Influence of the relative density on stage II of evaporation from homogeneous sandy soil profiles

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1. Introduction

Over recent decades, global warming has been altering the world's climate. The global rise in the average temperature has increased the evaporation rates and disrupted the natural water cycle, resulting in extensive droughts and desertification. A clear understanding of the surface-atmosphere boundary fluxes dominant in drylands is essential to predict droughts and combat desertification. The evaporation flux describes the upward movement and loss of water from the soil pores into the atmosphere. It is considered the governing flux in arid and semi-arid regions since the downward fluxes associated with precipitation are scarce due to low rainfall events.

Evaporation of water from soil profiles is a complicated multiphase process that follows an ambiguous mechanism. The process involves three stages based on the evaporation rates where the water transport mechanism differs. The constant rate stage (SI) is characterized by a relatively high and constant evaporation rate, and it is governed mainly by the atmospheric conditions. During SI, water is supplied to the soil surface by capillary flow from a receding drying front. At a certain drying depth, the hydraulic continuity is disrupted, marking the onset of the falling rate stage (SII). A sharp drop in the evaporation rate occurs, accompanied by a change in the transport mechanism, considered to be coupled between capillary flow and vapor diffusion. Philip (1957) addressed that soil properties mainly govern SII. Lastly, the residual rate stage (SIII) at which the evaporation rate converges to a low and constant value.

Van Barkel (1980) highlighted the complexity of the interactions between the influencing factors on the evaporation process. Several studies evaluated the climatic conditions' role, yet the influence of soil properties necessitates further research efforts. This paper discusses the influence of the relative density (Dr) on SII of evaporation, including evaporated water and water redistribution development through homogeneous sandy soil profiles.

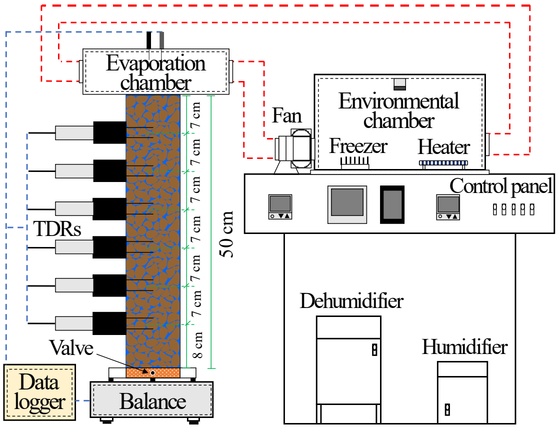

Figure 1: Experimental setup (Schematic)

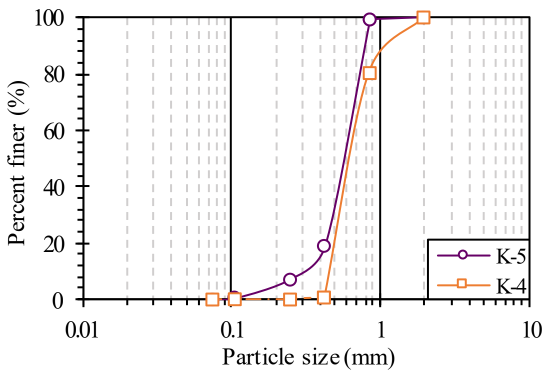

Figure 2: Particle size distribution curves

2. Methodology and materials

One-dimensional homogeneous soil drying column tests were conducted. The soil columns were initially fully saturated by the up-flow saturation method facilitated by water head difference. Additional 80 kPa vacuum pressure was applied from the column's top and bottom to achieve high degrees of saturation. During testing, the water loss from the soil column was continuously measured using a digital balance. The Time Domain Reflectometry probes (TDRs) were attached along the column to record the water content. The evaporative demand was unified to satisfy the study's objective. Therefore, the columns were attached to the climate control apparatus (Teng et al., 2014), as shown in Figure 1. The temperature was maintained at 27.2±1.2°C, relative humidity at 45.6±1.7%, and wind speed at 1.9±0.23 m/s. The tests were shut down once the actual evaporation rate (AE) converges to a low and constant value, announcing the onset of SIII.

Two different textures of silica sand, K-4, and K-5 were used for testing. The particle size distribution curves and the physical properties are shown in Figure 2 and Table 1. The soil columns were prepared by dry packing at three different relative densities; 70%, 80%, and 90% corresponding to the dry density, ρ_d, and the void ratio, e, in Table 1.

Table 1: Soil physical properties

		K-5 70%	K-5 80%	K-5 90%	K-4 70%	K-4 80%	K-4 90%
Specific gravity	G_s		2.6511			2.6512	
Effective size	D_{10} (mm)		0.31			0.47	
Median diameter	D_{50} (mm)		0.57			0.64	
Uniformity coefficient	U_c		2			1.457	
Dry density	ρ_d (g/cm^3)	1.469	1.501	1.535	1.475	1.509	1.544
Void ratio	e	0.802	0.763	0.724	0.794	0.754	0.714

3. Results and considerations

The AE rates were calculated using the data obtained from the digital balance. Figure 3 shows the normalized curves ($AE_{at\ time\ t}/AE_{initial}$) for K-5 samples prepared using the designated relative densities. Based on the evaporation curve, the zone between the highest and lowest constant evaporation rates indicates SII. This stage is characterized by a sharp drop and a continuous decrease in its evaporation rate. The duration of SII is indicted at the top of the scatters for each sample. It must be noted that all samples reached SIII between days 19 and 20. Besides, the duration of SII slightly decreased for denser soil profiles. Similar results were confirmed for K-4 samples.

Figure 4 shows the cumulative evaporated water from the soil columns during the evaporation process. The slope of the curve indicates the AE rate. At the early stages of evaporation, the slope is relatively linear, indicating the constant AE during SI. However, when the slope changes, the AE starts decreasing, announcing the onset of SII. The water loss during SII, indicated on the graph, has an average of 138±25.5 g, yet denser soil profile exhibits less water loss. Analogous results were observed for K-4 samples.

The development of the unsaturated layer was traced using the data obtained from the TDRs. Figure 5 illustrates the water redistribution profiles at different times during the evaporation process. At the beginning of SII, the unsaturated layer extended between 21 and 28 cm, while the saturation reached around 20%. Similarly, at the end of SII, the unsaturated layer's thickness did not recede significantly,

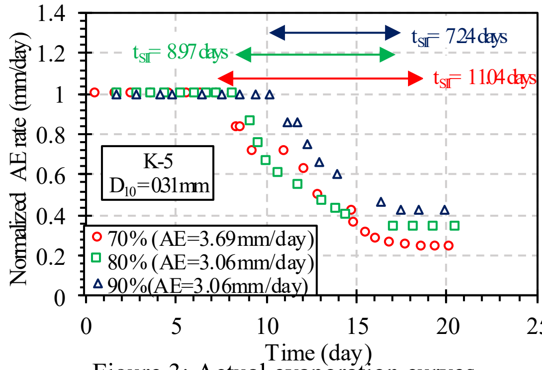

Figure 3: Actual evaporation curves

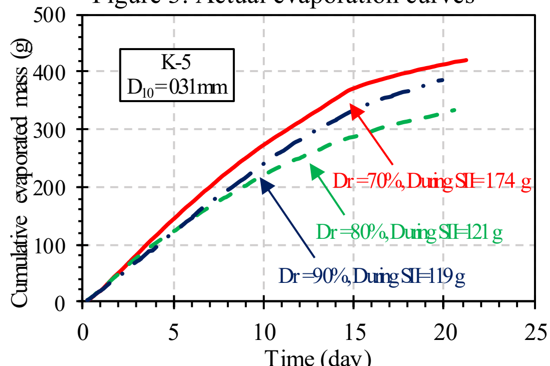

Figure 4: Cumulative evaporated mass curves

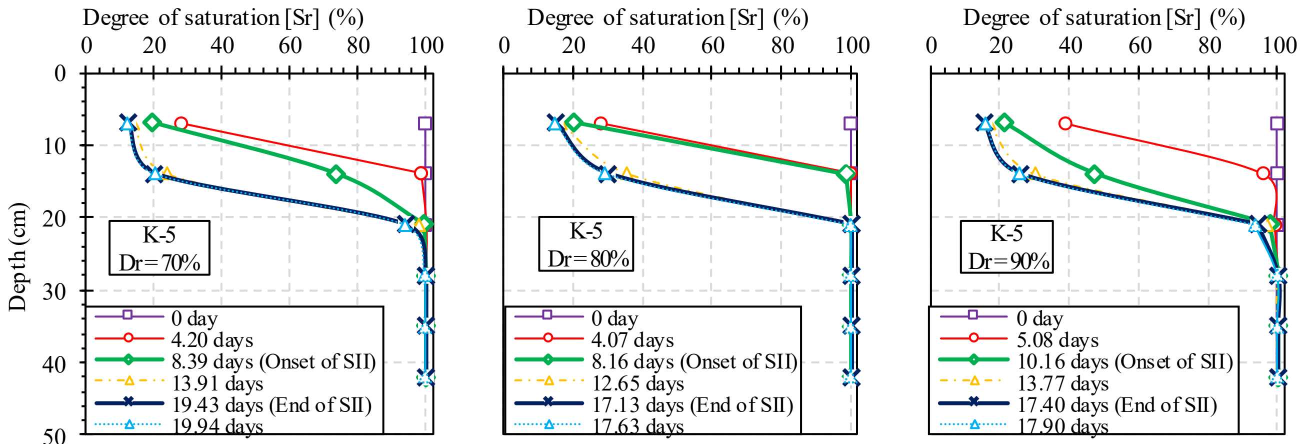

Figure 5: Water redistribution profiles

while the saturation reduced dramatically to 16-18% in the three profiles. The results demonstrate that the unsaturated layers' severity and thickness were almost similar despite the relative density, as is the case for K-4 samples. Therefore, it can be concluded that the influence of the relative density is remarkably low on SII compared to the soil texture, as concluded by Hussary et al., 2020.

Figure 6 illustrates the inverse relationship between the soil profile's density and SII characteristics. Despite its influence, a 10% increase in the relative density contributes to no more than a 17% change in SII duration and water loss for poorly-graded sandy soil profiles.

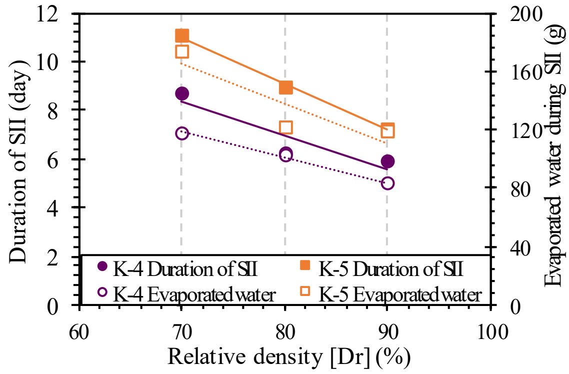

Figure 6: Relation between the relative density and SII duration and evaporated water

4. Conclusion

Under unified atmospheric conditions, each soil texture imposes a unique unsaturated layer development regardless of the relative density. A slight reduction in SII duration and water loss was observed for denser profiles. Therefore, it can be concluded that the relative density has a relatively low influence on SII, which might be attributed to its effect on the pore structure.

References

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