Journal of Engineering Science and Technology
Vol. 18, No. 6 (2023) 3128 - 3139

ASSESSMENT OF RED AND WHITE CLAY EVAPORATIVE RATE IN SIMULATING PERSPIRATION WITH TEXTILE

Wen-Pei Low[1], Tay Lee Thin[2],
Lee Yee Yong [2,*], Lee Yeong Huei[3], Ting Sim Nee[2]

[1]Department of Civil Engineering, Faculty of Engineering and Quantity Surveying, INTI International University, 71800, Negeri Sembilan, Malaysia
[2]Department of Civil Engineering, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia
[3] Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University, CDT250, 98009 Miri, Sarawak, Malaysia
*Corresponding Author: yylee@unimas.my

Abstract

Urban residents in most Malaysian cities are experiencing thermal discomfort from exposure of high environment temperature due to the emergence of urban heat island situation (UHI) and climate change. To increase comfortability of urban residents, a thermal comfort study needs to be done by assessing suitable material to be used as a thermal comfort sensor that can indicate heat exposure. This study aims to fabricate white clay and red clay pots with additional textile insulation in simulating sweating process under a controlled environment. Specifically, it was done to evaluate the evaporation rate of red and white clay as well as the effects of additional textile cover towards the evaporation rate. This research covered the aspects by adding textile insulation and checking for suitability of red and white clay pots as a thermal comfort sensor material. The study was conducted by carrying out experimental procedures to measure the evaporation rate and surface temperature of the red and white clay material in the condition of with and without textile cover by using cotton and polyester textile under a controlled environment, whereby the heat exposure towards the material is regulated. The findings showed that the saturated red and white clay pots could simulate perspiration process through the evaporation rate under controlled environment and the additional cotton and polyester textile provided greater evaporative cooling effect for the material. Therefore, the relationship between the evaporation rate of porous material and sweating mechanism will be the driving force for expansion on the innovation of human thermal comfort sensor in evaluating human thermal comfort in the future to maintain comfortable surroundings.

Keywords: Evaporation rate, Perspiration, Red clay, Textile, White clay.

1. Introduction

Urbanization causing the surrounding natural city lands started to be replaced with dense concentration of built spaces and artificial surface materials, such as pavements. Those rapid development processes contributed to the loss of green areas. Since the natural land area is being narrowed, tree crowns that can prevent penetration of sun rays and storage of energy decreased, causing radiation of accumulated energy that leads to temperature increase. As a result, humans will be exposed to direct heat and the increment of temperature will deteriorate thermal comfort amongst people and influenced the human's productivity while doing tasks.

Thermal comfort depends on a person's desirable state of mind in terms of the sensation that he/she is feeling, i.e., either hot or cold [1]. As stated by Elnabawi and Hamza [2], the study of thermal comfort should be done by considering the integration of a few factors, which included physical, psychological and physiological aspects. All factors should be considered in the process of evaluating thermal environment. Enescu [3] explained that to achieve and maintain heat balance between the human body and environment, the body needs to go through a process known as thermoregulation.

Naturally, a human body has its natural way to cool down the skin through sweat evaporation to adapt with heat conditions. The evaporative cooling efficiency of the skin is affected by the volume of perspired moisture that attached to the skin [4]. Consequently, the balanced sweating evaporative rate is crucial for heat dissipation process of the human body in adapting with the rising temperature nowadays. Sweating may play an important role as the physiological factors in assessing human thermal comfort.

In this respect, the usage of sweating thermal manikin in assessing outdoor thermal comfort is becoming more frequent worldwide, as it can avoid humans from going through direct exposure to sunlight in evaluating the thermal comfort. According to Lei [5], the purpose of sweating thermal manikin invention is to analyse the thermal interface between the human body and ambient environment. Comparing it to human subjects' usage, this type of testing is good in repeatability and high in accuracy. The thermal manikin is generally known as an indicator used to evaluate thermal comfort of the surrounding, as it has characteristics that is almost like human physiological systems, specifically the human skin. It was invented to enhance the conception and understanding by analysing thermal interface between the human body and ambient environment on the surroundings, mainly for the assessment of thermal comfort [6]. The usage of various types of thermal manikins is becoming more common worldwide, as it produces valuable data, emphasising direct trials with human subjects.

According to Mandal et al. [7], sweating thermal manikin is generally used to evaluate the thermo-physiological comfort of clothing, as it is capable to imitate the conditions that is comparable to the human body and simulate metabolic heat production and perspiration process. Sweating is a significant thermoregulatory process that assists in the dissipation of heat and prevents the human body from becoming overheated. Moreover, one of the typical uses of sweating thermal manikin is to evaluate the thermal and evaporative resistance of clothing [8]. Sweat evaporation can provide a cooling effect to the human body and prevents the increase in body temperature above values that lead to heat-related illnesses.

Utilisation of sweating thermal manikin is helpful in studying the heat and mass transfer of the human body.

However, there are limitations in obtaining the sweating thermal manikin, as it is a complicated, delicate and expensive tool [5]. The complications in obtaining or producing a sweating thermal manikin are due to the complex integration of materials that need some proper designing. This is to enable it to present the motion of human body by having joints and combinations of materials as well as having different segments on the surface of manikin with different usage. The production of that medium is complicated and might be costly. Additionally, there are limitations in acquiring the material medium to carry out the evaluation. In this study, sweating mechanism is the main concern, as it is a way to assess thermal comfort due to heat dissipation through sweat evaporation, other than using physical measurement and subjective measurement. On that account, sweating thermal manikin was used as a reference in this study to propose an alternative way to simulate the human perspiration systems in terms of evaporation process.

As a preparatory study, appropriateness of the material that poses the characteristic of human skin needs to be evaluated by studying the relationship between the evaporation rate and thermal characteristics of materials used. The intention is to simulate the workflow of sweating evaporation process to determine the evaporation cooling effect. In this case, a porous material, which is the red and white clay is proposed to be used as it is almost comparable to human skin in terms of its porosity characteristics especially when wet which providing cooling effect near the surface due to the heat extraction during water evaporation. It similar with human perspiration when the necessary heat was removed due to sweat evaporation. The utilisation of porous material is due to the existence of micro pores that can induce capillary forces supporting the formation of humid layer by drawing out water moisture to the surface of material, which is almost like human skin, and thus it is comparable [9]. With the additional features of having capillary effect on the porous material surface, this material will be used as an indicator resembling human physiology in terms of sweating mechanism. Besides that, porous material's suitability in simulating human perspiration can be associated with its evaporative cooling ability. This can be seen in clay pot coolers that are often used to store post-harvest vegetables that are ideally stored in high humidity and cool setting - are the most common use of a porous material in evaporative cooling. Evaporative cooling is the most effective in an arid and hot environment which includes the African Sahel region as stated in a study by Rehman et al. [10] where they carried out 17 field trials from Mali and Rwanda to obtain experimental data on clay pot coolers.

However, a previous study conducted by Kelundapyan et al. [11], explained that there was only a moderate correlation between evaporation rate of porous material with human sweating mechanism, as it only covered the physical and physiological aspects of the thermal comfort, excluding the personal aspect of physiological factor on textile insulation. Nonetheless, the former did not consider the usage of textile on the porous material as what an actual human would normally wear during perspiration. Therefore, a study will be conducted using porous material with textile to provide a good development of heat indicator and further development of thermal manikin can be continued. Consequently, an alternative option is proposed, which is to carry out a smaller scale experiment adapting to the concept of sweating thermal manikin through the usage of another simple material relating to the evaporative sweating mechanism. This study aims to fabricate red and white clay pots with additional textile cover in simulating sweating process under a controlled environment and determine the relationship between evaporation rate of red and white clay with human perspiration process.

2. Research Methodology

2.1. Material

Ten unglazed red and white clay pots were prepared. Two out of ten of the clay pots were used as controlled samples, while the rest were submerged in water to saturate and test in different conditions while observing the surface temperature and weight as well as the evaporation rate by acquiring the average value to get a higher accuracy of data. From eight of the saturated clay, four were tested without textile, two with cotton textile and the other two with polyester textile.

2.2. Experiment set up and procedure

The evaporation rates for the red and white clay pots were obtained by measuring the weight loss and surface temperature of the pots for every ten min interval from 8 a.m. to 5 p.m. This experiment was carried out in a controlled environment, whereby a 60W incandescent light bulbs were used to simulate the heat as the source of heat that was regulated by turning on and off during the experiment. This resembles the condition of the environment whether there is sunlight exposure or otherwise. The samples were placed in a box to regulate the temperature inside the box to create a consistent thermal environment. The samples were exposed to lighting from the 60-Watt tungsten light bulb to simulate constant heat gain, eliminating variables that interference from the surrounding temperature to enter or exit the box. The insides of the box were covered with polystyrene to ensure that the internal temperature was not affected by the surrounding temperature. The surface temperature was measured for every ten min. Furthermore, the mass of the red and white clay pots was recorded to identify the evaporation rate in the later stage.

Before the experiment was carried out, eight of the red and white clay pots were submerged in water for a few days until the clay pots reached a condition, whereby their weight is constant. This is to ensure that the pots are in a saturated state. There were two pots that acted as a controlled sample, whereby the pots were not required to be immersed in water and could be tested directly.

Next, all the pots were filled up with water and the tops were wrapped with aluminium foil to prevent direct process of evaporation through the openings on the surface of the pots by the high intensity incandescent light bulbs. Then, those samples were placed inside a controlled environment box under the exposure of heat from the incandescent light bulbs.

The weight of every pot was measured and recorded for every ten min interval to determine the evaporation rate. At the same time, the surface temperature was measured and recorded at every ten min. The tungsten light bulbs were switched off when the mass of the clay pots became constant, and the experiment continued until 5 p.m. by measuring the weight and surface temperature. Initially, the pots were tested without any textile, however, they were covered with textile at a later stage.

3. Results and Discussion

3.1. Surface temperature

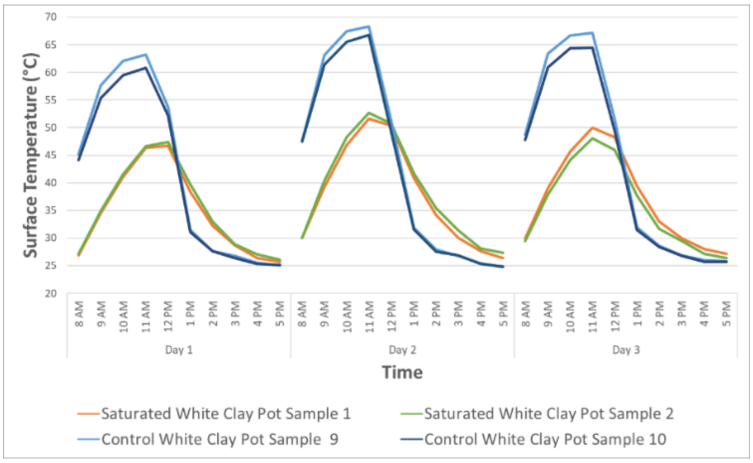
The surface temperature of the pots varies with the exposure of heat from the incandescent light bulbs and is regulated by turning on and off the incandescent light bulbs. The controlled environment was chosen with the necessities to control the parameters under study, which was the temperature as well as to ensure that the influence of other variables that could affect the results was minimised or eliminated [12]. According to the Materials Research Science & Engineering Centre of Pennsylvania State University, the light bulb efficiency for a 60W incandescent light bulb is only 10% of its energy, which is converted to light. The other 90% is being taken as heat produced by the light bulbs. Consequently, the equivalence of the heat energy for the 60W incandescent light bulb was 54W.

Figure 1 shows that there are significant differences between controlled sample pots and saturated sample pots surface temperature. Initially, with the lights turned on, the controlled sample pots' surface temperature increment was faster compared to the saturated pots for red and white clay pots without textile and with textile, respectively. Comparing the graphs for different conditions, the red and white clay pots without textile surface temperature increased gradually in time, which took about 4 h to reach a peak, while it took slightly more than 4 h for the red and white clay pots with textile to reach a peak.

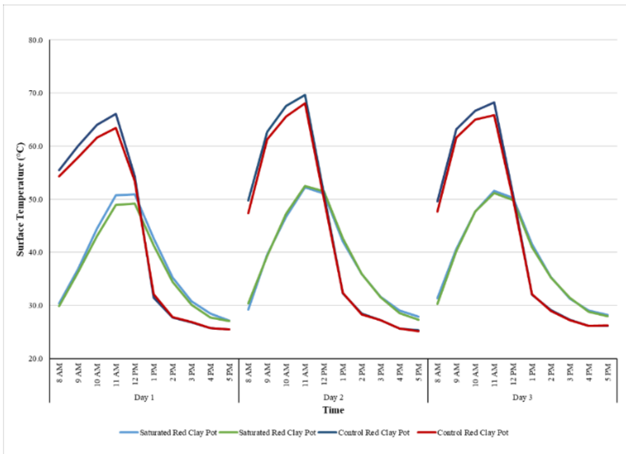
Meanwhile, for saturated red and white clay pots with textile, the cotton reached a peak in 1-2 h before the polyester, as shown in Fig. 2. This may be due to the percentage retention difference between the two fabrics. Generally, polyester is more hydrophobic than cotton. Polyester has 0.4% moisture retention and cotton has 8.5% moisture retention, which means that it only releases a slight amount of moisture while damp according to conventional moisture regains for textile. This is also supported through physical observation throughout the experiment, whereby polyester dries up faster than cotton. Therefore, the larger amount of water retained in cotton, which acted as a 'cooling agent' helped in cooling the surface of the saturated red and white clay pots faster. Consequently, this may explain the reason cotton reaches peak faster than polyester.

Besides, the trend of surface temperature for saturated red and white clay pots during the lights on condition was found to be in-line to the surrounding temperature in the controlled environment. The trend of the graphs corresponded to studies conducted by Choi and Loftness [13] on the forehead and chest areas of a human body. Furthermore, a study by Liu et al. [14] was conducted on local temperature of different skin parts of a human subject. From there, similarities that could be identified included relatively thinner fat layers in the human skin, resulting in sensitive responses to variations of the air temperature, which increased proportionally to the surrounding temperature. The variations of surface temperature concept were applicable for the conditions of saturated red and white clay pots with and without textile.

Next, the increase and decrease in rates of the saturated samples were determined to observe the pattern of the sample surface temperature's increment and decrement based on the heat exposure it received from the incandescent light bulbs. Based on the result, it could be deduced that the increased rate was higher compared to the decreased rate of the surface temperature for both saturated red and white clay pots conditions with and without textile. The change of surface temperature during the lights off condition was slower compared to the condition when the lights were on. The result analysis trend for saturated white clay pots gradients was close to the results of human skin temperature for different parts of the human body [8], whereby the local skin temperature was unable to increase immediately due to high radiant temperature that influenced the nature of thermal inertia possessed by the human body. Furthermore, the study in Liu et al. [14] regulated the temperature, specifically known as radiant temperature, by setting the temperature increasing from 26°C to 38°C and decreasing from 38°C to 26°C to provide unstable environment condition, which is almost like switching the light on and off to regulate the temperature inside the controlled environment. Mean radiant temperature is a measure of the surfaces average temperature that surround a particular point, whereby it will exchange thermal radiation that is usually measured by using a globe thermometer.

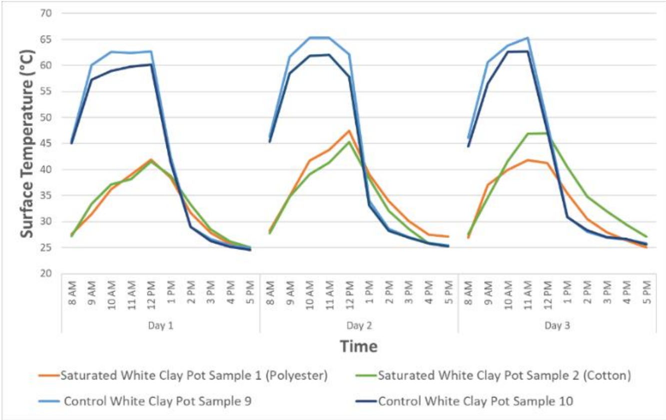


(a)

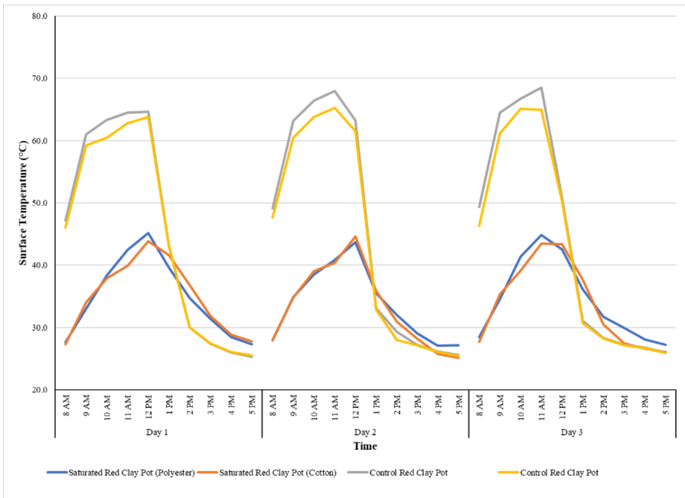


(b)

Fig. 1. Surface temperature against time without textile: (a) white clay, (b) red clay.



(a)



(b)

Fig. 2 Surface temperature against time graph with textile: (a) white clay, (b) red clay.

3.2. Evaporation rate

Evaporation rate is defined as the measure of air capacity to absorb moisture and one of the factors that affects the amount of absorption, which is temperature of the surrounding [15]. The values for the evaporation rate were calculated using Equation 1 that consisted of the values of sample pots weight loss (kg), external surface area for conical frustum (m2) as well as time interval (min). Based on the results, it showed that there was weight difference for the sample pots by time. The reduction in weight could be seen for the saturated sample, however, there were no changes recorded for the controlled sample. The differences might happen due to the moisture content on the surface of the pots. The presence of water moisture on the surface of the saturated sample pots allows the water evaporation process to happen due to the process ability to extract heat from the pots, which is like the human body, whereby heat is extracted during the sweat evaporation process [9, 10].

According to Guan et al. [4], previous studies have proven that sweat evaporation efficiency is related to skin wettedness. In this case, the saturated sample was assumed to simulate a sweating human skin where there is moisture on the surface of the pots (saturated condition). The evaporation process did not take place all the way till the end of the experiment. It only took place when there was a weight decrease, indicating that the moisture on the clay pots surface being evaporated. Since the experiment was conducted in a controlled environment, whereby the temperature was controlled by turning on and off the light bulbs, the evaporation rate was varied, depending on the temperature conditions.

Based on the graphs shown in Figs. 3 and 4, the average evaporation rate for the saturated white clay pots for both conditions with and without textile showed that the trend of the evaporation rate increased drastically in the first few hours and gradually decreased in time as the weight and surface temperature became constant. By comparison, it demonstrated that the evaporation rate for pots with additional textile cover was higher compared to the pots without textile. The differences were due to the textile fibre, which facilitated the distribution of water over a wide region increasing the total cooling potential by evaporation [16].

Meanwhile, Fig. 5 illustrates the occurrences of evaporation for the saturated red clay pots without textile, which could be seen when they were almost reaching the peak, causing a surface temperature drop. The drops for the three days occurred consistently around 11 a.m. to 12 p.m. for the condition of saturated red clay pots without textile, which indicated that constant evaporation, as mentioned by Mendes and Silva [9] was evident. The evaporative cooling for the saturated red clay pots with textile, however, occurred earlier than without textile, as there was additional ‘cooling agent’ present in the textiles because water is an excellent compound in cooling objects down. The drops occurred around 10 a.m. to 11 a.m., which also showed consistency for the condition of saturated red clay pots with textile (Fig. 6). The evaporation process of the saturated red clay pots occurred earlier with textile, as the process by which fibre facilitated the distribution of water over a wider region in a fabric increased the total cooling potential by evaporation. The evaporation efficiency of water from fabric would, however, also be impacted by the overall quantity of water stored within the fabric [16].

According to Arens and Zhang [17], the evaporative cooling mechanism is a latent heat transfer process, whereby heat dissipation process is done through the evaporation of sweat on the surface of the skin. As for the experiment, the moisture on the surface of the saturated pots underwent the same evaporation process. The presence of heat energy produced from the tungsten light bulbs accumulated on the surface of the saturated sample pots, which then induced evaporative cooling effect through the phase change from liquid state to gaseous state when the energy, known as latent heat energy, was used up [18]. The evaporation process, which allowed the retained water to go through a phase change from liquid to gaseous state with the presence of vaporisation heat from the environment provided cooling for the pots and reduced the surface temperature of the white clay pots. This phenomenon is also applied in human sweat evaporation process, whereby the sweat liquid will go through a phase change from liquid to gaseous state and with the presence of vaporisation heat from the environment that provided cooling for the human body.

As stated in a study by Qingqing et al. [19], the body evaporative rate of heat loss essential factor is the sweat loss, which is close to the saturated white clay pots where the evaporation rate depends on its weight loss. In this study, it was considered the metabolic rate and clothing insulation values, which were obtained from ASHRAE [1] of Addendum g and Addendum h. From Addendum g, the metabolic rate task for the saturated white clay pots was assumed to be in a seated position, quiet state and the value for the metabolic rate was 60 W/m2. While the clothing insulation values from Addendum h were assumed that the garments included for the experiment were trousers and short sleeve shirts with the clothing insulation values of 0.57 Clo.

In the same study conducted by Qingqing et al. [19], it also included the environmental conditions for metabolic rate and clothing insulation values, which were 50-250 W/m2 and 0.56-1.50 Clo, respectively. Moreover, the experiment was conducted in a controlled environment where the air temperature was controlled. The correlation of the evaporation rate for the saturated sample pots and sweating human skin could be seen through the trend of the results, whereby the evaporation rate was affected by the temperature surrounding the subject.

The resemblance in the trend as correspond in the study of Qingqing et al. [19] suggested that the saturated sample pot was able to simulate human perspiration process, specifically the sweating process and the evaporation rate could provide evaporative cooling for the material by reducing the surface temperature approaching thermal equilibrium. There was no reduction in the controlled sample weight because there was no moisture on the surface of the pots to be evaporated, and thus the evaporation rate for the controlled sample was not considered. As a result, a higher water content in clothes resulted in increased evaporative mass loss [20, 21]. In other words, greater evaporation rate results from higher sweat retention, for instance, higher clothing wettedness. Therefore, it is notable that cotton provides greater evaporation rate than polyester as it can retain more water.

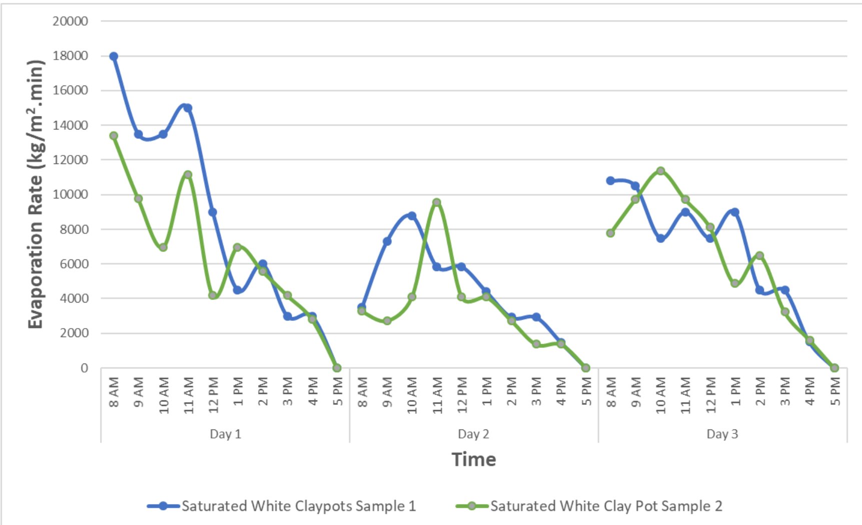


Fig. 3 Average evaporation rate against time graph for saturated white clay pots without textile.

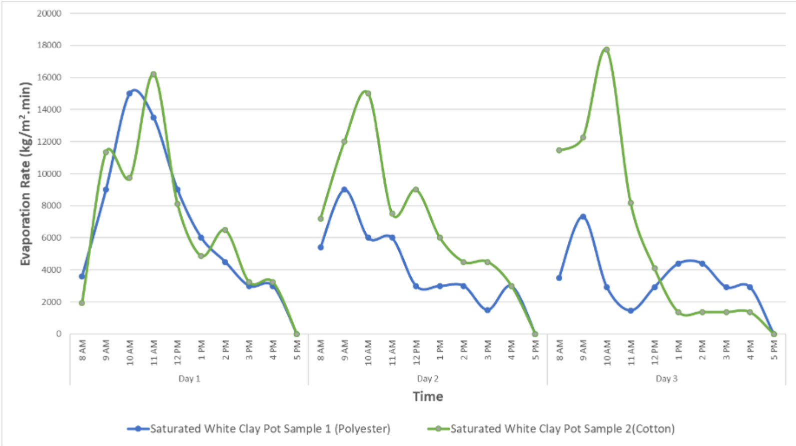
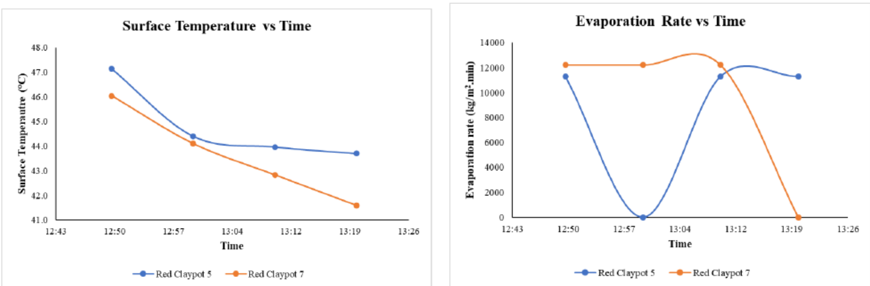
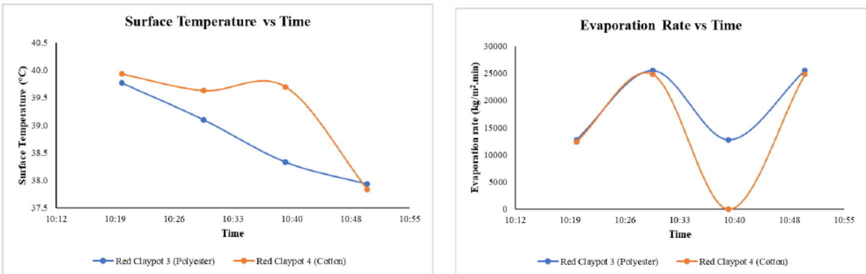


Fig. 4 Average evaporation rate against time graph for saturated white clay pots with textile.



(a) **(b)**

Fig.5 Variation of red clay pots without textile against time: (a) Surface temperature; (b) Evaporation rate.



(a) **(b)**

Fig. 6 Variation of red clay pots with textile against time: (a) Surface temperature; (b) Evaporation rate.

4. Conclusions

It can be concluded that the evaporation rate is identified with its porosity characteristics through the analysis and comparison that has been done. The findings also proven that the additional textile cover does provide more effective evaporative cooling and thermal insulation for the material with the utilisation of cotton and polyester textiles which is the same concept as the condition when a human is using garments to provide them thermal insulation. The white clay pots demonstrated better reproducibility and good response of the evaporation rate towards regulated surrounding temperatures which close to the human sweat evaporation mechanism which have the same sensitivity towards surrounding temperature. Other than that, from the analysis and discussion that have been done, it can be concluded that the evaporation rate does help in reducing the surface temperature and the weight loss of the saturated clay pots is directly proportional to the higher surrounding temperature as well as the higher rate of evaporation.

The material exhibited some characteristics resembling human perspiration process and was considered as an alternative of human skin in thermal assessments for thermal comfort evaluation. Hence, the saturated white clay has the potential be used in the expansion of the innovation of human thermal comfort sensor in evaluating human thermal comfort in the future so that a comfort surrounding can be maintained.

Acknowledgement

The authors would like to acknowledge Ministry of Higher Education, Malaysia (Kementerian Pengajian Tinggi Malaysia) through Fundamental Research Grant Scheme of FRGS/1/2019/TK10/UNIMAS/02/4 and INTI International University for their financial support and research facilities.

References

1. ASHRAE Standard (2004). Thermal environmental conditions for human occupancy 55-2004. *American Society of Heating, Refrigerating and Air-Conditioning Engineers*, Inc., 2004(ANSI/ASHRAE Standard 55-2004), 1-34.
2. Elnabawi, M. H.; and Hamza, N. (2020). Behavioral perspectives of outdoor thermal comfort in urban areas: A critical review. *Atmosphere*, 11(1), 1-23.
3. Enescu, D. (2019). Models and indicators to assess thermal sensation under steady-state and transient conditions. *Energies*, 12(5), 841.
4. Guan, M.; Annaheim, S.; Li, J.; Camenzind, M.; Psikuta, A.; and Rossi, R. M. (2019). Apparent evaporative cooling efficiency in clothing with continuous perspiration: A sweating manikin study. *International Journal of Thermal Sciences*, 137, 446-455.
5. Lei, Z. (2019). Review of application of thermal manikin in evaluation on thermal and moisture comfort of clothing. *Journal of Engineered Fibers and Fabrics*, 2019:14.
6. Holmer, I. (2004). Thermal manikin history and applications. *European Journal of Applied Physiology*, 92(6), 614-618.
7. Mandal, S.; Annaheim, S.; Camenzind, M.; and Rossi, R.M. (2017). Evaluation of thermo-physiological comfort of clothing using manikins. *Manikins for Textile Evaluation*. 2017, 115-140.
8. Koelblen, B.; Psikuta, A.; Bogdan, A.; Annaheim, S., and Rossi, R. M. (2017). Comparison of fabric skins for the simulation of sweating on thermal manikins. *International Journal of Biometeorology*, 61(9), 1519-1529.

9. Mendes, J.C.A.F.; and Silva, M.C.G. (2004). On the use of porous materials to simulate evaporation in the human sweating process. *European Journal of Applied Physiology*, 92(6), 654-657.
10. Rehman, D.; McGarrigle, E.; Glicksman, L.; and Verploegen, E. (2020). A heat and mass transport model of clay pot evaporative coolers for vegetable storage. *International Journal of Heat and Mass Transfer*, 162, 120270.
11. Kelundapyan, R.; Yong, L.Y.; Zakaria, M.A.; Nagapan, S.; and Segaran, V.C. (2020). The suitability of porous material to simulate evaporation in human sweating mechanisms. *International Journal of Engineering and Advanced Technology*, 9(3), 457-463.
12. Guedes, J.C.; Costa, E.Q.; and Baptista, J.S. (2012). Using a climatic chamber to measure the human psychophysiological response under different combinations of temperature and humidity. *Thermology International*, 22(3), 49-54.
13. Choi, J. H.; and Loftness, V. (2012). Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations. *Building and Environment*, 58, 258-269.
14. Liu, Y.; Wang, L.; Liu, J.; and Di, Y. (2013). A study of human skin and surface temperatures in stable and unstable thermal environments. *Journal of Thermal Biology,* 38(7), 440-448.
15. Bhatia, A. (2012). Principles of evaporative cooling system. PDH Online | PDH Center, 231, 1-55. Retrieved October 5, 2022, from https://www.pdhonline.com/courses/m231/m231content.pdf
16. Reischl, U. (2016). Fabric cooling by water evaporation. *Journal of Fiber Bioengineering and Informatics*, 9(4), 237-245.
17. Arens, E.; and Zhang, H. (2006). The skin's role in human thermoregulation and comfort*. Thermal and Moisture Transport in Fibrous Materials*, 560-602.
18. Parsons, K. (2019). *Human Thermal Comfort*. (1st ed.). CRC Press, 1-9.
19. Qingqing, W.; Jianhua, L.; Liang, Z.; Jiawen, Z.; and Linlin, J. (2020). Effect of temperature and clothing thermal resistance on human sweat at low activity levels. *Building and Environment*, 183, 107117.
20. Craig, F.N.; and Moffitt, J.T. (1974). Efficiency of evaporative cooling from wet clothing. *Journal of Applied Physiology*, 36(3), 313-316.
21. Moh, T.S.Y.; Jin, J.J.Y.; Wong, L.A.; Tiong, M.C.; and Chan, C.K. (2023). Wind-induced evaporative cooling passive system for tropical hot and humid climate. *Frontiers in Mechanical Engineering*, 9, 1-10.