Soil Moisture Equilibrium with Relative Humidity under Different Constant Temperatures for Clay and Calcareous Soils

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ADDITIONAL INDEX WORDS: Calcareous soil, Clay soil, Equilibrium moisture content ($\square_r$), Relative humidity (rh), Temperature (T).

ABSTRACT

A modified apparatus was used to study the effect of relative humidity (rh) on equilibrium moisture content (Θ_r), under different constant temperatures (T) K° for two soils. A clay soil taken from Behera Governorate and calcareous soil from Nubaria. The chemical and physical prosperities of the two soils were determined. Different air temperatures inside the chamber and (rh) were recorded and (Θ_r) was determined. A quantitative approach was used.

$1 - rh = e^{-\beta T \Theta_r^{\eta}}$ where: (β) and (η) are constants, their values depend on soil type.

The calculated values in average for (β) and (η) were 1.2×10^{-5} and 2.12 at temperature ranged between 290 and 314 (K°) for clay soil, respectively, while the corresponding values for calcareous soil were 3.7×10^{-4} and 1.431, at temperature ranged between 291 and 313 (K°), respectively. So, the developed formula for clay soil took the form:

$1 - rh = e^{-1.2 \times 10^{-5} T \Theta_r^{2.12}}$, while it was $1 - rh = e^{-3.7 \times 10^{-4} T \Theta_r^{1.43}}$ for calcareous soil.

The results indicated that exponential equations were *definitely* the more suitable to *describe* the relation between (rh) and (Θ_r). As expected, the results *revealed* that the (Θ_r) was increased with increasing (rh) for both clay and calcareous soils. With *respect* to soil types, the (β) value *for* calcareous soil was greater than that of clay soil at the same range of air temperature, therefore the (Θ_r) for calcareous soil was less than that of clay soil. This could be attributed mainly to the difference of clay content (i.e. surface area), porosity and pore size for both kinds of soils. The (Θ_r) and (rh) were decreased with increasing temperature. Such decreasing was, however, varied within *both* soil types.

INTRODUCTION

Water and air are very important factors in their effects on soil management and soil fertility. Soil expansion by wetting and shrinking by evaporation act on control the equilibrium between soil air and soil water, also micro morphology of soil pores is an important factor for movement of water and air in soil (Zein El-Abedin and Ayoub, 1975).

The moisture content (Θ) in equilibrium with normal relative humidity (NRH) is a matter of great interest in many branches of soil science and agriculture products. Soil moisture content (SMC) is an important character for microbial activity, germination and crop production. The quality of food and agriculture products depends on the dried packing and storage conditions for long time (Henderson, 1952; Iglesias and Chirife, 1976; Iglesias and Chirife, 1984; Rizvi, 1995; Alhamdan and Hassan, 1999). Equilibrium moisture data

(EMD) in relation to relative humidity **(rh)** is necessary to determine the perfect condition for storage of dried food and agriculture food production (Vanden Berg, 1984; Chen and Morey, 1989; Jayas and Mazza, 1993; Yu *et al.* 1999). Microbial activity decreased when relative humidity less than 0.1 (Hayes, 1987).

The removal of moisture from a solid is known as drying or dehydration. Drying is the removal of moisture to a **(Θ)** in equilibrium with normal atmospheric air (Henderson, 1952; Henderson and Perry, 1955; Ibrahim *et al.*, 1976; Coulson *et al.*, 1978; Atagilndilz, 1978, and Robert *et al.*, 1984). The removal of water vapor from the evaporating surfaces (leaves and soil) to the free air is governed by the vapor pressure gradient between surfaces and air by the aerodynamic resistance. The transport happens by the molecular diffusion in the very thin laminar boundary layer and by turbulence in the free air (Alan *et al.*, 1980; and Gates, 1976). The diffusion process is the process by which matter is transported from one part of a system to another, as a result of random molecular motion (vapor and salts) (Crank, 1975). The transport of heat by conduction is also due to random molecular motions, and there is an obvious analogy between the two processes. This was recognized by Fick (Crank, 1975), who first put the diffusion on quantitative basis by adopting mathematical equation for heat conduction derived by some years earlier by Fourier (Crank, 1975). Evaporation processes approaches zero at **(Θ_r)**, which is the lowest **(Θ)** obtainable with solid under the evaporation conditions used. Also the mechanism of liquid movement and consequently the rate of this movement vary markedly with the structure of the solid itself. With solids having relatively large, open void spaces, the movement is likely to be controlled by surface tension and gravity forces within the solid. With solids of fibrous or amorphous structures, liquid movement is by diffusion through the solid. Since the diffusion rates are much slower than the flow by gravity and capillary (Alan, *et al.*, 1980; Warren and Julian, 1976; Robert *et al.*, 1984). The amount of moisture held by a solid in equilibrium with humid air is depending upon the structure of the solid, temperature of the air and the **(Θ)** of the air (Robert *et al.*, 1984; Alan *et al.*, 1980).

The objectives of this study were (I) to quantify the **(Θ_r)** with normal **(rh)** in atmospheric air and (II) to calculate **(β)** and **(η)** for clay and calcareous soils by using mathematical approach.

MATERIALS AND METHODS

Two top layer soils (0-50 cm) differing in origin, texture, and total calcium carbonate content were sampled. One was a clay soil (vertic Torrifluvents) collected from Damanhour, Behera Governorate (60 Km. Alexandria-Cairo Agricultural high way), and the other one was sandy clay soil (Typic Calciorthids) collected from Nubaria Agricultural Experimental Station, Northern Tahreer (45Km. from Alexandria-Cairo Desert high way) and will be referred hereafter as calcareous soil. The main physical and chemical characteristics of the soil samples are given in Table (1).

The soil chemical properties pH; EC (dS m^{-1}) and total $CaCO_3$ (g kg^{-1}) were determined as described by Chapman and Pratt (1961), and FAO (1980). Soil physical properties were carried out according to American Society for Testing and Materials, (ASTM, 1992). Soil bulk density (kg m^{-3}) was determined in place by the Drive - Cylinder Method (ASTM, D 2937-83). Soil particle density (real particle gravity), kg m^{-3} was determined according to specific test method "specific gravity of soils" (ASTM D854-41). Soil porosity (void ratio %) was calculated from the relation (Porosity % or void ratio (ε%) = (V_p / V_b) x 100 = (1-(ρb / ρs)) x 100). Particle size analysis was determined by standard method of particle-size analysis of soils (ASTM, D 422- 63). Field capacity (FC) at 0.03 megapascal, (Mpa) was estimated by porous plate apparatus (ASTM, D 2325-68), and permanent wilting point (PWP) at 1.5 megapascal, (Mpa) by pressure membrane apparatus (ASTM, D 3152 - 72).

Table1. Physical and Chemical Analysis of the tested Soils.

Characteristic	Soils	
	Clay	Calcareous
EC, dSm^{-1}	0.4	1.2
pH, 1:2.5*	7.8	8.3
$CaCO_3$, g kg^{-1}	23.0	295.0
Particle size analysis		
Sand, g kg^{-1}	305.0	457.0
Silt, g kg^{-1}	189.0	151.0
Clay, g kg^{-1}	506.0	392.0
Texture	Clay	Sandy clay
Bulk density, kg m^{-3}	1240.0	1480.0
Particle density, kg m^{-3}	2640.0	2630.0
Porosity void ratio %	53.0	44.4
Field capacity, g kg^{-1}	493.0	365.0
Permanent wilting point, g kg^{-1}	275.0	173.0

* Measured in 1:2.5 soil to water suspension.

THEORETICAL CONSIDERATION

The ratio of the moisture vapor pressure, to the saturated vapor pressure of pure water at the temperature of the material is called the equilibrium relative humidity (**ERH**). A relation between the (Θ) and the **(rh)** is controlled by the following equation:

$$1 - rh = e^{-\beta T \Theta_r^{\eta}} \qquad (1)$$

Where: **(rh)** is the relative humidity in decimal, **(Θ_r)** the equilibrium moisture content (oven dry weight), **(T)** temperature, **K°**, **(β)** and **(η)** are constants depending on the material and defined as equilibrium moisture data **(EMD)**, (Henderson and Perry, 1955). A plot of the **(ERH)** abscissa and **(Θ_r)** ordinate is known as equilibrium moisture curve **(EMC)**. The **(EMC)** can be defined by equation (1). To calculate the values of the constants **(β)** and **(η)**, equation (1) could be rewritten in the forms:

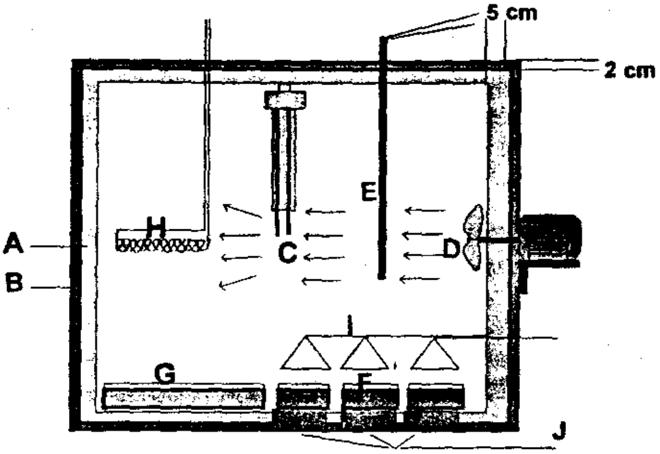
$$\ln(1 - rh) = -\beta T \Theta_r^{\eta} \qquad (2)$$

$$\ln(-\ln(1 - rh)) = \ln \beta T + \eta \Theta_r \qquad (3)$$

Equation (3) is a linear equation for which the **(Θ_r)** and **ln (1- rh)** are plotted on x-axis and y-axis, respectively using a log–log graph paper. The values of the intercept **(ln βT)** and the slope **(η)** of the given straight line were predicted over the range of temperatures between 290 and 314 (K°), for clay soil and 291 and 313 (K°), for calcareous soil. The average value of **(β)** is obtained for each soil by dividing its **(βT)** value by the corresponding average value of temperature **(T)**.

APPARATUS

The apparatus used in this study is presented in Fig. (1). The chamber (A) was made of an isolated material (foam) of 5 cm thickness with inside dimensions of 80 x 80 x 80 cm. The isolated chamber was covered with a wooden box of 2 cm thickness, (B). The chamber is provided with ventilated wet and dry bulb thermometer "Psycrometer", (C) to measure **(rh)** inside the chamber. (D) is an electric fan used for mixing air inside the apparatus, while (E) is a thermometer probe used to measure the **(T)** of the air inside the chamber. Three replicates of soil sample in three-aluminum cans (F) with a diameter of 12 cm and depth of 4cm were placed on the bottom of the chamber. (G) is an aluminum vessel filled with water and is considered as a free water surface. Its dimensions are 25 x 25 cm with a depth of 5 cm. The chamber is provided with a heater (H) adjusted to give the desired temperature and clamp (I) is used to hang the sample cans for weighting to avoid any disturbances for air inside the chamber. At the bottom of the chamber, three perforated holes under the cans were made and plugged to drop cans easily on the balance plate for weighting, and also to avoid any disturbance for air inside the chamber.



A) Isolated Chamber
B) Wooden Box
C) Wet & Dry Bulb Thermometer
D) Electric Fan
E) Thermometer rod
F) Soil Samples
G) Free Water Surface
H) Heater
I) Clamp
J) Three plugged holes

Figure 1. Moisture Equilibrium Apparatus

MEASUREMENTS

The heater (H) was adjusted to the desired **(T)** and the soil samples were weighted daily by dropping them on the balance plate until the cans weight be constant. At constant weight of cans, once measuring the air **(T)** inside the chamber, **(rh)** from wet and dry bulb thermometer by using "Psycrometer chart" and determining the (Θ_r) of the soil samples. The experiment was repeated for different selected set of chamber temperature by readjusting the heater for several times to give the desired **(T)**.

RESULTS AND DISCUSSION

Tables (2) and (3), show the effect of **(rh)** on (Θ_r) under different constant $(T\ K^{o})$, for clay and calcareous soil.

Figures (2) and (3) show that, the (Θ_r) for both clay and calcareous soil increased with increasing **(rh)**. The increasing was more pronounced for clay than calcareous soil. From tables (2) and (3) **(rh)** for clay soil were (87 %), and its (Θ_r) was (20.4 %), while for calcareous soil at the same value of **(rh)** 88%, its

(Θ_r) content was (7.8%). This results confirmed according to the physical analysis in table (1), mainly clay content, the bulk density (ρ_b), particle density (ρ_s) and porosity (ε) values were 506.0 (g kg^{-1}), 1240 (kg/m^3), 2640 (kg/m^3), and 53.03% for clay soil, respectively. The corresponding values were 392.0 (g kg^{-1}), 1480 (kg/m^3), 2630 (kg/m^3), and 44.36% for calcareous soil, respectively. Warren and Julian (1976) observed similar results. They reported that, soil porosity or void ratio is an important physical character in determination of **(EMC)** and capillary movement. Another affecting the **(EMC)** is micro morphology of soil pores and the geometry of these pore spaces (Zein El-Abedin and Ayoub, 1975). Voznaya (1983) stated that free surface energy depends on the size and shape of surface, which in turn depends on the size of particles. Bowles (1979) reported also that specific surface is a primary factor in soils subject to volume change and to the surface tension effects of water at particle interfaces.

As shown in tables (2) and (3) and Figs. (2) and (3), the calculated **(EMD)** data **(β)** and **(η)** values in average for clay were 1.2×10^{-5} and 2.12, respectively, at temperature ranged between 290 and 314 (K°), while for calcareous soil **(β)** and **(η)** values in average were 3.7×10^{-4} and 1.431 respectively, at temperature ranged between 291 and 313 (K°). These values were under the experimental conditions.

The positive slope value **(η)** of equation (3) confirmed the positive effect of **(rh)** on **(Θ_r)**. The data agree with other observations by Henderson and Perry (1955). They reported that **(β)** and **(η)** are constants depending on the material.

Table 2. Equilibrium moisture data for clay soil.

rh, decimal	(T), K°	Θ_r, %	(1-rh), decimal	$\eta \ln \Theta_r$	Θ_r^η	ln(1-rh)	$\ln \Theta_r$	βT clay	β clay
.87	290.0	20.4	.13	6.39	597.6	-2.0797	3.0155	0.00348	1.1467E-05
.82	292.5	18.6	.18	6.19	491.3	-1.7245	2.9232	0.00351	1.1566E-05
.76	296.5	16.9	.24	5.99	400.9	-1.4267	2.8273	0.00356	1.1725E-05
.68	299.0	15.1	.32	5.75	315.8	-1.1331	2.7147	0.00359	1.1823E-05
.66	302.0	14.6	.34	5.68	294.1	-1.0657	2.6810	0.00362	1.1942E-05
.63	305.0	14.1	.37	5.60	273.1	-0.9996	2.6462	0.00366	1.2061E-05
.61	307.0	13.7	.39	5.54	256.9	-0.9466	2.6174	0.00368	1.2140E-05
.57	309.0	12.9	.43	5.42	226.1	-0.8387	2.5572	0.00371	1.2219E-05
.55	311.0	12.6	.45	5.37	215.1	-0.8030	2.5337	0.00373	1.2298E-05
.53	312.0	12.3	.47	5.32	204.5	-0.7655	2.5096	0.00374	1.2337E-05
.52	314.0	12.1	.48	5.28	197.5	-0.7441	2.4932	0.00377	1.2417E-05
average	303.5	14.8	.30	5.70	315.7	-1.1000	2.7000	0.00400	1.2000E-05

Table 3. Equilibrium moisture data for calcareous soil.

rh, decimal	(T), K°	Θ_r, %	(1-rh), decimal	$\eta \ln \Theta_r$	Θ_r^η	ln(1-rh)	$\ln \Theta_r$	βT clca. soil	β clca. soil
0.97	291.0	12.0	0.03	3.5559	35.019	-3.7705	2.4849	0.10767	0.0003546
0.96	293.5	11.0	0.04	3.4314	30.920	-3.3577	2.3979	0.10860	0.0003572
0.94	296.5	10.0	0.06	3.2950	26.977	-2.9596	2.3026	0.10971	0.0003613
0.93	299.5	9.5	0.07	3.2216	25.068	-2.7779	2.2513	0.11082	0.0003650
0.90	302.0	8.5	0.10	3.0624	21.380	-2.3890	2.1401	0.11174	0.0003680
0.88	305.0	7.8	0.12	2.9395	18.905	-2.1335	2.0541	0.11285	0.0003717
0.83	307.0	6.9	0.17	2.7640	15.863	-1.8019	1.9315	0.11359	0.0003741
0.74	309.0	5.7	0.26	2.4906	12.069	-1.3798	1.7405	0.11433	0.0003765
0.69	311.0	5.1	0.31	2.3314	10.293	-1.1844	1.6292	0.11507	0.0003790
0.62	312.0	4.5	0.38	2.1523	8.605	-0.9934	1.5041	0.11544	0.0003802
0.59	313.0	4.2	0.41	2.0536	7.796	-0.9029	1.4351	0.11581	0.0003814
Average	303.6	7.8	0.18	2.8450	19.354	-2.1500	1.9880	1.12000	0.0003700

The following mathematical approach was used to express the (Θ_r) % as a function of **(rh)** and **(T)**:
For clay soil:

$$1 - rh = e^{-1.2\text{x}10^{-5} T \Theta_r^{2.12}} \qquad 290 < T > 314\ K^{\circ} \qquad (4)$$

For calcareous soil:

$$1 - rh = e^{-3.7\text{x}10^{-4} T \Theta_r^{1.43}} \qquad 291 < T > 313\ K^{\circ} \qquad (5)$$

The results indicated that exponential equations were definitely the more suitable to describe the relation between **(rh)** and **(Θ_r)**. As expected, the results revealed that the (Θ_r) was increased with increasing **(rh)** for both clay and calcareous soils. With respect to soil types, the (β value for calcareous soil was greater than that of clay soil at the same range of air temperature, therefore the (Θ_r) for calcareous soil was less than that of clay soil. This could be attributed to the difference of clay content, porosity and pore size for both kinds of soils. The (Θ_r) and **(rh)** were decreased with increasing temperature. Such decreasing was, however, varied within both soil types.

Henderson and Perry (1955) stated that, **(EMD)** could, therefore, be reported in terms of constants (β) and (η). These constants are depending on the material. Their calculated data for (Θ_r), (β) and (η) of natural clay were $7.53\text{x}10^{-5}$ and 1.72, respectively. Mokabel (1988) found that the calculated **EMD**, (β) and (η) for sandy soil at temperature ranged between 289.5 and 310 K°, were $2.46\text{x}10^{-2}$ and 0.752, respectively. As expected, the **EMD** (β) and (η) for clay soil was less than that of calcareous and sandy soil, respectively. As already stated, tables (2) and (3) illustrated that, with increasing temperature the (Θ_r) and (rh) decreased. These results agree with Alan *et al.* (1980) and Warren and Julian (1976). They stated that (Θ_r) and (rh) decreased with increasing temperature.

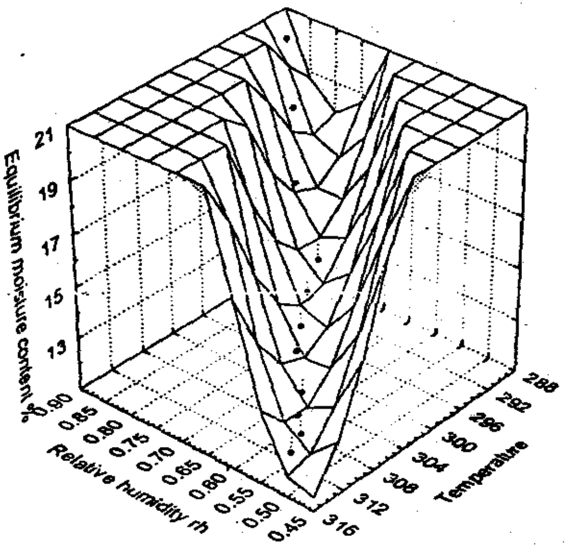


Fig. (2) : Equilibrium moisture content (%) as affected by relative humidity and temperature (K^0) for clay soil.

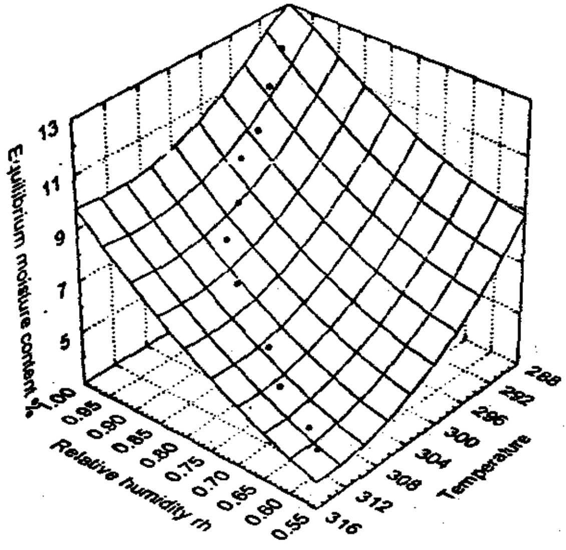


Fig. (3) : Equilibrium moisture content (%) as affected by relative humidity and temperature (K^0) for calcareous soil.

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الملخص العربي

المحتوى الرطوبى المتوازن للتربة مع الرطوبة النسبية عند ثبات درجة الحرارة للأراضي الطينية والجيرية

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مركز البحوث الزراعية

أجري هذا البحث لدراسة تأثير الرطوبة النسبية (rh) علي المحتوي الرطوبى المتوازن (Θ_r) لنوعان من التربة عند ثبات درجة الحرارة (T) درجة كلفن. أخذت أرض طينية من محافظة البحيرة وأرض جيرية من النوبارية وقدرت الخواص الكيماوية والطبيعية لهما. وباستخدام جهاز معدل معزول حراريا ومزود بمقياس

رطوبة نسبية ومقياس حرارة ومروحة خلط و سطح ماء حر تم تسجيل كلا من درجات الحرارة (T) درجة كلفن والرطوبة النسبية (rh) وعند ثبات درجة الحرارة تم تقدير المحتوى الرطوبى المتوازن (Θ_r) كنسبة مئوية.

واستخدم نموذج هند رسون $1 - rh = e^{-\beta T \Theta_r^{\eta}}$ لتقدير قيم الثوابت (β) ، (η) لكل من الأرض الطينية والأرض الجيرية حيث [illegible] قيمتهما علي نوع التربة وكانت قيم (β) ، (η) المحسوبة للأرض الطينية ١,٢ × ١٠ $^{-٥}$ ، ٢,١٢ علي التوالي عند مدى حرارى تراوح من ٢٩٠ إلي ٣١٤ درجة كلفن، بينما كانت القيم المقابلة للأرض [illegible] ٣,٧ × ١٠ $^{-٤}$ ، ١,٤٣١ علي التوالي عند مدي حراري تراوح من ٢٩١ إلي ٣١٣ درجة كلفن. من هذا فإن النموذج [illegible] للأرض الطينية يكون $1 - rh = e^{-1.2x10^{-5} T \Theta_r^{2.12}}$ بينما للأرض الجيرية يكون $1 - rh = e^{-3.7x10^{-4} T \Theta_r^{1.43}}$.

أوضحت النتائج أن المعادلة الأسية أكثر تمثيلا في وصف العلاقة بين الرطوبة النسبية (rh) والمحتوي الرطوبى المتوازن(Θ_r) عند ثبات درجة الحرارة. وكما هو متوقع فإن المحتوي الرطوبى المتوازن للتربة (Θ_r) لزداد بزيادة الرطوبة النسبية (rh) لكلا النوعان من التربة الطينية والجيرية.

بالنسبة لنوعي التربة وجد أن قيمة (β) للأرض الجيرية كانت أعلي من الأرض الطينية عند نفس المدى من درجة حرارة الهواء. ولهذا كان المحتوى الرطوبى المتوازن للأرض الجيرية أقل من الأرض الطينية وهذا يرجع إلي نسبة الطين والمسامية وحجم الفراغات لكلا النوعان من التربة، أيضا مع ازدياد درجة الحرارة انخفض المحتوي الرطوبى المتوازن والرطوبة النسبية. و أختلف هذا الانخفاض باختلاف نوع التربة.