American Journal of Environmental Protection
2024; 13(1): 1-9
http://www.sciencepublishinggroup.com/j/ajep
doi: 10.11648/j.ajep.20241301.11
ISSN: 2328-5680 (Print); ISSN: 2328-5699 (Online)

Water Evaporation and Soil Suction Measurements of Different Soil Types in Jordan

Monther Abdel Hadi[1, *], Nidhal Saada[2], Jumana Hussary[3]

[1]Civil Engineering Department, American University of Madaba, Madaba, Jordan
[2]Civil Engineering Department, Al-Ahliyya Amman University, Amman, Jordan
[3]Civil Engineering Department, Kyushu University, Fukuoka, Japan

Email address:

m.hadi@aum.edu.jo (Monther Abdel Hadi), n.saada@ammanu.edu.jo (Nidhal Saada), jumanahusary@gmail.com (Jumana Hussary)
[*]Corresponding author

To cite this article:

Monther Abdel Hadi, Nidhal Saada, Jumana Hussary. (2024). Water Evaporation and Soil Suction Measurements of Different Soil Types in Jordan. *American Journal of Environmental Protection*, *13*(1), 1-9. https://doi.org/10.11648/j.ajep.20241301.11

Received: December 6, 2023; **Accepted**: December 27, 2023; **Published**: January 23, 2024

Abstract: Jordan is considered a semi-arid region with an average annual precipitation of 111 mm/year. Therefore, it is essential to study and understand the soil properties to reduce water losses and maximize water storage within the land. The current research offers the results of evaluating the evaporation rates and the soil suction for four types of soils, Silica sand, Brown clay, Limestone and Marlstone in Jordan. An experimental approach was conducted for the evaluation of evaporation from a soil column, made up of one single soil type and single gradation, for measured soil properties and climatic conditions. Using the filter paper approach, the matric and total suction were measured for the same samples at different saturation levels. Results show that the evaporation rates start to decline from the potential evaporation to lower rates of actual evaporation. The results also show a direct relationship between the evaporation rate and saturation. In addition, the soil suction test results show an inverse relationship between suction, degrees of saturation, particle size and texture of the soil. It is recommended to use small particle-sized Limestone to reduce evaporation in Jordan. It is also recommended to use Brown clay in deeper soil layers due to its ability to suction water to the surface of unsaturated soils. Finally, further studies could be conducted to investigate the percentage of soils to be mixed with the original ones and the proper soil layering and their effective thicknesses.

Keywords: Jordan, Evaporation Rates, Soil Suction, Soil Type, Soil Gradation

1. Introduction

1.1. Background

Jordan is one of the poorest countries in terms of water resources per inhabitant in the world. It is considered a semi-arid region with an average annual precipitation of 111 mm/ year from 1962 to 2014 [1]. Global warming plays a great role in reducing water resources leading to the phenomenon of desertification, which is one of the most global alarming environmental problems in the world. Figure 1 shows the huge reduction of those renewable internal freshwater resources flows or the internal river flows and groundwater from rainfall in Jordan.

Evaporation and soil suction are two essential parameters in geotechnical engineering projects. Once the wind and sun remove water vapours from the ground surface, the soil holds onto it and stores water in the pores (soil suction). Soil suction and water content are vital parameters for controlling many significant geotechnical properties, including deformability, permeability, shear strength, and volume change [2]. Therefore, it is essential to study and understand the soil properties to reduce water losses and maximize water storage within the land. Evaporation and soil suction are two concepts that must be well-studied for top soils in Jordan to help solve water shortage problems.

Tran, D. T. Q. et al. [3] defined evaporation as the net radiation from the sun that heats the ground surface and the air above the ground surface. In other words, evaporation is the process where the water state is converted from liquid to vapour. It’s important to determine the soil evaporation rates to, say, design soil cover systems for the long-term closure of hazardous-waste sites, to model the saturated and unsaturated groundwater flow, and to predict heave for shallow foundations on expansive soils.

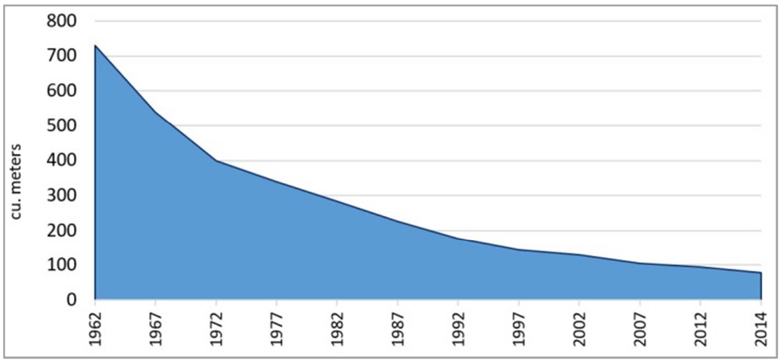

Figure 1. *Renewable internal freshwater resources per capita in Jordan, from 1962 to 2014 (Source: FAO (2014)).*

Many engineering-related problems are associated with partly saturated soils in which water and air fill the voids between particles, resulting in a negative-pore water pressure or soil suction, which is defined as the potential with which a given soil absorbs and retains pore water at given moisture contents [4]. At low moisture contents, soil suction becomes more difficult since the coefficient of permeability of the unsaturated soil can become extremely low [4]. In engineering practice, soil suction is composed of two components, namely Matric and Osmotic suction, whose sum is called Total suction [5]. Matric suction comes from capillarity, texture, and surface adsorption forces of the soil, while Osmotic suction rises from salts present in the soil pore water [5].

Barbour, S. L. [2] found that when the amount of water in soil decrease, the salt concentration increase resulting in an increase in Osmotic suction. Soil water characteristic curve (SWCC) labels the linkage between soil suction and moisture content in unsaturated soils, and it is also vital for learning the physical behavior of unsaturated soils [4].

Engineers, geologists and hydrologists have been attempting to evaluate evaporation and soil suction from soils for decades. Some of the methods that are being used are discussed below.

1.2. Determination of Evaporation Rates and Soil Suction

Potential evaporation (PE) is the maximum water loss via evaporation from the surface of saturated soil with plentiful water as if it is an open water surface [6]. The underlying physical approaches to potential evaporation are pretty well acknowledged. However, the process of water loss through evaporation from unsaturated soil surfaces on a normal day (actual evaporation, AE) is more complex and is less understood than the potential evaporation. The actual evaporation rates from unsaturated soil surfaces are typically significantly reduced compared with the potential rates of evaporation [7]. Due to low soil moisture and strong atmospheric demand, evaporation from partially wet soil profiles is possible in dry regions [8, 9].

To understand the relationship between the potential and the actual evaporation, Figure 2 shows the “Drying curve”, which shows a relation between the ratio of actual to potential evaporation (AE/PE) and the water availability. It describes the three stages of soil drying [10]. Stage I, which is called the constant rate stage, is the potential or the maximum drying that depends only on the climatic conditions, where the actual evaporation equals the potential evaporation [11]. Stage II, which is called the falling rate stage, initiates once the conductive properties of the soil no more allow an adequate water flow to the surface for maintaining maximum evaporation [11]. Finally, Stage III occurs when the surface continues to dry and reaches a specific value [7]. In stage III, the liquid flow to the surface stops, and water molecules might only travel through vapour diffusion [11]. Therefore, here one can see that the actual evaporation depends on both the soil properties and the climatical conditions like hydraulic conductivity and vapour diffusion [7].

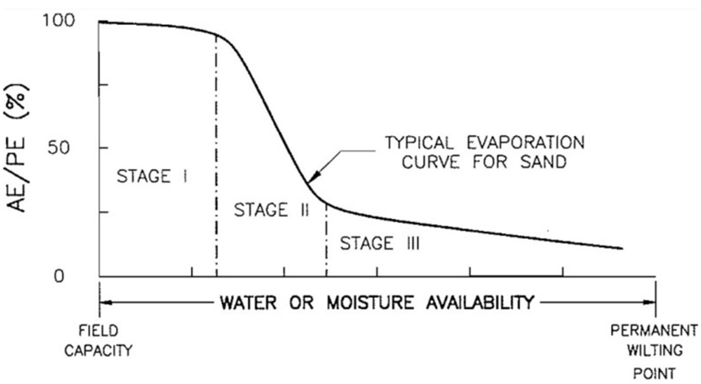

Figure 2. *Relationship Between the Rate of Actual Evaporation and Potential Evaporation (AE/PE) and Water Availability (Source: [7]).*

Many methods are used to determine the potential or the maximum evaporation, such as the energy-based approach [12] as well as the temperature-based approach [13]. However, the most used experimental method to find the potential evaporation is the pan evaporation method, which assumes an open water surface built of unpainted galvanized iron, where the loss of water by evaporation from the pan is measured at regular time intervals [14]. On the other hand, determining the actual evaporation is not simple, but there are two experimental methods that were previously used in the literature; the thin soil section drying test and the soil column drying test [7].

Many methods and techniques are used to determine soil suction. These methodologies can be alienated into two types; direct and indirect methods. Direct methods are those that measure the negative pore water pressure owing to direct suction. On the other hand, the indirect methods measure other parameters, for instance, conductivity, water content, relative humidity, and resistivity and then associate them to the suction through calibration [15].

The filter paper approach advanced in Europe in the 1920s and was then used in the United States later. It is an indirect method and is widely used because of its simple setup, procedure, and data analysis. [4] adopted the thermocouple psychrometer as well as the filter paper method for determining soil suction. As per their outcomes, the filter paper method turned out to be reliable for soil suction measurements as long as the method was properly conducted. This method is grounded upon the assumption that a filter paper will reach equilibrium with soil either through vapour or liquid flow. The Equilibrium time for the Matric suction, done by direct contact with soil that depends on the fluid flow, is less than the Total suction done by non-direct contact with soil that depends on the vapour flow. After equilibrium, the water content of the filter paper is determined, and then the suction of the specimen is obtained from the calibration curve (that is given by ASTM for specific filter papers or lab-calibrated filter papers) in accordance with the moisture content of the filter paper.

1.3. Study Objectives

This study presents an experimental approach for the evaluation of evaporation from a soil column, made up of one single soil type and single gradation, for measured soil properties and climatic conditions. For the same samples and at different degrees of saturation, the Total and the Matric suction are measured by the filter paper method. Through a geo-environmental approach, we aim to study the evaporation and suction behavior of four abundant soil types (Silica sand, Brown clay, Limestone and Marlstone) in Jordan and find possible solutions and methods to reduce the high evaporation rates from the soil surfaces and increase soil suction for the aforementioned soil types.

2. Materials and Method

2.1. Evaporation Experiment Setup

Four soil types that were collected from different sites in Jordan were used in this study. These are Silica sand, Brown clay, Limestone and Marlstone. Table 1 shows the basic properties of the used samples in this study. These are the specific gravity, the uniformity coefficient (Cu), and the Curvature coefficient (Cc). The Atterberg limits for the plastic soils (Brown clay and Marlstone) are also shown in Table 1. Three gradations from each sample were used in this study. These are described as follows:

1) Samples with a diameter of 1 mm (passing Sieve No.16 and retained on No.18)
2) Samples with a diameter of 0.6 mm (passing Sieve No.18 and retained on No.30)
3) Samples with a diameter of 0.3 mm (passing Sieve No.35 and retained on No.50)

Table 1. *Basic Properties of the Samples Used in this Study.*

Soil Sample	Specific Gravity	Uniformity Coefficient (Cu)	Curvature Coefficient (Cc)	Atterberg Limits (%)			
				LL	PL	PI	SL
Silica Sand	2.6144	2.67	1.26				
Brown Clay	2.6500	8.08	0.67	51.1	24.7	26.4	19
Limestone	2.6973	12.67	0.16				
Marlstone	2.5999	13.33	0.77	40.8	21.6	19.2	20

LL: Liquid limit, PL: Plastic Limit, PI: Plasticity Index, SL: Shrinkage limit

The column drying test was used to determine the evaporation rates from the exposed sample soil surfaces. Figures 3 and 4 illustrate the setup that was used in this study. The evaporation occurred under controlled laboratory conditions in a glass chamber, closed with a lid that has openings to let the vapour leaves the chamber. A glass cylinder with an inner diameter of 7.3 cm, an outer diameter of 7.7 cm and a length of 12 cm was used. Then the cylinder was filled with fully saturated Silica sand, Brown clay, Limestone and Marlstone, all in their three different gradations, respectively. The soil column was supported on a sensitive balance (0.01 g) to give measurements of the soil column mass and change in mass during evaporation. To increase the evaporation rate, a lamp was set above the column as a source of heat, and a thermo-hygrometer was installed in the chamber to record the temperature and humidity at each reading.

The actual rate of evaporation was determined based on the change in mass of the column. The first reading was taken at 6 AM, and the light was turned on for 12 hours, and then a second reading was taken at 6 PM, where the light was turned off. One-week readings were taken for each soil sample.

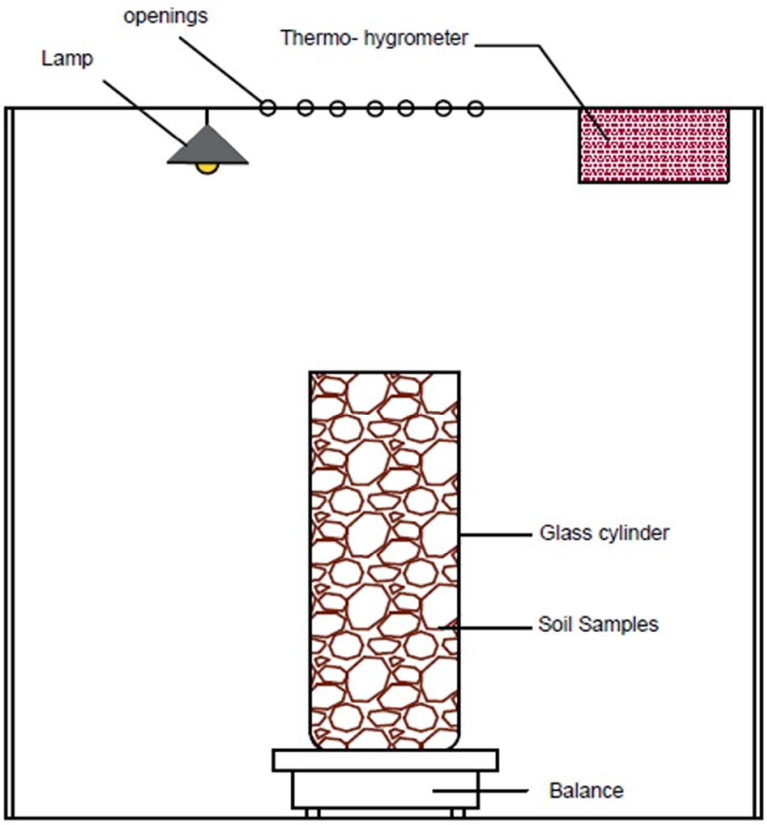

Figure 3. *Schematic Representation of the Experimental Setup for the Evaporation Test.*

Figure 4. *Actual Experimental Setup for the Evaporation Test for the Brown Clay Sample.*

2.2. Soil Suction Experiment Setup

The four soil samples, Silica sand, Brown clay, Limestone and Marlstone with their three gradations, previously sieved, were prepared at different degrees of saturation, 60, 70, and 80%, to determine the Total and the Matric suction. In total, twelve soil suction tests were made in this study.

Schleicher and Schuell No. 589-WH filter papers that have a calibration curve by ASTM D 5298 were used in the test. The filter paper must not come in contact with the jar's interior walls, soil, underneath the lid, or in any way, and must be held using tweezers only. Three filter papers were sandwiched and inserted in the soil sample, and the middle one was used for determining the water content of the Matric suction, and the rest were used as protection from soil contamination. Two other filter papers were implanted on the top of the sample with tweezers, and the top one was used to determine the Total suction.

The total and the matric suction were computed at the same time with an equilibrium time of one week. Two 5 cm diameter PVC rings were sealed well from the bottom by a plastic tap. The first one was filled with a soil sample, and its surface was carefully smoothed and flatted before adding the three filter papers to satisfy a very good contact with the soil. The other PVC ring was attached to the first one using an electrical plastic tap and was filled to the top with soil from the same sample. A PVC ring smaller than the filter paper was inserted on the top to hold the two other filter papers. Then the connected PVC rings containing the samples with the embedded filter papers were put into a glass jar container. The glass container was firmly sealed up using plastic tape. All twelve containers were left for one week in an incubator for equilibrium. After the equilibrium time, the aluminium cans were removed from the incubator and weighed before placing them half-opened in the drying oven at 105 ∓ 5℃ for water content determination.

3. Results and Discussion

The evaporation rates for the 0.3 mm, 0.6 mm, and 1 mm samples for the Silica sand, Brown clay, Marlstone, and Limestone are shown in Figures 5, 6, and 7, respectively. The evaporation rates versus time are clearly manifested. Starting from the highest volume of evaporation, which is potential evaporation (PE), which is the maximum water loss from saturated soil surfaces, as if it is an open water surface. This is certain because the soil columns were entirely saturated at the initiation of the test. After the first 24 hours, we can see a continuous drop in the volumes of evaporation from soil surfaces. Here we can see the appearance of the actual evaporation (AE), which is the water loss through evaporation from unsaturated soil surfaces, and AE is less than PE.

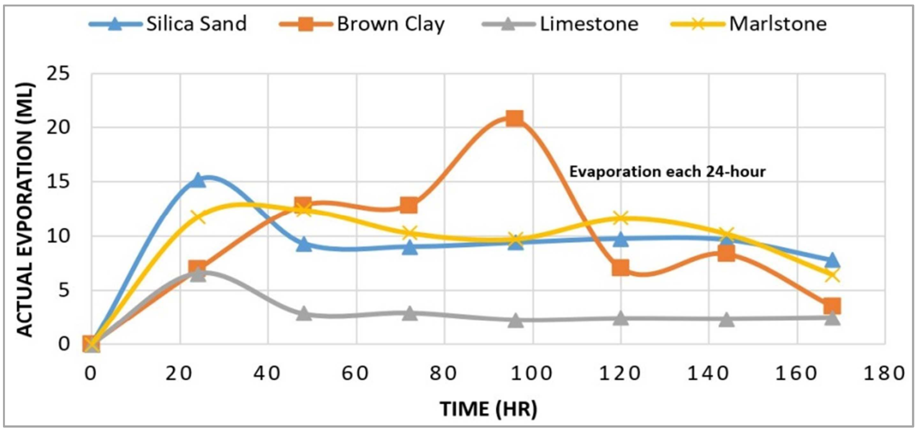

Figure 5. Actual Evaporation Rates for the 0.3 mm Samples.

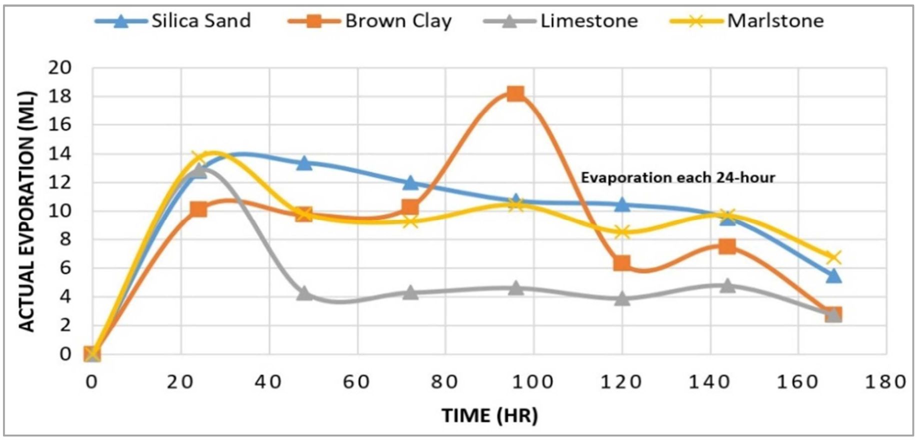

Figure 6. Actual Evaporation Rates for the 0.6 mm Samples.

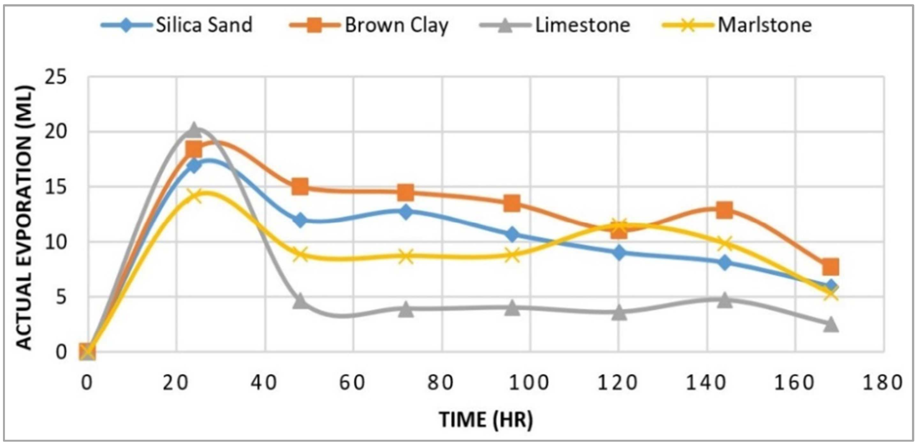

Figure 7. Actual Evaporation Rates for the 1 mm Samples.

Comparing the total actual evaporation rates of the Silica sand 0.3 mm, Brown clay 0.6 mm, Limestone 0.3 mm and Marlstone 1 mm, one can notice that the Limestone 0.3 mm gradation has the lowest evaporation rates, as shown in Figure 8. This would suggest that it is probably, the most effective soil type that can be used as soil tops in arid areas with high temperatures in Jordan to reduce the evaporation rates and hence save more water in the soil for greater times. On the other hand, the Brown clay 1 mm has the highest evaporation rate and thus is the worst soil type to be used as a soil top.

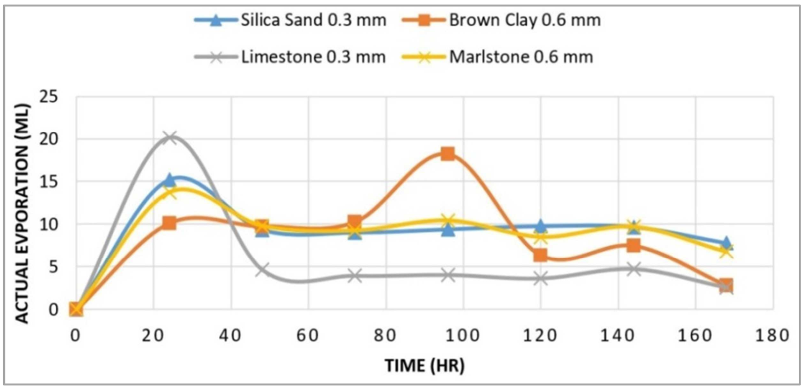

Figure 8. *The Least Actual Evaporation Rates of All Samples and Gradations Tested.*

Figure 9 shows the association between the degree of saturation and the evaporation rates for the 1 mm samples of the four soil types tested. It is observed that the higher degree of saturation has a bigger impact on increasing the actual evaporation from soil surfaces, as shown in Figure 9. Similar results were obtained for the other sample gradations of 0.3 and 0.6 mm. As a result, one would argue that there is no need to fully irrigate crops' soils in order to maintain lower water evaporation.

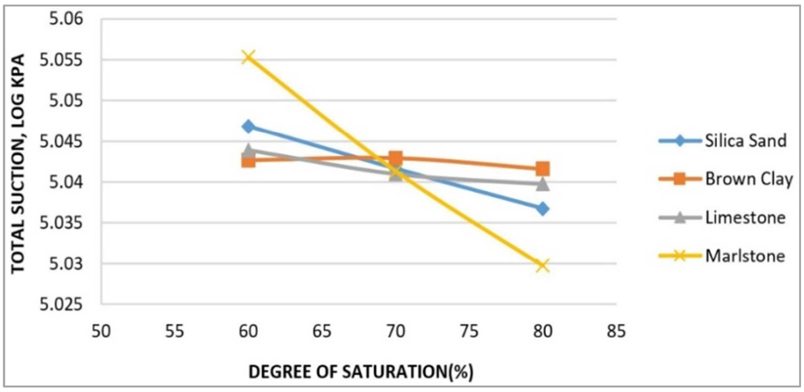

Figure 9. *Degree of Saturation Vs. Evaporation.*

Figure 10 shows the Total suction vs. the degree of saturation for the 0.3 mm samples. An inverse relationship is apparent where the suction increases with the decrease in saturation. A similar inverse relationship exists for the Metric suction, as shown in Figure 11. Similar results were obtained for the 0.6 mm and 1 mm.

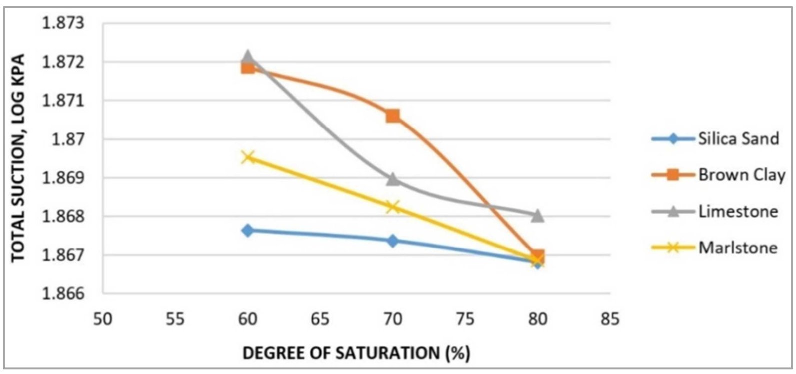

Figure 10. *Total Suction for the 0.3 mm Samples.*

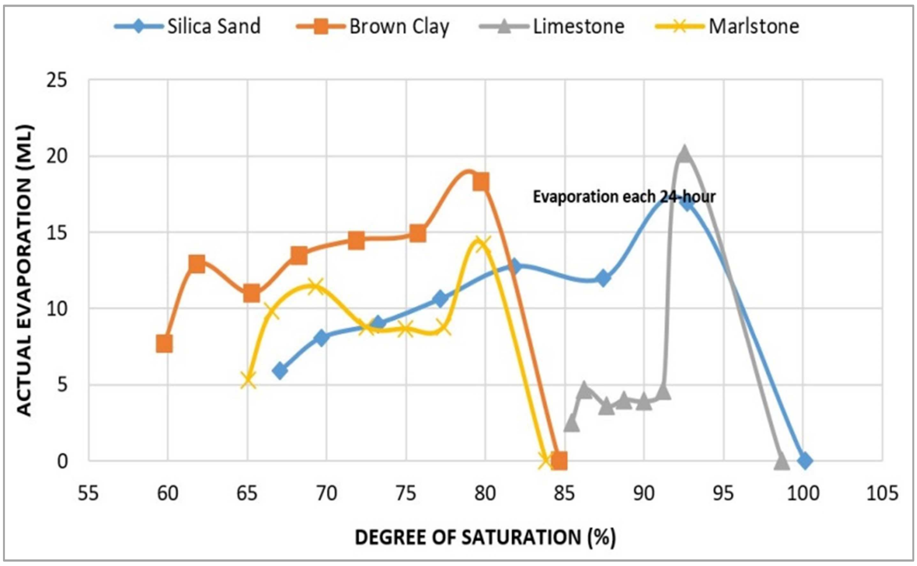

Figure 11. *Matric Suction for the 0.3 mm Samples.*

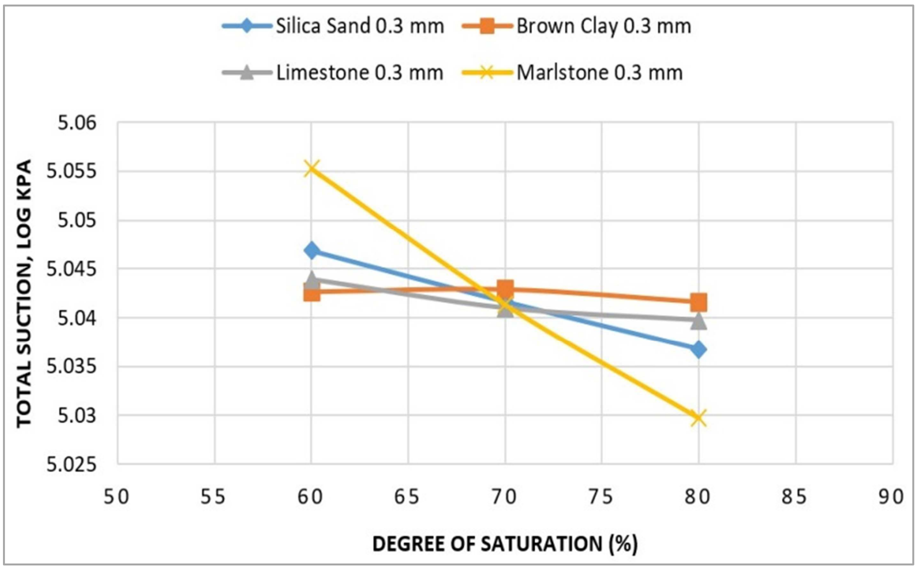

Figure 12. *Highest Total Suction for all Samples Tested.*

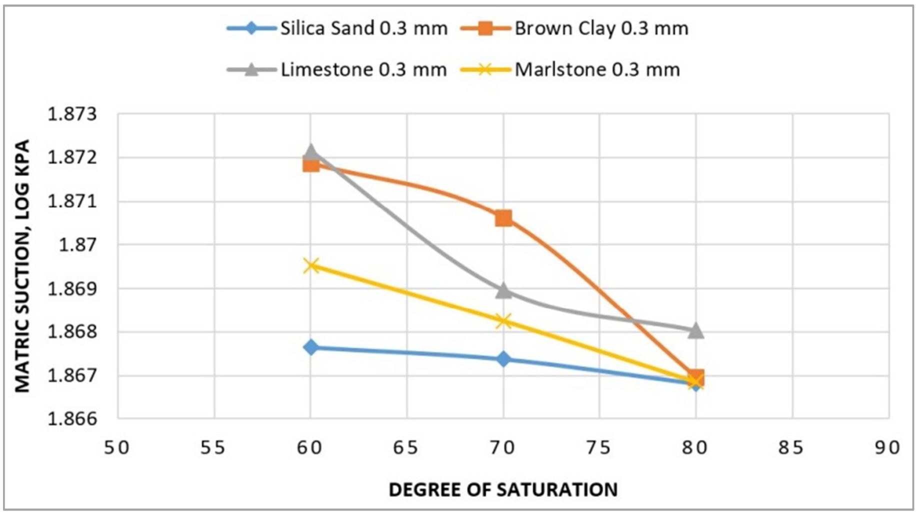

Figure 13. *Highest Matric Suction for all Samples Tested.*

In comparing the Total suction values against the gradation of the soil, it was observed that the Total suction increases with the smaller gradation size samples. Figure 12 shows the Highest Total suction results among the 3 gradations (0.3, 0.6, and.1 mm) for the four soil types tested. For example, the 0.3 mm Limestone produced the highest Total suction when compared with the 0.6 mm and the 1 mm samples. Similar results were obtained for the Metric suction, as shown in Figure 13. Since the suction depends on the capillary rise, and the last depends, in turn, on the pores' size, then the smaller the voids, the smaller the capillary tube and, hence, the larger the suction. In addition, the Matric suction depends on the adsorption, and the 0.3 mm diameter for the different soil types have the same surface area, but they differ in hardness. Therefore, the hard soil particles, like the Silica sand, adsorb less water resulting in low Matric suction magnitudes. On the other hand, softer soils, like Brown clay, adsorb more water resulting in higher Matric suction to move water to the unsaturated soil layers.

4. Conclusions and Recommendations

Since the vast majority of life on earth is at least indirectly tied to the supply of water, and when the water demand is continually increasing, it is vital to use water wisely to reduce the impact on the environment. Starting with enhancing water efficiency in agriculture or in any other project leaves a good impact on the economy and on society as well. Having soil that restores water to the maximum reduces the water needed to satisfy good results; that means saving money. Similarly, the energy that will be used in pumping water and treating it will be reduced. In Jordan, the agricultural sector faces many challenges. One of the most critical problems is the scarcity of irrigation water and high evaporation. Therefore, implementing good solutions to save water for a longer time within the soil will improve agriculture.

The results of the evaporation test show that the evaporation rates start to decline from potential evaporation to lower rates of actual evaporation. Moreover, the higher saturation results in increasing evaporation rates, so it's recommended not to fully irrigate crops' soils to maintain lower water loss. Additionally, the results of the soil suction test show that both the Total and the Matric suction depend on the degree of saturation, where suction increases with the decrease of the saturation. Likewise, the size of the soil, where suction increases with the decrease of the gradation. Finally, we conclude that the suction is affected by the hardness of the soil, where hard soils adsorb less water resulting in low Matric suction.

From a geotechnical point of view, to decrease the evaporation rates in any project, small particle-sized Limestone is recommended to be used. However, from an agricultural point of view, we recommend mixing or layering the Limestone with the soil already being used to minimize water evaporation and reduce the amount of water needed for irrigation. Furthermore, to minimize evaporation and to maintain a better self-watering environment, it is recommended to use Brown clay in deeper soil layers because it's the best in suctioning water to the surface of unsaturated soils.

To expand the knowledge in improving water-efficient irrigation to save more water, further studies should be done to investigate the proper percentage of soils to be mixed with the original ones. Furthermore, investigating the soil layering and their possible most effective thicknesses is also suggested.

Nomenclature

SWCC	Soil Water Characteristic Curve
PE	Potential Evaporation
AE	Actual Evaporation
SWCC	Soil Water Characteristic Curve
Cu	Uniformity Coefficient
Cc	Curvature Coefficient
LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index
SL	Shrinkage Limit

Authorship Statement

All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] FAO. (2014). The State of Food and Agriculture: Innovation in Family Farming. In *Food and Agriculture Organization of the United Nations, Rome*.

[2] Barbour, S. L. (1998). Nineteenth Canadian Geotechnical Colloquium: The soil-water characteristic curve: A historical perspective. *Canadian Geotechnical Journal*, *35*(5), 873–894. https://doi.org/10.1139/t98-040

[3] Tran, D. T. Q., Chan, D. H., & Fredlund, D. G. (2014). Reassessment of Soil Suction at the Evaporation Rate Reduction Point for Saturated-Unsaturated Soil Surfaces. *Geo-Congress 2014: Geo-Characterization and Modeling for Sustainability*, 4084–4096. https://doi.org/10.1061/9780784413272.397

[4] Yang, S.-R., Huang, W.-H., & Chung, S.-H. (2015). Combined effects of temperature and moisture content on soil suction of compacted bentonite. *Journal of Marine Science and Technology*, *23*(3), 281–287. https://doi.org/10.6119/JMST-014-0326-2

[5] Bulut, R. (2001). *Total and matric suction measurements with the filter paper method*. Doctoral dissertation, Ph. D. Thesis, Texas A&M University.

[6] Lehmann P., Assouline S., Or D. (2008): Characteristic lengths affecting evaporative drying of porous media. Physical Review E - Statistical, Nonlinear, and Soft Matter Physics, 77(5), 1-16.

[7] Wilson, G. W., Fredlund, D. G., & Barbour, S. L. (1994). Coupled soil-atmosphere modelling for soil evaporation. *Canadian Geotechnical Journal*, *31*(2), 151–161. https://doi.org/10.1139/t94-021

[8] Hussary J., Alowaisy A., Yasufuku N., Ishikura R. (2021): Significance of Stage 2 of evaporation in homogeneous sandy soil profiles. The 56 th Anuual Meeting of the Japan National Conference, 12-3-2-08.

[9] Hussary J., Alowaisy A., Yasufuku N., Ishikura R., Abdelhadi M. (2022): Pore structure and falling rate stage of evaporation in homogeneous sandy soil profiles. Soils and Foundations, 62(2), 101108.

[10] Jumana Hussary, Adel Alowaisy, Noriyuki Yasufuku, Ryohei Ishikura, Monther Abdelhadi, Pore structure and falling rate stage of evaporation in homogeneous sandy soil profiles, Soils and Foundations, Volume 62, Issue 2, 2022.

[11] Hillel, D. (1980). *Applications of Soil Physics*. Academic Press, New York.

[12] Priestley, C. H. B., & Taylor, R. J. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, *100*(2), 81–92. https://doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2

[13] Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geographical Review*, *38*(1), 55–94. https://doi.org/10.2307/210739

[14] Viessman, W., & Lewis, G. (2003). *Introduction to Hydrology* (5th ed.). Prentice Hall, Upper Saddle River, New Jersey.

[15] Agus, S. S., Schanz, T., & Fredlund, D. G. (2010). Measurements of suction versus water content for bentonite–Sand mixtures. *Canadian Geotechnical Journal*, *47*(5), 583–594. https://doi.org/10.1139/T09-120