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The Effects of Cumulative Soil Moisture Evaporation on Light Intensity using He-Ne Laser Sensor

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Abstract- Soil moisture evaporation plays an important role in the fields of surface water balance and the surface energy balance. Measurements of cumulative evaporation on soil moisture have been carried out in the laboratory using laser sensor. In this study, moisture content of clay loam and beach sandy soils were monitored using an unexpanded 5 mW Helium –Neon Laser (λ = 0.63 μm) incident through an optical fibre on one side of an equilateral triangular glass prism which was partly buried in the soil sample. The total internal reflected beam from the sample through the prism was collected from an output optical fibre into a detector and a multimeter. In order to dry and evaporate water from the soil, a 60 Watts incandescent light and a fan were placed above the soil sample container and made to operate simultaneously. In calibrating the soil moisture content, various light intensities were measured with different values of moisture content in soil. Measurements were taken on Cumulative Evaporation for undisturbed soil samples to evaluate moisture content. The light intensity and cumulative evaporation relationship was observed with negative slope. Also, it was observed that the beach sand has a greater value of slope compared with clay loam at the undisturbed state due to its low retainability of water. Although, the relationship took a negative linear slope, the correlation coefficient for both were high (r = 0.9). Measurements of soil moisture by cumulative evaporation were used to evaluate the relationship between gravimetric moisture content and moisture monitoring by optical method, which was linear. The value of intercept of clay loam was found to be greater than that of beach sand due to their different chemical compositions. Hence, the findings prove that cumulative soil moisture evaporation by laser method was accurate.

Index Terms- Soil Moisture, Moisture Content, Cumulative Evaporation, Light Intensity, Total Internal Reflection, Laser

I. Introduction

Evaporation is one of the critical sinks in the water balance, of extreme importance in arid ecosystems. In arid ecosystems where vegetation is scarce and the water table is low, evaporation may make up the only water sink. Evaporation is also of importance to agricultural managers, as it can have an impact on field irrigation applications. Evaporation dynamics also play an important role in liquid waste management. A modeling exercise was undertaken to determine and quantify some of these evaporation dynamics. Two sets of models were run. The first was designed to determine the effect of soil texture and evaporative demand on short and long term evaporation. This set investigated evaporation from short (0.5 m) saturated soil cores. The second set of numeric experiments modeled evaporation and salt redistribution from soil cracks. This set of experiments determined the effect of a 0.5 m soil crack on evaporation and salt redistribution, and the effect of pore salinity on evaporation rates. Therefore, evaporation is the transition of water from a liquid to a gaseous state. Anywhere, there is liquid water, evaporation is occurring. While the vast majority of evaporation (>90%) occurs over the ocean, lakes and other open water bodies, a considerable amount of water is evaporated from soil surfaces.

Philip (1957) in his research explained the term desorptivity which is a reverse of sorptivity which is a measure of the ability of the soil to absorb water [1].. Gardner (1959), Rose (1968) and Black et al. (1969) showed theoretically that in the absence of gravity effect, the amount of water removed through evaporation from soil with uniform water content and constant suction at the surface is proportional to the square root of time, where the constant of proportionality is termed desorptivity [2], [3], [4], [5].

Evaporation from the land surface is affected mainly by the following factors: degree of saturation of soil surface, temperature of air and soil, humidity and wind velocity. Several of these factors are greatly influenced by the vegetation cover. The density of vegetation is an important factor that influences evaporation from land surfaces. It is difficult to generalize on the amount of evaporation from land surfaces due to the differences in soil moisture characteristics of soils. At high moisture contents, evaporation from land surfaces is nearly equal to that from free water surface. At lower moisture levels, evaporation may decrease in proportion to the content of water remaining in the soil. Evaporation from land surface is usually confined to shallow depths and the evaporation rate reduces rapidly with the increase in depth below the surface [6].

Philip (1957a) and Gardner and Hillel (1962) explain the three stages in the evaporation of water from an initially saturated soil column into a constant environment. At the first stage which is referred to as the constant rate stage, water is not limiting and evaporation rate is controlled by meteorological conditions. At the second stage known as falling rate stage, evaporation rate falls rapidly because water loss is limited by the rate of water transport through the drying soil. This stage of evaporation is governed by the soil hydraulic properties. At the third stage, the soil surface layer is sufficiently dry. Evaporation at this stage becomes sensitive to the heat flux in the soil and transmission of water occurs primarily by vapour diffusion due to external source of radiation [3], [7]. Idso et al.(1974) by the method of measurement of soil albedo known as coefficient of reflection of solar radiation, were able to detect all the three stages of evaporation[8].

Hillel (1971) explains atmospheric evaporativity as the maximum flux at which the atmosphere can vaporize water from free water surface [9]. Gardner and Hillel (1962) state that cumulative evaporation under higher atmospheric evaporativity is always greater than that under lower atmosphere evaporativity. However, the rate of evaporation during the falling rate stage is independent of atmospheric evaporativity since atmospheric evaporativity is controlled by the air temperature, the wind velocity and the relative humidity of the atmosphere[7]. Cumulative evaporation is therefore controlled by the water retention and transmission characteristics of the soil during the falling rate stage [3] . Cumulative evaporation from a bare soil can also be influenced by soil texture. Jalota and Prihar (1986) experimented that evaporation losses from silt loam was higher than that of sandy loam and loamy sand. This was due to higher transmission rate in the silt loam in the dry range. Their research indicates that evaporation from soil tends to be higher in the dry range as the soil becomes finer in texture. The rate of evaporation depends on a number of factors, including the energy needed for phase change from liquid to vapor states, the humidity of the surrounding air, soil texture, and initial water content, competing sinks and contributing sources and other factors [11]. Therefore, there is a need to measure the amount of water loss in the soil through evaporation using He-Ne laser sensor.

II. THEORETICAL BACKGROUND

2.1 Theory of Evaporation from Soil

Many researchers have given theory of soil water evaporation. These include Gardner (1959), Rose (1968) and Black et al. (1969). In the theory of evaporation, Gardner (1959) established the rate of evaporation, q ,as

$$q = \left(\theta_i - \theta_f\right)\left(\frac{\overline{D}}{\pi t}\right)^{\frac{1}{2}} \quad (1)$$

Where θi is the initial soil water content, θf is the final soil water content, $\overline{D}$ is the weighted mean of diffusivity and t is the time taken.

It is chosen that $\theta f < \theta i$ and by integrating equation (1) with respect to t, the equation (1) now becomes

$$E = 2\left(\theta_i - \theta_f\right)\left(\frac{\overline{D}t}{\pi}\right)^{\frac{1}{2}} \quad (2)$$

as proposed by Black et al (1969). Equation (2) is similar to the equation of Philip (1969) for the infiltration case with $\theta f > \theta i$. It is assumed that $\overline{D}$ is a constant, hence equation (2) becomes

$$E = S_d t^{\frac{1}{2}} \quad (3)$$

where

$$S_d = 2\left(\theta_i - \theta_f\right)\left(\overline{D}/\pi\right)^{1/2} \quad (4)$$

By analogy with sorptivity (Philip, 1957), the constant Sd has been termed desorptivity [5]. Therefore, it can be stated that cumulative evaporation from a uniform wet soil into a constant environment is proportional to the square root of time. This is true for t > 0 when the water content is reduced to the extent that the column still behaves as semi--infinite. Like sorptivity, desorptivity is a soil hydraulic property, but there is a paucity of quantitative data on desorptivity in the literature [6].

2.2 The Helium - Neon Laser

The Helium-Neon gas laser emitting at a wavelength of 633nm is a continuous light beam which is filled with an 80%-20% mixture of the noble gases helium and neon, the neon being the "lasing" medium and the Helium buffer gas to extract heating effect at the walls. A typical low-output power He-Ne laser operates between 1 and 10 mW for a tube length ranging between 20 and 50 cm. A laser of such length or less gives a single longitudinal mode and at TEM_{00} mode, has a coherence length of about 25cm, beam of diameter of about 1mm and low overall efficiency of about 0.1%. The output intensity of the laser is Gaussian with a divergence angle of about 0.92^0 as such the laser is directional with a high focussing spot [12].

2.3 The Empirical Formula

An empirical relation can be deduced between light intensity and moisture content since the behaviour of moisture in soil seems exponential. It is observed that the light intensity increases as moisture content increases for the following soil samples at undisturbed states: Clay loam and Beach sand.

Thus the expression is given by

$$I = a \exp(b\theta_g) \quad (5)$$

The expression finally becomes

$$\ln I = \ln a + b\theta_g \quad (6)$$

where I is the light intensity across the soil sample, θ_g is the moisture content by mass and *a* and *b* are constants. This is the regression equation for the soil samples and it differs from the type of soil sample, since the constants differ. The correlation between light intensity and moisture content for the soil sample resulted in a highly significant (r^2 =0.99).

III. EXPERIMENTAL PROCEDURES AND MEASUREMENTS

3.1 Description of the Experimental Set-up

An equilateral prism sensor was buried initially 2mm deep in a soil sample contained in a 800 ml beaker serving as the container. Light from Helium- Neon Laser (wavelength=633nm and output power 5mW) was carried through a plastic multimode optical fibre on to the surface of the glass prism. The optical plastic fibre was supported on the sensor surface by a polyethylene material. After being refracted and totally internally reflected, the light was refocused in a second fibre at the other side of the glass prism and carried onto the surface of the detector. The output light intensity signal was measured.

The working principle of this sensor relies on the light being propagated from a medium of higher refractive index to that of a lower refractive index. For glass-air interface when the soil is dry, the interface condition of equation

$$\theta = Sin^{-1}(n_2/n_1) \quad (7)$$

holds, which implies the critical angle of the totally internally reflected light is greater than 42^0 to obtain a maximum signal from the sensor. If the soil is completely filled with moisture the glass-water interface satisfies a condition for total internal reflection to be greater than a critical angle of 62^0 since refractive index of water is 1.33. In order to dry and evaporate water from the soil, a 60 Watts incandescent light and a fan were placed above the soil sample container and made to operate simultaneously. The whole experimental set up was mounted on an optical bench as shown in figure 1.

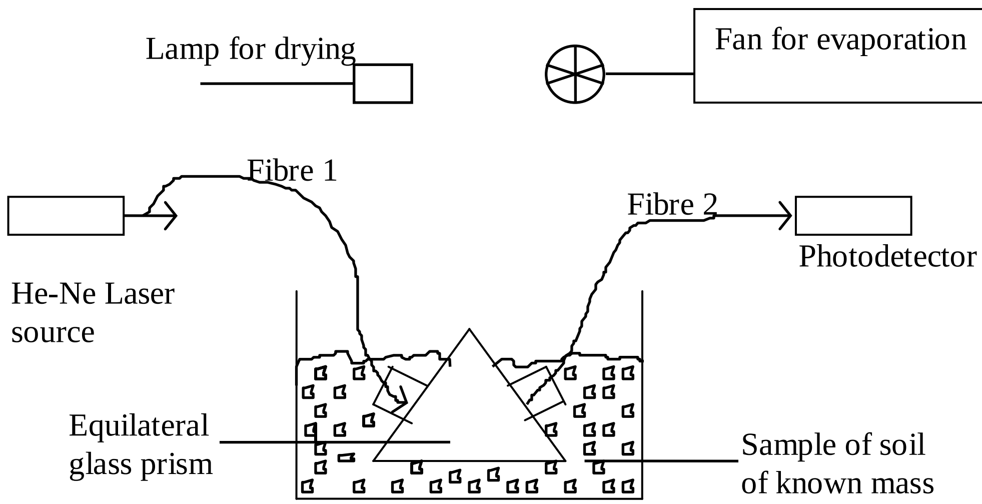

Figure (1): Experimental System Set-up

3.2 Monitoring of Moisture using Undisturbed Soil Samples (Cumulative Evaporation Method)

Clay loam soil from University Farm (Edina series) and beach sand from Cape Coast Beach were collected directly from the ground in the form of a core. These undisturbed samples were initially weighed and recorded after which the optical method was applied to determine the light intensities across each sample. The procedure was then applied by monitoring the light output from fiber 2 as the moisture in each soil sample changed over a period of time as a result of evaporation. Their corresponding light intensities were measured respectively. The moisture was also dried by heating the soil samples from above with a 60 Watts incandescent light and well-designed micro fan. This is shown in Figure 1. After that the samples were oven-dried at 105 degree Celsius for 24 hours to determine the end water content using the gravimetric method. The use of fan also helped to determine the evaporation. The difference in mass between any two successive hours gave the mass of the water that was lost through evaporation. This was determined for each of the samples. The moisture contents at various times were determined by finding the sum of the mass of evaporation and the ratio of the water lost to the oven-dried mass of the sample-gravimetric method. Data from soil moisture showing the variation of Light intensity and Cumulative evaporation was plotted. Calibration curves were then determined using the above measurements.

IV. RESULTS AND DISCUSSIONS

4.1 The Calibration Equations for Undisturbed Soil Samples

The constants a and b for each soil sample using equation, $I = a \exp(b\theta_g)$ are obtained and presented in Table 1. From this table, the values of the constants a and b in relation to the two parameters (light intensity and moisture content) vary for different soil samples. These also describe the effects of the light intensity on moisture content for all the soil samples used, since the constants a and b were derived from the intercept and slope on the light intensity- moisture content plots.

The regression equations as determined in Table 2 showed that the light intensity was exponentially related to the soil moisture content under moist conditions. The semi-log plots of light intensity against soil moisture content gave an intercept which indicated that other soil factors such as organic matter, soil texture, bulk density, etc might also influence the light intensity. Finally, the correlation coefficients between the log-transformed light intensity (I) and untransformed moisture content (θ_g) were highly positive and significant (r>0.9, P=0.1%).

Table 1 : Calibration equations relating Light Intensity to Moisture Content for different soil samples derived from measurements of Cumulative Evaporation Method

Soil Type	Location	Empirical Formula	R
Undisturbed Clay loam	U.C.C. Farm	$I = 38.34 \exp(0.011\theta_g)$	0.9996
Undisturbed Sand	Cape Coast Beach	$I = 19.67 \exp(0.015\theta_g)$	0.9988

Table 2 : Regression parameters for the Gravimetric Method and Moisture Monitoring by optical method for undisturbed soil samples.

Sample	Regression Parameters		
	a	b	R
Clay Loam	0.42051	0.7163	0.9918
Beach Sand	-0.64762	0.9238	0.9965

a - intercept on the gravimetric moisture content axis and it determines whether or not the plots obtained are perfect.
b - slope of the graph and it gives the linearity of the plots.
R - correlation coefficient and it gives the closeness of the two parameters (gravimetric moisture content and moisture content by optical method)

4.3 The Relationship between Gravimetric Method and Moisture Monitoring by Optical Method for Undisturbed Soil Samples

The plots of gravimetric moisture content θ_{gm} as a function of moisture content θ_{gc} by optical method for the samples at the undisturbed state are shown in figures 3a and 3b respectively. The plots showed a linear relationship between the gravimetric moisture content and the moisture content by optical method. Comparison of the gravimetric moisture content and moisture content by optical method showed that they are linearly dependent and has rank of 0.9918 for clay loam and 0.9965 for beach sand. The correlations were found to be highly positive and significant. The linear dependency indicated that the optical values over-estimated the gravimetric values by 24% and 12% for clay loam soil and beach sand respectively.

For both clay loam and beach sand at the undisturbed state only, their coefficients of determination (R^2) were found to be 0.9836 and 0.9930, respectively. Therefore, using the plot of gravimetric moisture content versus moisture content by optical method values indicated that the moisture content was more than 80 percent reliable, when compared with the gravimetric moisture content values depicting that there were some errors in the optical technique based on some of the equipment used for the experiments.

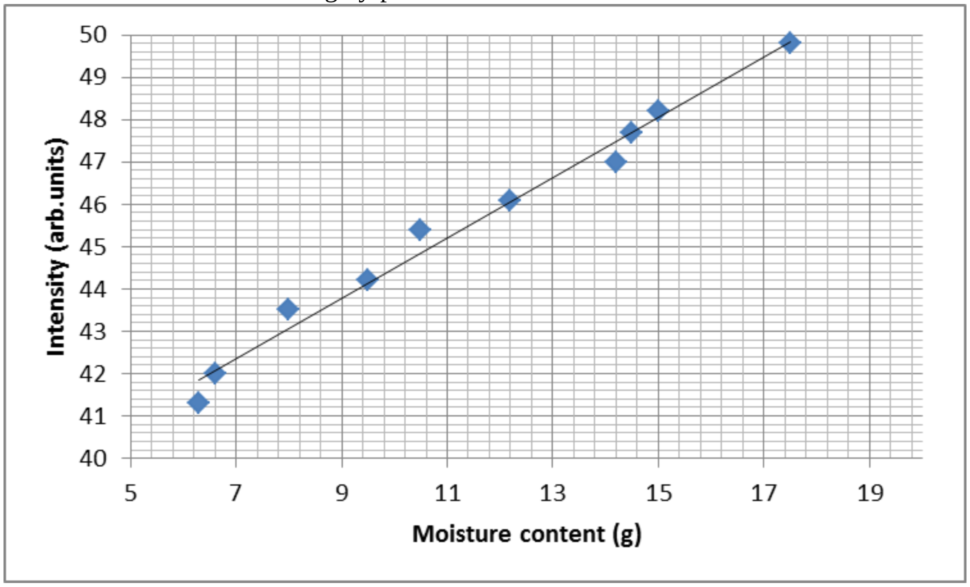

Fig 3 a: A graph of Intensity versus Moisture content for undisturbed Clay loam

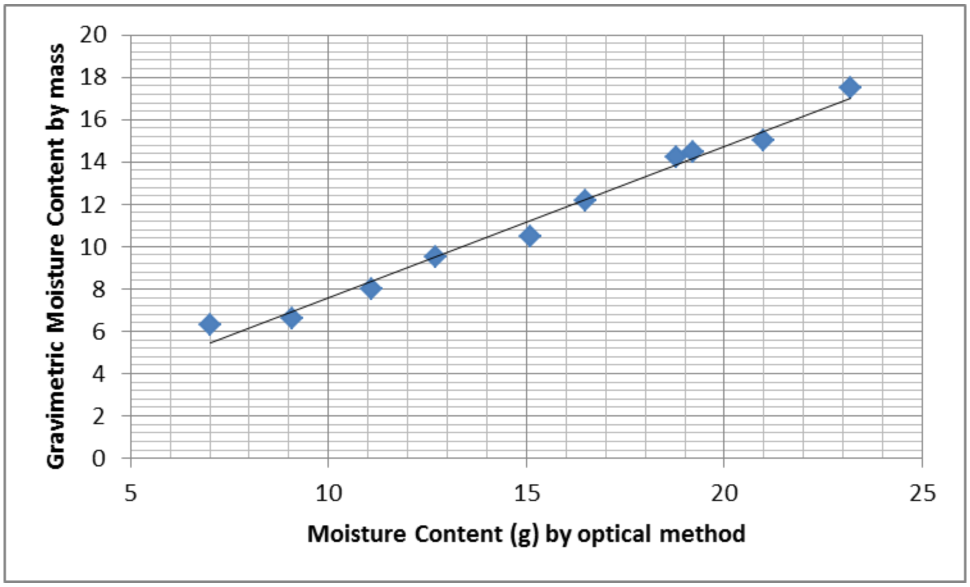

Fig 3b : A graph of Gravimetric moisture content versus Moisture content by optical method for undisturbed Clay loam

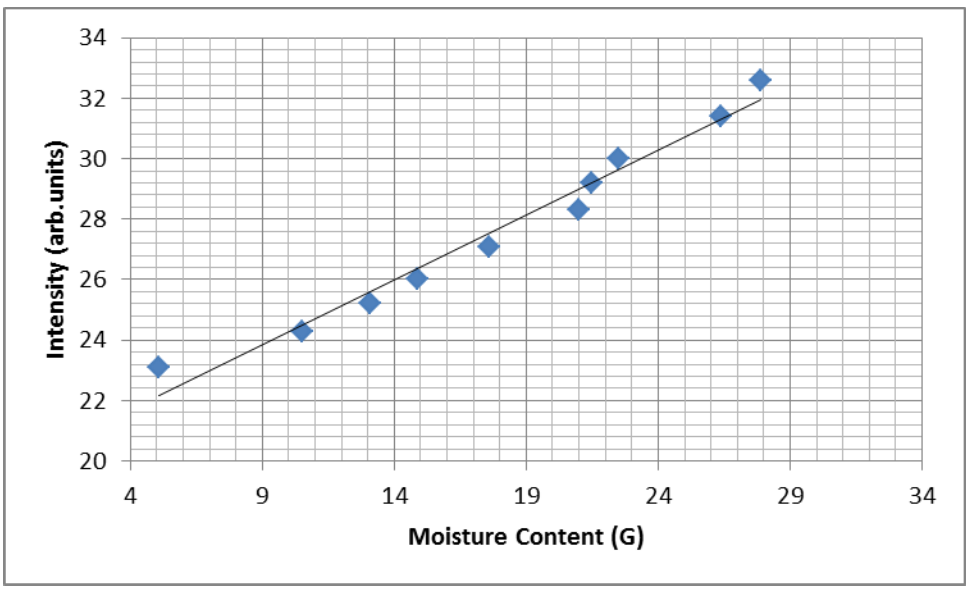

Fig 4a : A graph of Intensity versus Moisture content for undisturbed Sand

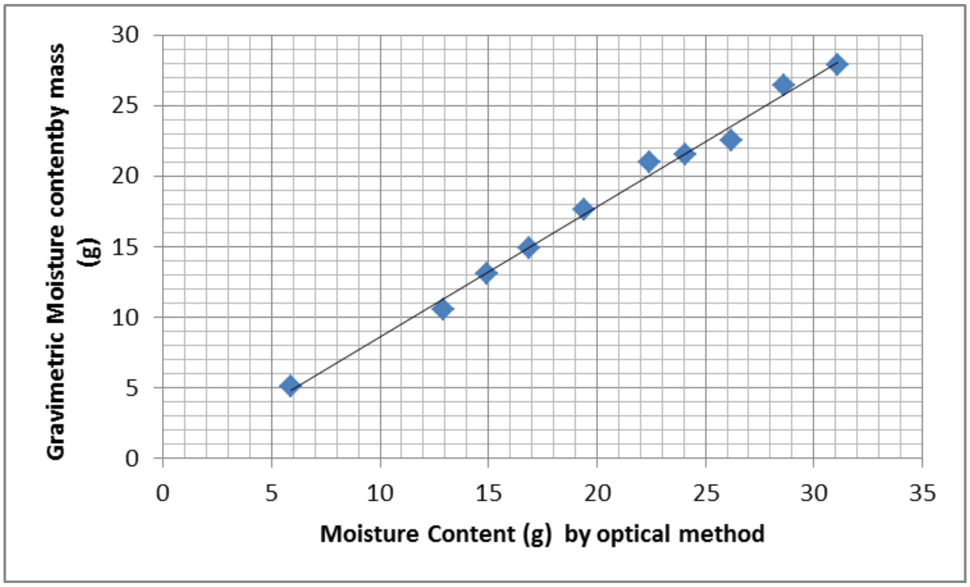

Fig 4b : A graph of Gravimetric moisture content versus Moisture content by optical method for undisturbed Sand

4.4 The Relationship between Light intensity and Cumulative Evaporation

The plots of these values are presented in Figures 5 a and 5 b respectively. The plots showed almost linear relationship between light intensity and cumulative evaporation with a negative slope. The beach sand has a greater value of slope compared with clay loam at the undisturbed state due to its low retainability of water. Although, the relationship took a negative linear slope, the correlation coefficient for both were high (r=0.9).

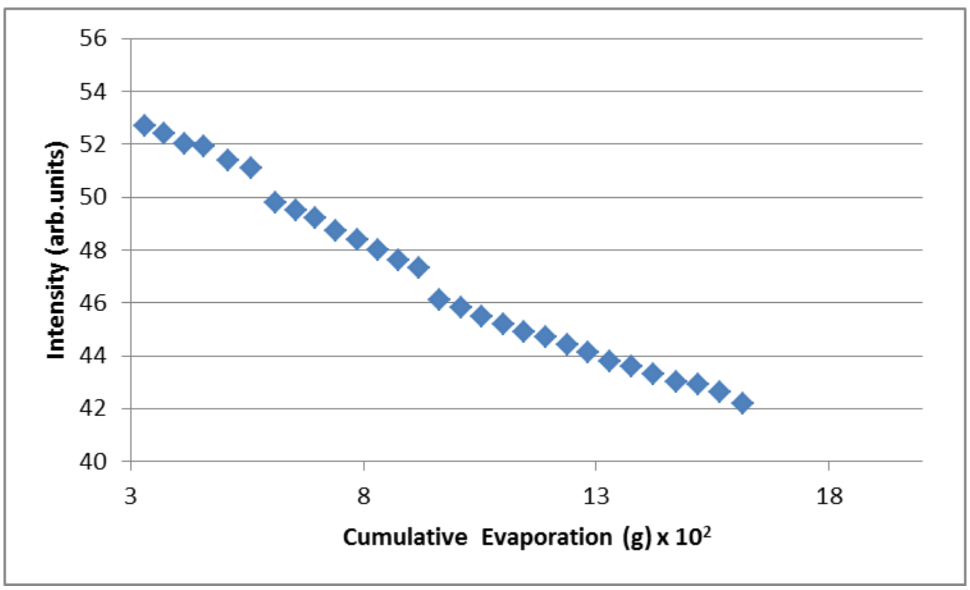

Fig 5 a: A graph of Intensity versus Cumulative Evaporation for undisturbed Clay loam

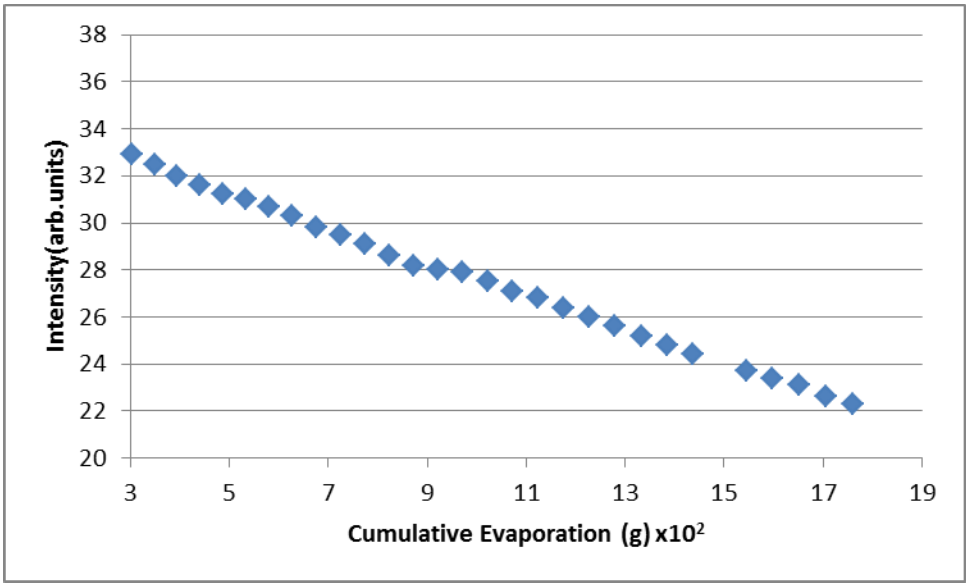

Fig 5 b : A graph of Intensity versus Cumulative Evaporation for undisturbed Sand

4.5 Effect of Cumulative Evaporation on Moisture Content and Light Intensity

For the undisturbed soil samples where evaporation was used to vary the soil moisture content, it was also found that the light intensity increased as the moisture content increased. The relationships between the log-transformed light intensity (I) and untransformed moisture content (θg) were also highly positive and significant ($r > 0.9$, $P = 0.1\%$).

The intercept values of both the clay loam and the beach sand for the semi-log plots of light intensity against moisture content were found to be 3.65 and 2.98 respectively. The values of slopes obtained for both the clay loam and the beach sand from the plots were 0.01 and 0.02 respectively. Again, although the two plots looked alike, the light intensities and moisture contents values for clay loam were greater than that of beach sand. This was because clay loam soil was able to retain more water than beach sand. The value of intercept of clay loam was found to be greater than that of beach sand due to their different chemical compositions. The plots of light intensity and cumulative evaporation were found to be negative slope and also continuous for undisturbed beach sand and not continuous for undisturbed clay loam, since beach sand is able to lose water easily.

V. CONCLUSION

The cumulative evaporation on soil moisture content as a function of light intensity is monitored using laser. The laser sensing instrument that uses prism as a sensor relies on the variation of moisture from the soil on the prism surface. This is monitored using the intensity of light from laser source onto the water-glass interface based on the total internal reflection. The light intensity is independent of the soil type. The cumulative evaporation method of measurements was for the soil samples to evaluate the moisture content. The empirical formula obtained from the intensity-moisture content plots was in the form $I = a \exp(b\theta_g)$, where the constants a and b represent the intercept and slope on the plots and also differ for a particular soil sample. The cumulative evaporation method was then used to evaluate the relationship between gravimetric moisture content and moisture monitoring by optical method for clay loam and beach sandy soil samples at undisturbed state. The relationship was found to be linear. The linear dependency and correlation analysis used indicated that the values of moisture monitoring by optical method overestimated that of gravimetric moisture content by 12 percent for beach sand and 24 percent for clay loam soil. Moreover, the relationship between light intensity and cumulative evaporation of the soil samples at undisturbed state gave a linear relationship and the correlation coefficients for the soils were highly positive and significant ($r = 0.9$), hence the laser sensor found to work perfectly at the lower moisture content. The results also suggest that some soil properties like organic matter, soil texture, and particle sizes may influence the use of laser beam in determining the effect of evaporation on soil moisture, since at the higher moisture content the plots deviated from the semi-log linearity. Finally, the above information shows that the laser sensing technique based on cumulative evaporation could be used in the field, since it agrees with the gravimetric technique.

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