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Clay Deposits for Water Management of Sandy Soils

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Water management practices in conserving water for arid lands are crucial in sustaining agriculture and food production. Sandy soils (Typic Torrripsamments) are practically important land resources in many Middle Eastern countries. In a laboratory experiment, five naturally occurring clay deposits were applied at different rates to sandy calcareous soil in order to evaluate their effect on relative swelling, infiltration and water conservation. Relative swelling index (RSI), cumulative infiltration (D), and advance of wetting front (Z) were measured in the laboratory for untreated and treated soil samples mixed with 1, 2, 3, and 5% of the clay deposits. Results indicated that addition of natural deposits significantly increased RSI. The differences in RSI values between natural deposits at any rate of application were significant and related to clay content and presence of smectite type clay. RSI values for each clay deposit fitted to the following exponential function with the application rate x ($RSI = ae^{bx}$). Results of D indicated that increasing natural deposit rate significantly increased the time required for the wetting front to reach 40 cm. There was a significant difference between the clay deposits at 5% rate and the difference was related to the type of clay and clay content in each deposit. The presence of $CaCO_3$, dominance of kaolinite type clay and low clay content in the deposits enhanced water movement while dominance of smectite clay and high clay content decreased D. Advance of wetting front was markedly affected by the type and the rates of clay deposit applied. Z decreased with increasing rates of clay deposits. Soil water distribution profile was characterized by three zones based on the type and the rate of applied clay deposit to the soil.

Keywords cumulative infiltration, wetting front, swelling index, water conservation

The ecosystem of arid and semiarid regions in many areas is impoverished by scarcity of water resources and predominance of marginals sandy soils which consists more than 45% of the cultivated soils in Saudi Arabia (Bashour et al., 1983).

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The productivity of these soils is limited by low water holding capcities, high infiltration rates, high evaporation, low fertility levels, very low organic matter content, and excessive deep percolation losses that may induce low water use efficiency. Water is the most important resource and a limiting factor for sustaining agricultural development in arid and semiarid regions. As the demand for water in agriculture increases, an effective way of water conservation and management is of primary importance (Al-Rashed & Sherif, 2000). Therefore, practices that increase water use efficiency and reduce excessive amount of water applied to the field are important in water management. The use of organic and chemical amendments may improve the chemical and physical properties of sandy soils. Sewage sludge along with other organic wastes are commonly used as soil amendments. Also, synthetic soil conditioners were used to improve some soil physical properties and productivity (Falatah et al., 1999; Miller, 1979; Mustafa et al., 1988). These materials can thus increase water supply to growing plants and improve water use efficiency (Al-Harbi et al., 1996; Al-Omran et al., 1987; El-Hady et al., 1981; Terry & Nelson, 1986). The application of these synthetic conditioners on a large scale in agricultural land could be unrealistic, however, because of their high cost, insufficient longevity, reduction of their effect with salintiy (Al-Darby et al., 1993; Armbrust & Dickerson, 1971). Thus, the use of natural deposits may improve the above constraints and thus increase soil productivity, especially in the areas where these materials are avilable in abundance and cheap.

There have been studies in some arid and semiarid areas of the world on the use of natural deposits to alleviate some soil constraints to production. Afifi (1986) reported that the addition of bentonite to sandy soil increased the retention and the availability of soil moisture as well as the cohesive forces among their particles. He concluded that the addition of bentonite reduced the velocity of downward water movement and restricted the deep percolation and leaching out of nutrients. Das & Dakshinamurti (1973) showed that the infiltration rate and hydraulic conductivity of sandy loam soils treated with bentonite were reduced compared to untreated soils. They concluded that the horizontal infiltrations as well as the diffusivity were very much reduced in the treated soils. Sallam et al. (1995) concluded that mixing shale deposits (clay content 72%, dominated by smectite) with sand at different rates improved the physicochemical properties, and in particular the soil moisture characteristics and cation exchange capacity. Abou-Gabal et al. (1990) found that the addition of local Tafla (dominated by bentonite) to the sandy soils in Egypt improved the soil texture and consequently soil-water plant relationships. El-Sherif & El-Hady (1986) reported that mixing sandy soil with local bentonite improved soil mechanical, hydrophysical, and chemical properties, and consequently increased water use efficiency. However, the research is scanty on the effect of the use of clay deposits on infiltration rates and other soil physical properties. Recently, in a study of using bentonite in Saudi Arabia, Al-Omran et al., (2002a,b) reported a marked decrease in cumulative infiltration, evaporation, and depth of wetting front with the increase in concentration of bentonite up to 4% in sandy soils.

The main objective of this study is to investigate the effect of different rates of natural clay deposits collected from different locations in Saudi Arabia on relative swelling, cumulative infiltration, and water conservation in sandy calcareous soils.

Materials and Methods

A bulk surface (0–30 cm) sandy calcareous soil sample (Typic Torripsamment) was collected from the College Experimental and Research Station at Dierab (24° 25′ N, 46° 34′ E), 40 km SW of Riyadh, Saudi Arabia. Five samples of clay deposits collected from different locations of Saudi Arabia designated No. 1, 2, 3, 4, and 5, were used in this study. These deposits are soft, plastic, porous rock composed essentially of clay minerals of the smectite or kaolinite groups. The soil sample and the five deposits were air-dried, ground and passed through a 2-mm sieve. Texture was determined according to Gee & Bauder (1986), while Ca- carbonate content was measured using calcimeter (Nelson, 1982). Cation exchange capacity (CEC) was measured according Rhoades (1982). Electrolytic conductivity of the saturated soil paste extracts (ECe) was measured using EC meter. Some characteristics of the soil used are as follows: ECe 1.7 dS m^{-1}, $CaCO_3$ 32%, particle distribution: clay 5%, silt 5%, and sand 90%. Some physical, chemical and mineralogical characteristics of the clay deposits are presented in Table 1.

Relative Swelling Index

Relative swelling index is defined as the amount of water retained in cm^3 at 1 kPa water potential g^{-1} soil minus the amount of 1*M* $CaCl_2$ solution similarly retained by a nontreated sample. The procedure used was similar to that described by Koenigs (1961). The method consisted of a Buckner funnel of 6.2 cm inside diameter with the outlet tube connected by rubber tubing to a small glass tube, creating a water manometer. Fifty grams of air-dryed soil treated or untreated with clay deposit sample was poured on to a filter paper disc placed on the bottom of the funnel, leveled, and lightly pressed. Distilled water or 1 *M* $CaCl_2$ was introduced through the

TABLE 1 Locations and selected properties of the five tested clay deposits used in the experiment

Deposit characteristics	Clay deposits no.				
	1	2	3	4	5
Location					
Lat.	24°47′	24° 6′	22° 09′	25°25′	26°31′
Long.	45° 53′	47° 32′	39° 20′	49° 35′	49° 51′
pH	7.50	8.01	7.25	7.63	7.59
EC_e dS m^{-1}	10.26	15.30	22.00	12.09	13.5
SP%	51.00	71.00	53.00	184	155
CEC cmol kg^{-1}	21.69	25.69	39.55	62.93	55.74
SAR	16.08	25.04	23.13	15.70	16.29
$CaCO_3$%	3.00	39.00	3.00	3.00	1.61
Sand %	4	32.00	4.00	2.00	0
Silt%	22	20.00	36.00	2.00	14
Clay%	74	48.00	60.00	96.00	86
Texture	Clay	Clay	Clay	Clay	Clay
Smectite	++	+++	++++	++++	++++
Kaolinite	++++	+	+++	+	T
Vermiculite	T	+	−	++	++
Attapulgite	−	+	−	+	++
Mixed layers	++	+	+	−	+
Fe_dg kg^{-1}	42.9	19.4	49.3	20.2	

Relative mineral contents: ++++ dominant, +++ medium, ++ small, + low T = traces.

Fe_d = free iron oxides, extracted by Na-dithionite citrate bicarbonate method (Mehra & Jackson, 1960).

EC_e = Electrical Conductivity of saturated paste extract.

CEC = Cation Exchange Capacity.

SAR = Sodium Adsorption Ratio.

SP = Saturation Percent.

glass tube to saturate the soil carefully by capillary rise. The soil sample was flooded by maintaining a head of 1-cm of water for 30 min above the soil. The soil sample was then subjected to a suction of 1-kPa. Water content of the soil was determined gravimetrically after equilibrium at this suction. Three measurements were made for each rate of clay deposits and as well as for untreated soil (control). Oven dry weight of the soil in this case corrected for the salt content in the retained salt solution. It was assumed that soil swelling with this salt solution was equal to zero.

Infiltration Rate

Soil samples were packed at 1.5 g cm^{-3} bulk density in transparent sectioned Lucite cylinders (5 cm internal diameter, 60 cm long). The five rates of all clay deposits used were 0, 1, 2, 3, and 5% (on dry weight basis), and applied to the upper 0–10 cm of the soil columns in the cylinders. A Marriote-siphon type apparatus was designed to maintain a constant head (2.5 cm) above the soil surface by means of a bubbler tube to allow accurate measurement of infiltration data as a function of time. Observations made during the infiltration included change in the bubbler reading and the visible wetting front advance. When the wetting front reached about 40 cm depth below the soil surface, infiltration was terminated and distribution of water content was determined gravimetrically. Soil samples were dried at 105 °C at 5-cm increment. Each treatment was replicated three times. All analyses and calculations were conducted in triplicate and mean values are presented. Statistical differences among treatment effects and their significances were evaluated by LSDs.

Results and Discussion

Relative Swelling Index

The relative swelling index values of the studied soil at different clay deposit rates are presented in Table 2. It is evident that increasing rates of clay deposits substantially increased RSI values of the sandy soil, which is generally in accordance with Al-Omran et. al.(2002b). This increase of the RSI value differs significantly among the various mixtures of the sandy soil and clay deposits. In the soil amended by using 1, 2, 3, and 5% of clay deposit No. 1, the magnitude of the increase in RSI values were 0.98, 2.38, 4.14, and 5.13 times that of untreated soil, respectively, while for deposit No. 2 these values were 2.94, 3.69, 5.61, and 0.85, respectively. For the same rates in sequence the increase in RSI values were 2.66, 4.77, 5.61, and 8.04 times that of untreated soil for soil samples treated with deposit No. 4. The highest RSI values were obtained with the soil mixed with different rates of 1, 2, 3, and 5% deposit No. 4, and the lowest values were obtained with soil treated with the same rates of

TABLE 2 Relative Swelling Index of Sandy Calcareous Soil as Treated with Different Rates of Clay Deposits

	Clay deposit no.					
Rate	1	2	3	4	5	$LSD_{0.05}$
Control	.006	.006	.006	006	0.006	–
1%	0.012	0.024	0.015	0.022	0.010	0.004
2%	0.020	0.028	0.023	0.035	0.015	0.008
3%	0.031	0.034	0.029	0.040	0.027	0.009
5%	0.037	0.040	0.036	0.054	0.033	0.014
$L.S.D_{0.05}$	0.008	0.010	0.008	0.007	0.013	–

TABLE 3. Effect of Clay Deposits on the Mean Best Fitting Exponential Equations $RSI = ae^{bx}$

Clay deposit no.	a	b	r^2
1	0.008	0.361	0.874
2	0.011	0.320	0.657
3	0.009	0.336	0.822
4	0.011	0.389	0.756
5	0.007	0.352	0.922

deposit No. 1. The increasing value of RSI is an obvious consequence of the swelling nature of the clay deposits. The eventual swelling seemed to depend on the amount and type of the clay present in the deposit. Therefore, the higher RSI values of soil mixed with deposit No. 4 were due to the dominance of smectite clay in this deposit, which increases surface area and cation exchange capacity of the soil particles. In contrast, the lower RSI values of the soil mixed with deposits No. 1 and 3 could be related to the dominance of kaolinite in these deposits (Table 1). Other investigators have reported similar findings (Al-Omran et al., 2002b; Afifi, 1986).

Regression analysis indicated that for each clay deposit RSI was fitted to an exponential function $RSI = ae^{bx}$, where x is the application rate and a and b are fitted parameters. The equation constants are given in Table 3. The similar relationship was observed by Al-Omran et al. (2002b) using bentonite natural deposit in sandy soil. The same trend followed using these deposits.

Cumulative Infiltration

Table 4 shows that increasing the rate of any deposit significantly increased the time required for water to infiltrate to the 40-cm soil depth, but for the 5% rate, the time required to reach the 40-cm depth was different among the deposits. For example, the sandy soil amended with 5% deposit No. 4 gave a longer time, while the sample with the same rate of deposit No. 2 showed shorter time compared to other deposits. This behavior was due to type and amount of clay content of each deposit. The mineralogical composition of the deposit No. 4 consists mainly of smectite with a lesser amount of kaolinite. The swelling properties of these natural deposits caused a reduction of the effective pores as a result of expansion, therefore increasing the time required for water to infiltrate into the sandy soil treated with deposit No. 4. On the other hand, the high $CaCO_3$ and lower smectite content of deposit No. 1, compared to No. 4 enhanced water movement, and reduced the time required for water to infiltrate.

TABLE 4. Time(min.) Required for Water to Infiltrate the 40-cm in Soil Column as Affected by Different Rates of Clay Deposits

	Clay deposit no.					
Rate	1	2	3	4	5	$LSD_{0.05}$
Control	15.7	15.7	15.7	15.7	15.7	–
1%	17.9	20.2	18.3	16.8	19.2	2.29
2%	20.9	21.8	20.2	21.2	24.2	2.73
3%	29.0	23.1	23.3	30.6	25.0	2.29
5%	33.5	24.4	29.0	60.2	30.6	13.38
$LSD_{0.05}$	1.76	1.81	2.39	13.2	2.92	******

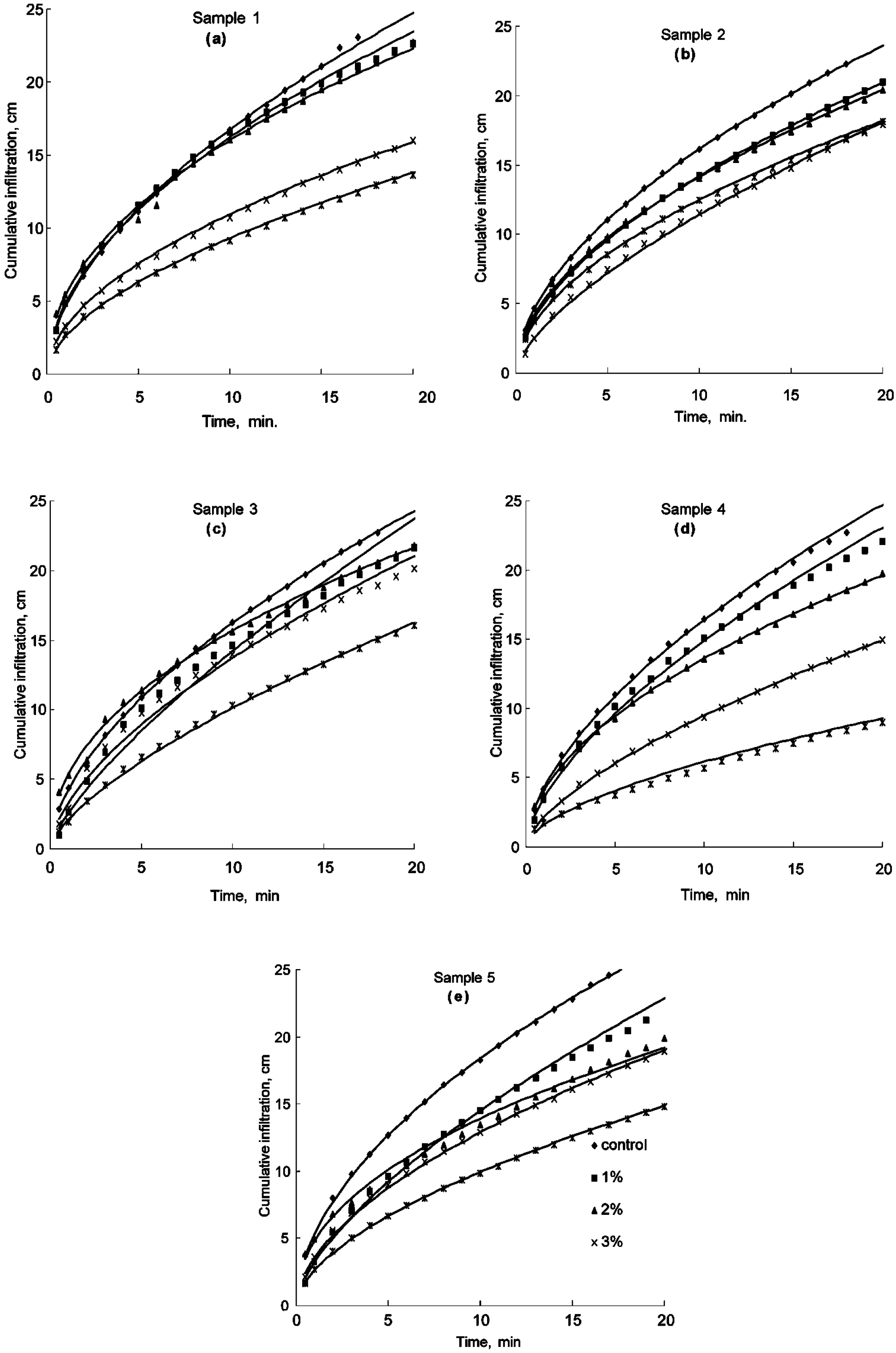

FIGURE 1 (a–e) Cumulative infiltration in sandy calcareous soil treated with different rates of clay deposits.

Figure 1 shows the cumulative infiltration (D) versus time (t) relationships for sandy soil as affected by the type and rate of the natural deposits. These relationships were fitted to the Philip (1957) equation:

$$D = At^{1/2} + K_o t \tag{1}$$

where D is the cumulative infiltration depth in cm and t is time in minutes. The constants A and K_o are infiltration parameters of the soils, sorptivity and hydraulic conductivity, respectively. The data fit in equation 1 with significant correlation coefficients (r) ranging from 0.98 to 0.999 (Table 5). Furthermore, the plots indicate that D decreased with increasing rate. The decrease in D was more pronounced with increasing rate of each of the clay deposits. Clay deposit No. 4 was more effective in reducing infiltration when compared to other deposits studied. This decrease in D values could be attributed mainly to the presence of high clay content (96% in sample No. 4, Table 1) as well as to the dominance of smectite type clay, which improved the texture of the sandy soils, promoted soil swelling, and increased water retention of the soil.

An attempt was made to relate the equation constants with increasing rate of clay deposits. The A value was affected by both the type and the rate of the deposits (Table 5). For instance, A values of clay deposit No.1 indicated that these values

TABLE 5 Philip Equation Constants as Affected by Clay Deposits and Rates of Application

Clay deposit no.	Rate (%)	A	K_o	Coefficient of determination, r^2
	0	3.006	0.488	0.992
	1	2.732	0.269	0.991
1	2	2.660	0.132	0.996
	3	2.105	0.075	0.998
	5	1.674	0.085	0.999
	0	3.006	0.488	0.992
	1	2.988	0.358	0.993
2	2	3.341	0.248	0.994
	3	2.842	0.221	0.998
	5	3.432	0.148	0.999
	0	3.006	0.488	0.992
	1	2.744	0.448	0.980
3	2	3.093	0.296	0.987
	3	3.288	0.187	0.997
	5	2.365	0.271	0.998
	0	3.006	0.488	0.992
	1	2.844	0.465	0.988
4	2	3.135	0.261	0.996
	3	2.164	0.259	0.999
	5	1.287	0.169	0.999
	0	3.006	0.488	0.992
	1	2.447	0.546	0.990
5	2	3.328	0.224	0.999
	3	3.757	0.097	0.998
	5	2.647	0.150	0.999

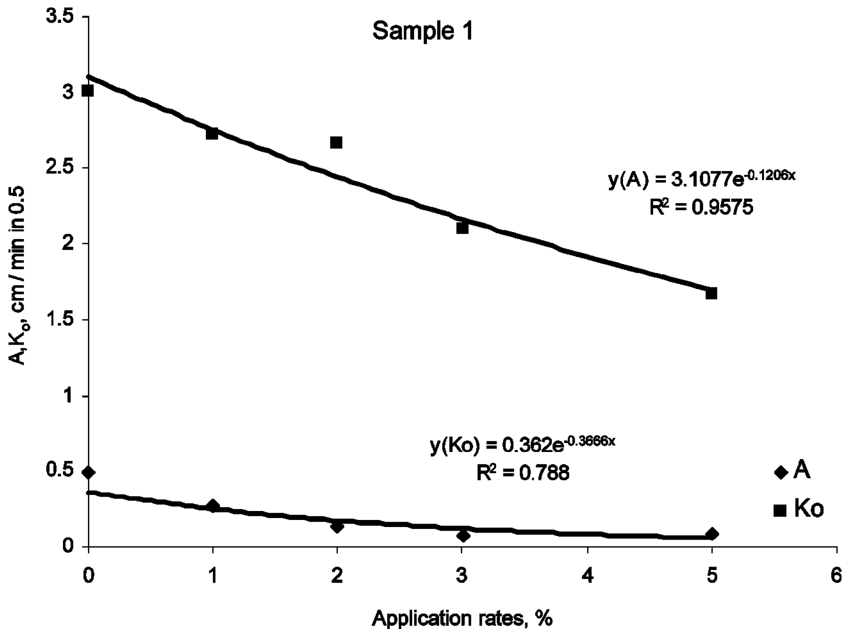

FIGURE 2 A and K_0 values of Philip's equation for sandy calcareous soil amended with different rates of clay deposits No. 1.

were fitted to an exponential function with deposits rate (Figure 2). This relationship suggests that with each addition of clay, A decreased. Compared to untreated soil, the percentage of decreased A values were 9.13, 11.50, 29.95, and 44.30% when the soil was mixed with 1, 2, 3, and 5% of deposit No. 1, respectively. The respective decrease in A values with deposit No. 4 were 5.5, 0.0, 31.0, and 57.0%. All other deposits showed somewhat different trends in the decrease in A values compared with the untreated soil. The trends in decrease of K_o values were quite similar to that for A values, but K_o decreased more steadily with the increase in the rate of clay deposit applications to the soil. At any type of clay deposits and rates, K_o values decreased. For instance, K_o values for sample No. 1 decreased by 45.0, 72.8, 85.6, and 82.6% when soil was mixed with 1, 2, 3, and 5% compared to untreated soil. The respective decrease in K_o values with sample No. 4 was 4.7, 46.6, 47.0, and 65.3%. Again, the decrease in A and K_o values with the addition of deposits was attributed mainly to the higher clay content and the swelling nature of clay present in these deposits.

Advance of Wetting Front

Figure 3 (a–e) depicts the relationships between the advance of the wetting front (Z) in cm and time (t) in minutes as affected by the type and rates of application of clay deposits to sandy calcareous soil. This relationship fitted in the empirical power equation giving highly significant correlation coefficient (Table 6). $Z = at^b$, where Z is the depth of wetting front in cm, t is time in minutes , and a and b are parameters dependent on soil and clay deposit rates. The wetting front moved slowly as more clay deposit was added. The values were strongly influenced by either the type or the rate of applications. Data indicated that Z values with clay deposits No 4 and 5 were decreased drastically at the highest rates (3 and 5%) of the former deposit, while the decrease was quite low in the latter one. Again presence of high clay content dominated by smectite in the deposit soil mixture seems to block the available pores,

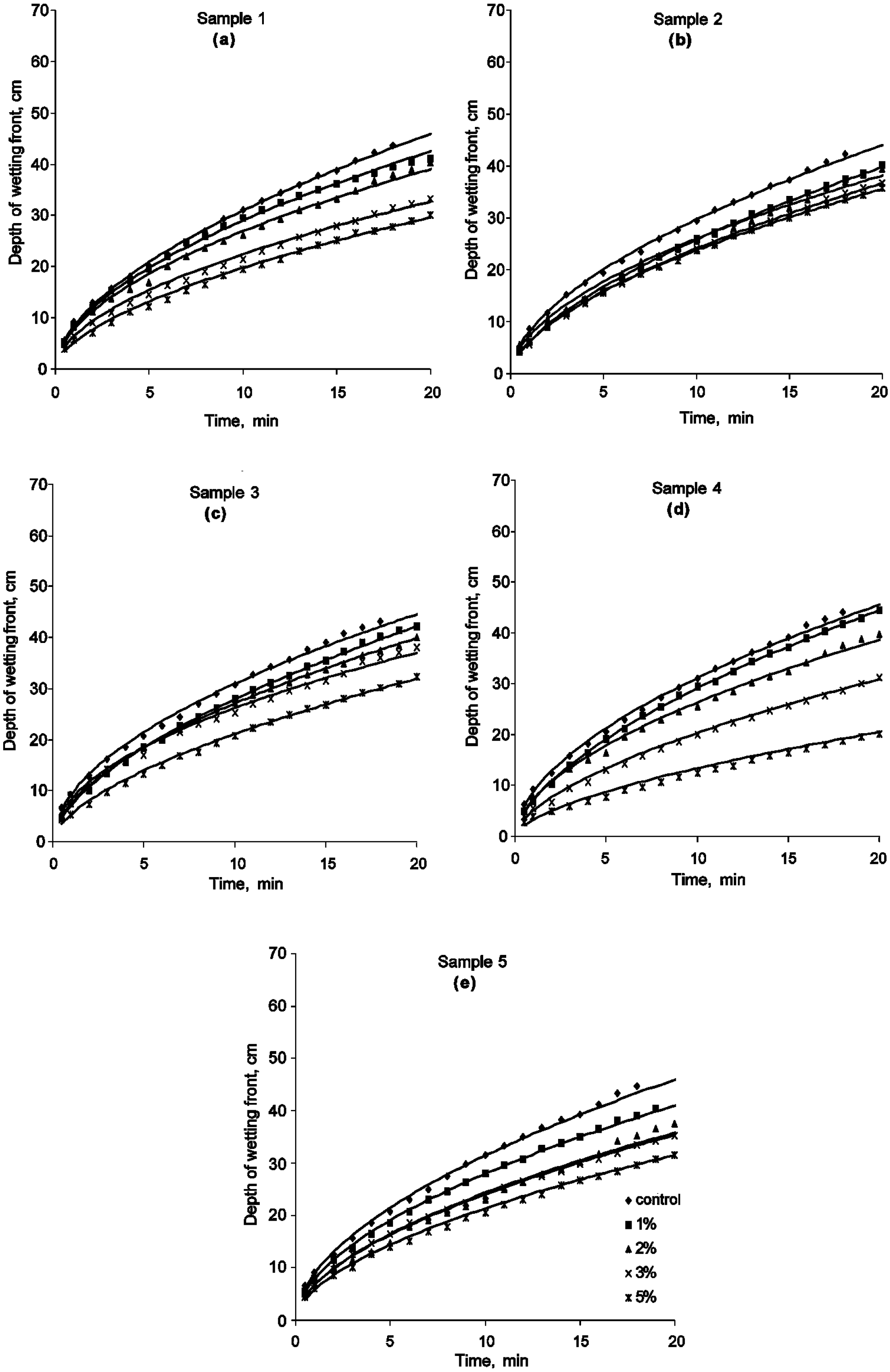

FIGURE 3 (a–e) The advance of wetting front in sandy calcareous soil treated with different rates of clay deposits.

TABLE 6 Effect of Clay Deposits Type and Rates Application to Sandy Calcareous Soil on the Empirical Constants of the Fitted equation ($Z = at^b$)

Clay deposit no.	Rate (%)	Empirical constant a	Empirical constant b	Coefficient of determination r^2
	0	8.376	0.566	0.996
	1	8.118	0.553	0.996
1	2	7.829	0.536	0.996
	3	6.437	0.542	0.993
	5	5.164	0.583	0.994
	0	8.053	0.567	0.998
	1	6.123	0.624	0.998
2	2	7.264	0.554	0.993
	3	5.995	0.604	0.997
	5	6.175	0.585	0.999
	0	9.182	0.527	0.997
	1	7.0649	0.597	0.999
3	2	7.494	0.558	0.999
	3	8.284	5.000	0.995
	5	5.311	0.599	0.993
	0	8.828	0.548	0.998
	1	7.185	0.608	0.999
4	2	7.328	0.556	0.997
	3	5.094	0.602	0.993
	5	3.300	0.610	0.986
	0	8.889	0.548	0.998
	1	7.836	0.552	0.999
5	2	6.700	0.559	0.989
	3	6.638	0.558	0.999
	5	5.814	0.564	0.996

hence decreasing the wetting front. The results indicated that (a) values in the equation decreased with increasing rate of clay deposits. Compared to untreated soil, the percentage decreases in (a) values were 3.08, 6.45, 23.05, and 38.30 when sandy soil was mixed with 1, 2, 3, and 5 % of deposit No. 1, respectively. The respective decrease for sample No. 4 was 18.68, 17.01, 42.3, and 62.63%. This trend may be attributed to a higher percentage of clay and swelling characteristics of the clay deposit No. 4 when compared to No. 1.

Time required for the wetting front to reach 20-cm depth as affected by clay deposit rates is presented in Figure 4. It is evident that clay deposit No. 4 resulted in more time than other clay deposits. The relationship between time and clay deposit rates was found to be as follows:

$$T_{20} = a + bX, \qquad (2)$$

where T_{20} is the time in minutes to reach the 20-cm soil depth and X is the clay deposit rate. Figure 4 and equation 2 showed how T_{20} is increased by increasing the clay deposit rates. Again, clay deposit No. 4 showed the highest increase. This increase was mainly due to the swelling properties and very high clay content in clay deposit No 4.

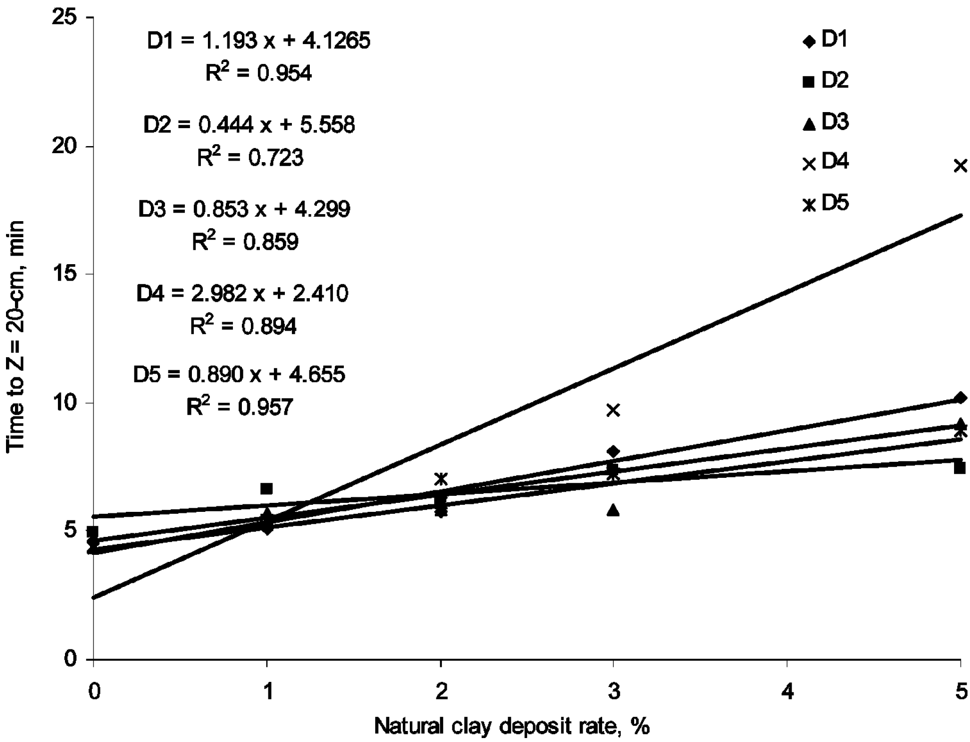

FIGURE 4 Time required for the wetting front to advance to 20 cm depth as a function of added clay deposit rates.

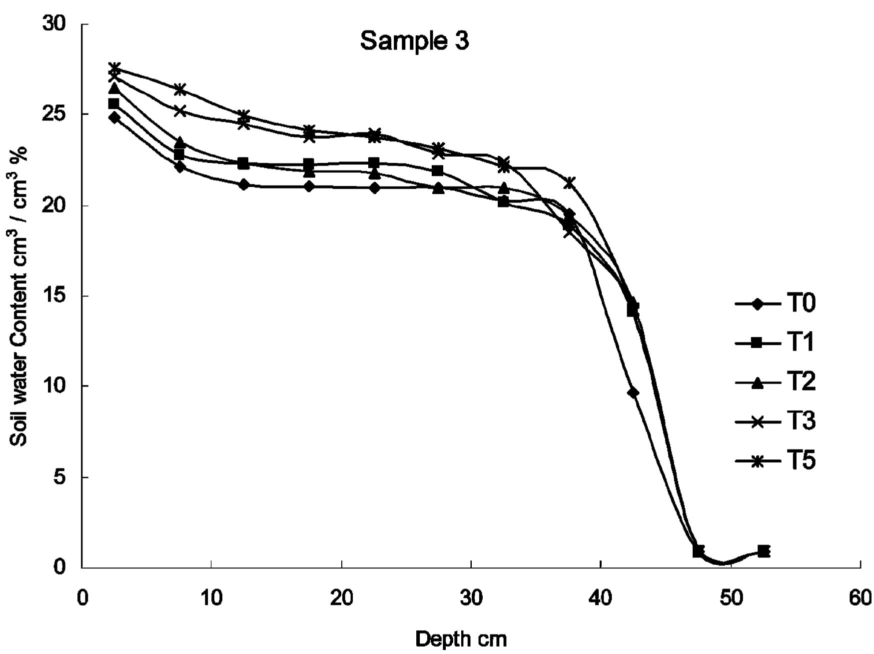

FIGURE 5 Soil water content as a function of soil depth in sandy calcareous soils mixed with clay deposit No. 3 at different rates.

Soil Water Distribution

Soil water contents with soil depth treated with clay deposit No. 3 under infiltration are shown in Figure 5. The soil water profile was characterized by three zones. The first zone extended to 38 cm depth and was highly influenced by the rate of clay deposits applied. That is, soil water content increased with increasing rate of applications of clay deposit. The second zone was from 38 cm to about 48 cm, and the third zone is the dry zone > 48 cm. The results indicated that water content increased with increasing clay deposit rate. As infiltration proceeds, an increasing part of soil moisture content profile becomes almost horizontal to the soil depth axis. This zone of fairly uniform soil water content is called the transmission zone (Philip, 1957). The average water content to the 38 cm depth for 0, 1, 2, 3, and 5% was 21, 22, 24, 26, and 26%, respectively.

Conclusion

The results suggest that the mineralogy of the clay deposits studied had an effect on RSI, D, and water distribution of the sandy calcareous soil. Most of the five clay deposits were dominated by smectite with fewer amounts of kaolinite, vermiculite, and attapulgite. All soil samples amended with clay deposits dominated by smectite increased RSI and soil water content but decreased D. This observation was attributed to the swelling nature of the smectite clay that caused expansion of the soil matrix. In contrast, all soil samples treated with clay deposits dominated by kaolinite with relatively high $CaCO_3$ content slowed infiltration into the soil. Moreover, the obtained results in this study could be applicable to improve the predominantly sandy soils in the Middle Eastern countries using local abundance of clay deposits.

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