C. However, after the soil was irrigated in the early morning and covered by a 10 cm thick gravel layer, the temperature of the wet soil at the same level under the ground is 22°C. Furthermore, the temperature fluctuations throughout a day for the dry soil and wet soil are only 2°C and 1°C respectively. Hamada et al. [6] performed an experiment using

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a polyethylene (PE) tube with the inner diameter of 0.052m and length of 83.2 m. The tube was buried at the depth between 3 m and 12 m. When the volumetric flow rate of the brine is 0.12 ms^{-1}, the brine's return temperature from ground is 18.4°C, while the outdoor temperature is 26.2°C, and the rejected heat is 0.638 kWh. Sanusi et al. [7] buried three PE tube with the inner diameter of 0.076 m and length of 30 m separately at the depth of 0.5 m, 1.0 m and 1.5 m. When the air flow in the tube is 5.6 ms^{-1}, they found that the average temperature drop of the return air from polyethylene pipes 1 m under the ground is 6.7°C.

However, little work has been done to justify the cooled soil being an ideal cooling source for building in hot-humid tropical countries like Malaysia. The previous researches are mainly conducted in arid regions [10–13]. Hot and dry climates accelerate the evaporation rate as well as the cooling process. However, tropical countries such as Malaysia, is warm and humid throughout the year. The humidity of the ambient air can affect the evaporation process in soil, thus reducing the cooling effect. Wanphen and Nagano [1] investigated several porous and non-porous materials, namely pebbles, silica sand, volcanic ash and siliceous shale, on their performance to moderate the roof surface temperature. Samples of 0.250 m × 0.250 m × 0.075 m were tested in a wind tunnel. When the Metal Halide lamp above the sample was switched on, the surface temperature of the silica sand was the highest, reaching 50°C. Meanwhile the pebbles and siliceous shale with diameter more than 10 mm have the lowest surface temperature (38°C). The tests were conducted under controlled conditions that might not reflect the performance of the materials in hot and humid regions.

In this paper, several surface conditions were adopted to investigate the basic cooling performance of the coverings. The diurnal soil temperature beneath gravel, wood chips and a building model were measured and compared. Subsequently, the porous materials were further examined under the desired solar radiation intensity. Temperature and weight loss were measured and applied for the evaluation.

2. Experimental Setup

2.1. Soil under Different Coverings – Open Outdoor Condition

The experiment was conducted at School of Mechanical Engineering Universiti Sains Malaysia, Penang, Malaysia. A soil surface with dimension of 3.0 m × 2.0 m was divided into four sections, three of the section surfaces were covered by gravel, wood chips and a 0.5 m × 0.5 m × 0.4 m building model respectively (Figure 1). One of the section surface, was used as the controlled area, which was left empty on its surface. The thickness of the gravel and wood chips layers are 1 cm. Four supporting rods with the length of 1.2 m were pierced into the ground to the depth of 1.0 m. Calibrated Type K thermocouples were attached to the supporting rod to measure the soil temperature at the depth of 0.0 m (surface), 0.25 m, 0.50 m and 1.0 m below the surface. The soil temperature was recorded for a continuous 72 hours (3 days) using PicoTech TC-08 data logger.

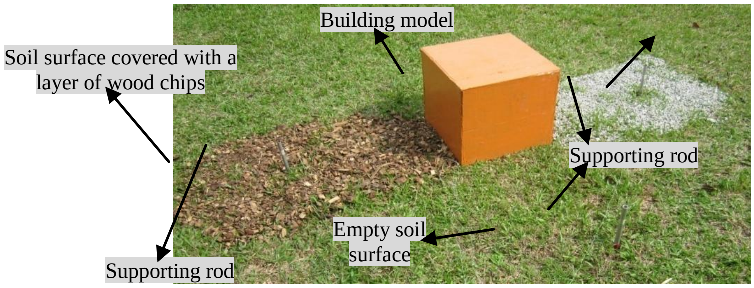


Fig. 1: Experimental set-up

2.2. Soil under Different Coverings - Indoor Controlled Condition

Four different conditions were set up, containers with dimension of 0.14 m × 0.17 m × 0.23 m were first filled with soil to a depth of 0.18 m, then three of them were added a layer of gravel and wood chips (Figure 2). Iso-Tech ISM410 solar power meter was used to determine the height of each container so that the soil surface receives the desired radiation intensity (1000 Wm^{-2}) from the halogen lamp. In order to block the heat and light from neighbouring compartments, each container was segregated by a separator. Three calibrated Type K thermocouples were inserted into each container, namely surface, middle and bottom. The soil temperature was recorded for three cycles of 90 minutes using PicoTech TC-08 data logger.

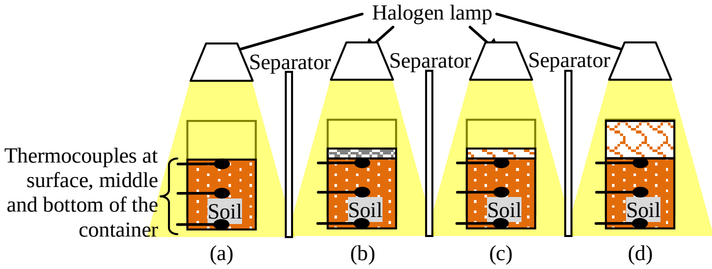


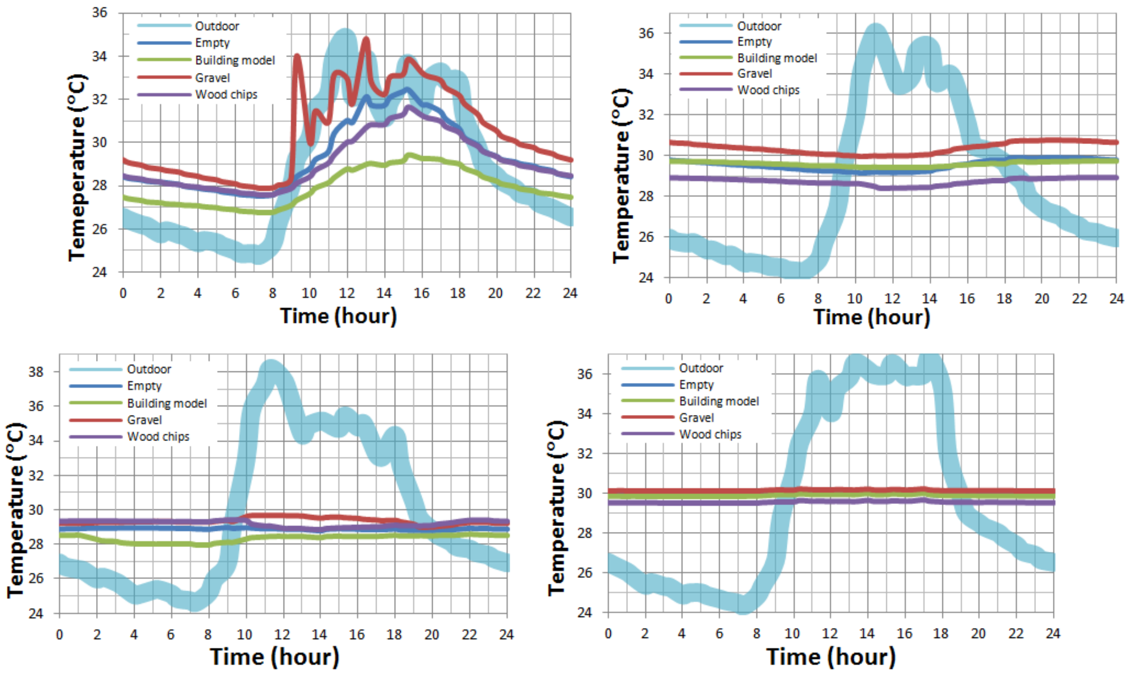
Fig. 2: Schematic diagram of the experimental setup: (a) empty soil surface, (b) soil covered by 2 cm gravel layer, (c) soil covered by 2 cm wood chips layer, and (d) soil covered by 5 cm wood chips.

3. Result and Discussion

3.1. Soil under Different Coverings – Open Outdoor Condition

Figure 3 shows that the outdoor temperature increases rapidly after 8.00 am, and starts decreasing after 6.00 pm, ranges between 24°C and 38°C. The temperatures at soil surface have big variation (Figure 3(a)) compared to temperatures below the surface. As the depth increases, the variation of the soil temperature throughout a day decreases. The variation at the soil surface is 7°C, it drops to 0.9°C, 0.7°C and 0.1°C at 0.25 m, 0.50 m and 1.00 m below the surface respectively (Figure 3(b)–(d)). This shows that the temperature of soil surface is influenced by both convection and radiation heat transfers from surroundings.

The soil surface covered by gravel has the highest temperature amongst the samples regardless the depth of soil (Figure 3). This is because gravel has higher thermal conductivity compared to wood chips and soil. Gravel absorbs the energy from sunlight and transfers it to the soil surface through conduction and radiation. This causes the soil surface to dry. As the soil surface dries, the thermal conductivity of the soil reduces. The dried soil becomes an insulative layer and moderates the heat transfer from underground to ambient. Meanwhile, as the soil surface inside the building model is not exposed to the direct sunlight, it has the lowest temperature (Figure 3(a)) compared to soil surfaces with other coverings. The heat gain of the building model from surroundings causes the indoor air and the indoor soil surface temperatures to increase via the convective and radioactive heat transfer.



(a) (b)

(c) (d)

Fig. 3: Soil temperature (a) at the surface, (b) at the depth of 0.25 m below soil surface, (c) at the depth of 0.50 m below soil surface, and (d) at the depth of 1.00 m below soil surface

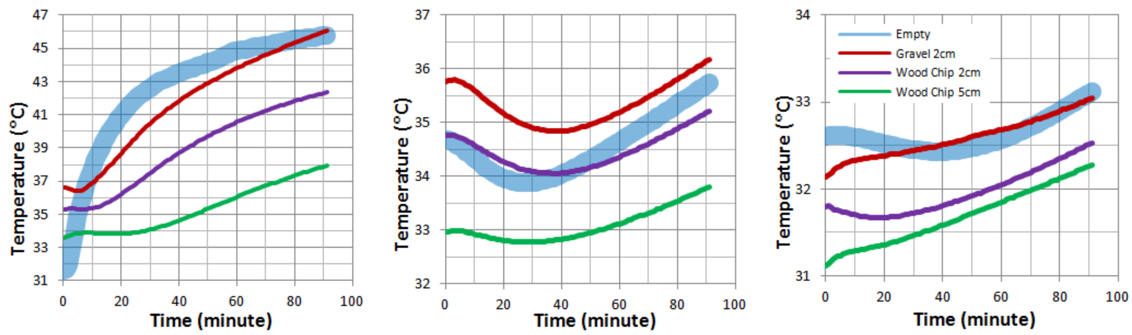
Figure 3(b) and (d) show that the soil temperatures below the uncovered surface and the surface covered by a building model are close, yet the latter is slightly lower than the former as the uncovered soil is exposed to direct sunlight. Figure 3(c) shows that the soil at the depth of 0.50 m below a building model has the lowest soil temperature. This situation occurs due to the rainy days. Rain water and low ambient temperature cool the building model and induce the convective and radioactive heat transfer from the soil to the indoor air and to the building model. In addition, wet soil has a higher thermal conductivity, hence, all the soil temperatures at the depth of 0.50 m are below 30°C.

Referring to Figure 3(a), the temperatures for soil surface without covering and with wood chips covering are approximate. However, the soil surface covered by wood chips is 0.8°C lower compared to the empty soil surface during daytime. The soil temperature at the depth of 0.25m and 1.00 m below the surface covered by wood chips is the lowest amongst the samples (Figure 3(b), (d)). Even at noontime, the soil temperature at these depths under the wood chips is 0.8°C and 0.4°C lower compared to the uncovered soil at the respective depths. Wood chips have a lower thermal conductivity than soil. They can to absorb water during rainy days and act as a heat barrier for the soil surface. During noontime, the solar radiation falls on the wood chips induce the absorbed water to evaporate. Through the evaporation process, the heat within soil is extracted.

3.2. Soil under Different Coverings - Indoor Controlled Condition

In the first experiment, the wood chips layer has proven their ability to reduce the soil temperature though the layer was only 1 cm thick. The second experiment was carried out to further investigate the performance of the wood chips to reduce the temperature of the soil.

Figure 4 shows that the soil temperatures at different depths for various surface coverings, namely gravel (2cm-thick layer) and wood chips (2cm-thick layer and 5cm-thick layer). Figure 4(a) shows that the temperature of the empty surface increase rapidly when the halogen lamp was switched on. This is because the soil surface was exposed to the light directly. The soil surface with gravel is hotter than the soil surface with wood chips. Furthermore, as the experiment continued beyond 90 minutes, the temperature of the soil surface covered by gravel overtook the empty soil surface. Meanwhile, the temperatures for the soil covered by wood chips (both thickness) are 3-4°C (at the surface) and 0.5-0.8°C (at bottom) lower than the soil covered by gravel at the same depths.



(a) (b) (c)

Fig. 4: Soil temperature (a) at the surface, (b) at the middle of container, and (c) at the bottom of container

Table 1: The weight loss of the container

Type of surface	Average weight (kg) Before experiment	After experiment	Weight loss (kg)
Empty	7.74	7.62	0.12
Gravel (2cm-thick)	7.20	7.16	0.04
Wood Chips (2cm-thick)	7.24	7.18	0.06
Wood Chips (5cm-thick)	7.49	7.40	0.09

Table 1 shows the (moisture) weight loss after the experiment. Soil with open surface experienced the highest weight loss amongst the samples as it is exposed to the direct heating from the halogen light. In spite of the soil surface covered by gravel has the highest temperature, the weight loss of this sample is the least. The gravel layer might have become a shield that holds the moisture within the soil from evaporating.

Compared to gravel, wood chips is a highly porous medium that is capable to absorb water like sponge and release through evaporation under the stress of heat.

4. Conclusion

Givoni [10,11] found that the temperature of the wet soil at 60 cm under the ground covered by 10cm-thick gravel layer was 7°C lower than the dry bare soil while the maximum ambient temperature was 34°C. However, in hot-humid tropical countries like Malaysia, when a soil surface was covered by gravel, its soil temperature was the highest among the samples regardless the depth of soil. This is because Malaysia has humid climate and wet soil throughout the year. The gravel layer might act as a shield that holds the moisture within the soil from evaporating. Furthermore, gravel has a higher thermal conductivity compared to wood chips and soil. Gravel absorbs the energy from sunlight and transfers it to the soil surface through conduction and radiation. This causes the soil surface to dry. As the soil surface dries, the thermal conductivity of the soil reduces. The dried soil becomes an insulative layer and further moderates the heat transfer from underground to ambient.

In conclusion, wood chips performed better in enhancing the cooling effect of the soil as they have lower thermal conductivity than gravel but higher porosity than gravel. Wood chips could be soaked by wet soil as they can absorb water and act as a heat barrier on the soil surface. The solar radiation falls on the wood chips may cause the absorbed water to evaporate. Through the evaporation process, the heat within the soil is extracted and the soil is cooled down.

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