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Influence of a Highly Swelling Gel-forming Conditioner (Acryhope) on Hydrophysical Properties of Layered Sandy Soils

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Abstract. A laboratory column study was conducted on a layered sandy soil to investigate the effect of a cross-linked polyacrylate gel-forming conditioner (Acryhope) on water retention and flow. Five concentrations (C) of Acryhope ranged from 0 to 1% (on dry weight basis) were applied to the upper layer (10 cm depth) as dry grains. The conditioner-gel particles were highly swollen upon water absorption resulted in large soil expansion. The resulted soil bulk densities were evaluated and used to obtain the water content by volume (θ). The increase in height of the surface was also measured. The amount of water retained by the soil at two suctions 10 and 1500 kPa increased exponentially with increase of C ($r = 0.999$). Increasing C at the upper treated layer substantially decreased the rate of wetting front advance through the profile and increased θ in the upper 20- cm depth under ponded infiltration. Although the relative expansion (L_r) had increased with increase of C at apper layer, the value of L_r for each C remained approximately constant during ponded infiltration and a logarithmic relationship between L_r) had increased with increase of C at upper layer, the value of L_r for each C remained approximately constant during ponded infiltration and a logarithmic relationship between L_r and C was found ($r = 0.972$). Evaporation losses was effectively reduced with increase of C applied to the upper layer. Increasing C at the upper - treated layer substantially lowered the rate of capillary rise and increased the water content at this layer. The average water content at the upper layer ($\bar{\theta}_u$) was exponentially related to C ($r = 0.992$). In general, the effects of Acryhope were more pronounced when C at the upper treated layer (10 cm) of sandy soil ranged from 0.75 to 1%. However, it may be recommended to apply Acryhope conditioner to the upper layer of sandy soil and adjacent to the plant at concentration ranging from 0.5 to 0.75% for cost-benifit considerations.

Introduction

The soil conditioning chemicals have been used extensively during the recent years. Many formulations, often based on industrial by products, have been marketed as soil conditioners under different trade names even without specification of their chemical composition or their exact physical effects. Substance such as polysaccharide (PSD) and polyacrylamide (PAM) promote aggregate stability and improve soil structure [1-9]. Soil gel-conditioner that were once applied mostly for structurization and stabilization are being used today to improve other physical characteristic [10-13]. Soil gel-forming conditioner, which in part of hydrophilic nature, can increase water holding capacity and decrease deep percolation of sandy soils [14-20]. The soil gel-forming conditioners may increase water supply to growing plants and improve water use efficiency [21; 22]. However, to our knowledge little work has been done on the magnitude of surface soil expansion as a result of adding gel-forming conditioner to the soil and its effect on soil water flow. Among these works, Miller [23] observed a hydrolyzed starch-polyacrylonitrile graft polymer increased surface soil swelling and decreased infiltration rate of sandy soils and Terry and Nelson [24] found that the surface bulk density was lowered by PAM-treatment for flood-irrigated soils.. Thus the main objective of this study was to determine the magnitude of soil surface expansion as influenced by highly swelling gel-conditioner (Acryhope) concentrations at the upper layer and their effect on hydrophysical properties such as infiltration, evaporation, and capillary rise of sandy soil.

Materials and Methods

The gel-forming conditioner used was cross-linked sodium polyacrylate, commercially known as Acryhope and provided by Nippon Shokubai company, Japan[1]. The Acryhope particles were 0.2-1 mm in diameter.

The soil used was sandy (Typic Torripsamments) collected from the upper 0-30 cm layer at the College Experimental and Research Farm at Dierab, Saudi Arabia. The soil was air dried and passed through a 2- mm sieve. The initial air dry water content was 0.4% by weight. The soil was 2% clay, 1% silt, 97% sand, and had $CaCO_3$ of 25%. The soil contained low amount of soluble salts (EC_e = 1.3 dS m^{-1}) and very low organic matter (0.04%). Tap water with an EC of 0.5 dS m^{-1} and SAR of 0.9 was used.

The Acryhope conditioner was applied to the 10 cm upper layer of the soil column at five concentrations (C): 0, 0.25, 0.50, 0.75 and 1% (on dry weight basis). The corresponding amounts of Acryhope were thoroughly hand-mixed with the air-dried soil.

Pressure-cooker and pressure plate apparatus were used to determine the water content at 10 and 1500 kPa matric suctions [25]. The treated soil samples were initially

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[1] The trade name and company are included for the benefit of the reader and do not imply endorsement or preferential treatment of the product by King Saud University.

packed in brass rings (5 cm i.d., 3 cm height) to a depth of 1.5 cm at 1.5g cm^{-3} bulk density. After saturation for 24 hr, the resulted bulk densities due to expansion were determined and used for obtaining water contents on volume basis. All the treatments were simultaneously exposed to the same matric suction.

For ponded infiltration experiment, the soil samples were packed at 1.5g cm^{-3} bulk density (D_b), to simulate D_b observed in the field, in transparent sectionized lucite cylinders (5 cm i.d., 60 cm long). The soil treated with the predetermined concentrations of Acryhope were applied to the 10 cm upper layer. A flooding apparatus [26] was used to obtain accurate infiltration data as a function of time. Periodic observations were made during infiltration included changes in the position of the soil surface due to expansion, height of the water surface, Mariotte tube reading, and the visible wetting front advance. When the wetting front reached approximately 40 cm depth below the initial level of soil surface, infiltration was terminated and the distributions of water content and bulk density were measured by sectioning the soil column at 5 cm intervals.

For evaporation experiment, the soil samples were packed 30 cm deep at the same bulk density (D_b) of 1.5g cm^{-3} in transparent lucite cylinders (4.4 cm i.d., 35 cm long). The soil treated with the predetermined concentrations of Acryhope were applied to the 10 cm upper layer. The upper 20 cm depth of the soil was brought to water content equivalent to that of 10 kPa suction and then the soil columns were exposed to evaporation at constant room temperature (22.5°C). The daily evaporation measurement (by weighing) continued until approximately half of the water added had been lost from each column.

For capillary rise experiment, the soil samples were packed 30 cm deep at D_b of 1.5 g cm^{-3} in similar cylinders (4.4 cm i.d., 35 cm long) but with perforated bottom. The soil treated with the predetermined concentrations of Acryhope were applied to the 10 cm upper layer. Upward capillary rise of water in the treated soil columns was determined until water reached the erected soil surface. At the end of the experiment, the distributions of volumetric water content (θ) were measured by sectioning the soil columns at 2.5 cm intervals.

The results reported were the average of three replicates.

Results and Discussion

The amount of water retained by soil at each of the two suctions (ψ) 10 and 1500 kPa substantially increased with increase of Acryhope concentration (C) as shown in

Fig. 1. The relationship between the soil water content on volume basis (θ) and C was found to be an exponential type with correlation coefficient (r) >0.9996.

$$\theta = 15.20 \quad e^{1.13\,C} \qquad \text{for } \psi = 10 \qquad (1)$$

$$\theta = 2.13 \quad e^{2\,C} \qquad \text{for } \psi = 1500 \qquad (2)$$

where θ and C are in percent and ψ in kPa. There is a general consensus among the soil workers that the values of 10 and 1500 kPa suctions approximate the field capacity and wilting point of sandy soils, respectively. Accordingly, it can be concluded from Eqs. 1 and 2 that the available water (AWC) also increases exponentially with increase of C. For example, the AWC was increased from 12% and 30% by volume with the increase of C from 0.0 to 1%. This finding indicates that the AWC of sandy soil was by approximately 150 % as a result of adding Acryhope at C = 1%. This result may be attributed to the superabsorbing nature of Acryhope conditioner which is associated with the water being tied up in a very viscous gel-form.

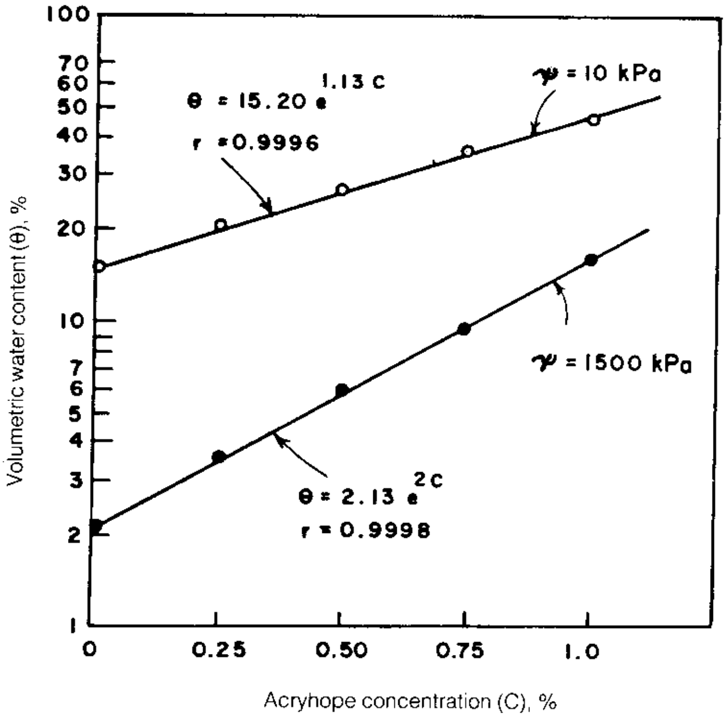

Fig. 1. Water content as a function of Acryhope concentration at two matric suctions (ψ) for sandy soils.

It was evident that wetting front advanced downward and upward with respect to the initial soil surface, during infiltration. This was due to that gel particles formed as a result of adding Acryhope which were swollen by water absorption causing surface expansion. Figure 2 illustrates that it makes big difference whether one selects the initial soil surface (Fig. 2a) or the new erected surface (Fig. 2b) as datum line for measuring the wetting front advance. The absolute expansion value (Z_e) ranged from 0 to 7.5 cm above the initial soil surface for 0 to 1% Acryhope concentration (C), respectively. The distance to the wetting front (L) as a function of time (t) can be represented by a power equation with $r = 0.9996$.

$$L = A\,t^{B} \tag{3}$$

where L is in cm and t is in minutes. One may detect from Fig. 2 that the exponent (B) possessed approximately the same average value 0.584 for both the two cases a and b. While the constant of proportionality (A) had larger values in case b than those in case a and decreased with increase of C. It might be interesting to draw the following example. At $t=10$ minutes, $Z=L=35$ cm for $C=0.0\%$; and $Z=27$ cm (Fig. 2a) and $L=32$ cm (Fig. 2b) for $C=0.50\%$. This means that although the treated soil exhibited 5 cm expansion, still the resulted $L=32$ cm is lower with comparison to the untreated soil. As result, the addition of Acryhope to sandy soil not only restricts the downward advance of wetting front below the initial soil surface (Z), but also decreases the distance to the wetting front from the new erected surface (L) resulted from expansion. It seemed there was no significant difference in the time required for wetting front to advance the treated 10 cm depth between the different concentration of Acryhope (Fig. 2). The wetting front reached the 10 cm depth within 2 minutes for all C, under ponded infiltration.

The relative expansion of the soil (L_r) as introduced by El-Shafei *et al.* [27] was determined along the time of infiltration. L_r is the increase in the height of the soil surface divided by the distance to the wetting front.

$$L_r = \frac{Z_c}{L} = \frac{Z_e}{Z + Z_c} \tag{4}$$

where Z_e is the absolute expansion above the initial surface (cm) and Z is the depth of wetting front below the initial surface (cm). It can be deduced from Fig. 3 that L_r was approximately constant with time within the range of Z used in this study (40 cm), which was considered as practical depth. Both values of L_r and Z_e increased with increase of C. The values of L_r were 0, 0.05, 0.09, 0.12, and 0.17 for the corresponding C: 0, 0.25, 0.50, 0.75, and 1%, respectively. While the values of Z_e were 0, 1.7,

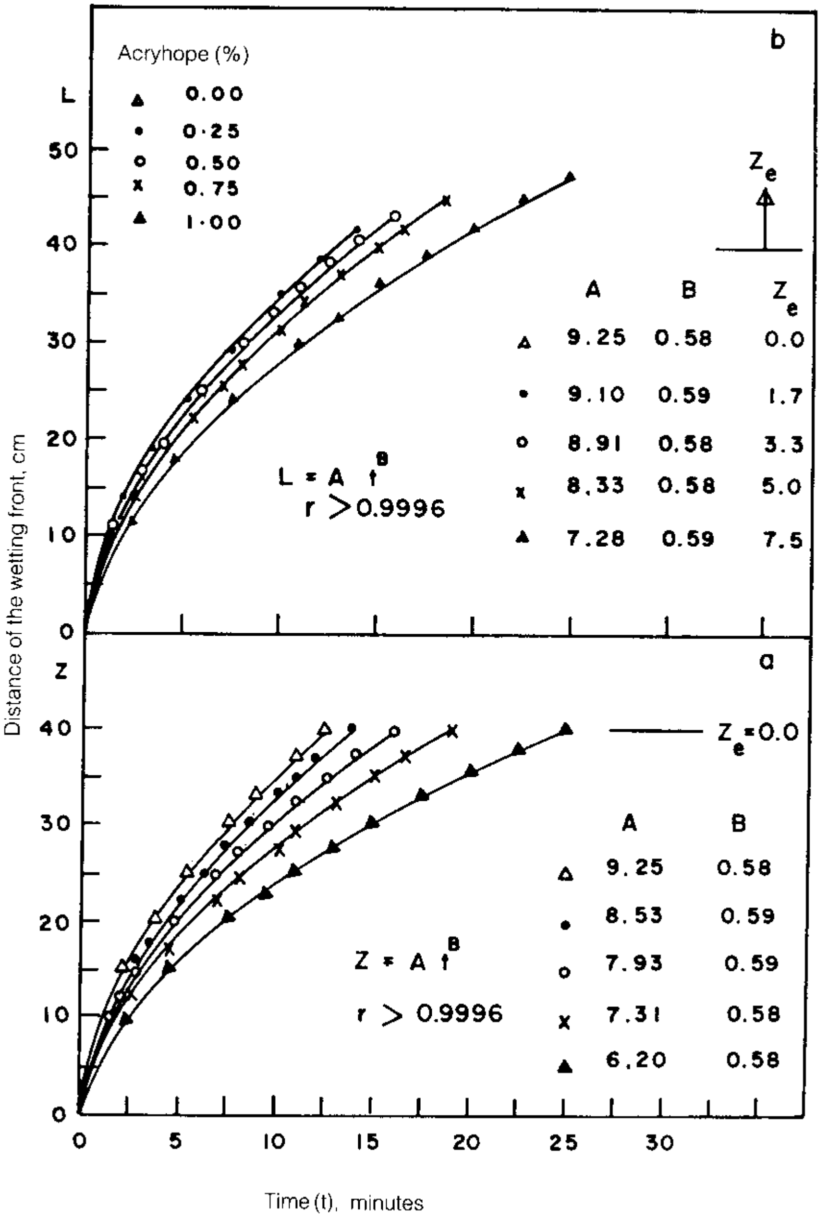

Fig. 2. Advance of wetting front under ponded infiltration as affected by Acryhope added to the upper layer (10-cm depth) of sandy soil. The datum line was taken at the initial soil surface in (a), while in (b) was at the new erected surface. Z_e is the absolute expansion (cm).

3.3, 5.0, and 7.5 cm for 0, 0.25, 0.50, 0.75, and 1% (C), respectively. It is worthy of mentioning here that in recent study by El-Shafei *et al.* [27] on Acryhope by uniform sandy columns, they found that L_r was decreasing with time until eventually it became approximately constant under ponded infiltration and within the same range of Z. The relationship between L_r and C can be presented by the following logarithmic equation with r= 0.972.

$$L_r = 0.157 + 0.081\, ln\, C \tag{5}$$

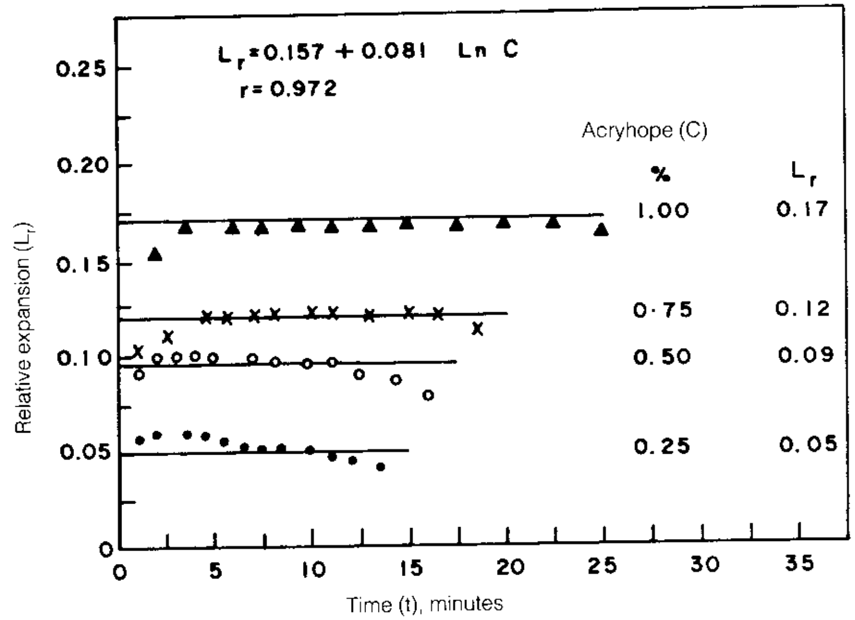

Fig. 3. Relative expansion as influenced by Acryhope added to the upper layer (10-cm depth) of sandy soil during infiltration .

The cumulative infiltration (D) as cm depth was corrected for the height of the free water surface on the soil column, which was changing due to expansion. Figure 4 presents the cumulative infiltration (D) versus time (t) as influenced by Acryhope concentration (C). It is interesting to notice that the infiltration period can be divided to two stages, i.e. there was a point of intersection. The first stage lasted up to approximately 27 min, where the wetting front (L) have advanced $\geqslant$ 50 cm depth depending on the value of C (Fig. 2). Accordingly and from standpoint of practical view, one may discard the second stage of infiltration in sandy soils. During the first stage of infiltration, which was characterized by high absorption of water, D increased with increase of C. The relationship between D and t was also a power equation with r=0.9998.

$$D = A\,t^{B} \tag{6}$$

However, the exponent (B) in Eq. 6 decreased while the constant of proporitonality (A) increased with increase of C. Accordingly, one can expect that D will decrease with increase of C during the second stage of infiltration (Fig. 4). The Acryhope effects provided by Figs. 1, 2, and 4 are consistent with the superabsorbing and retention nature of Acryhope conditioner. The higher the Acryhope concentration (up to 1%), the higher the resultant infiltration rate and the lowest advance rate of wetting front, during the first stage of infiltration.

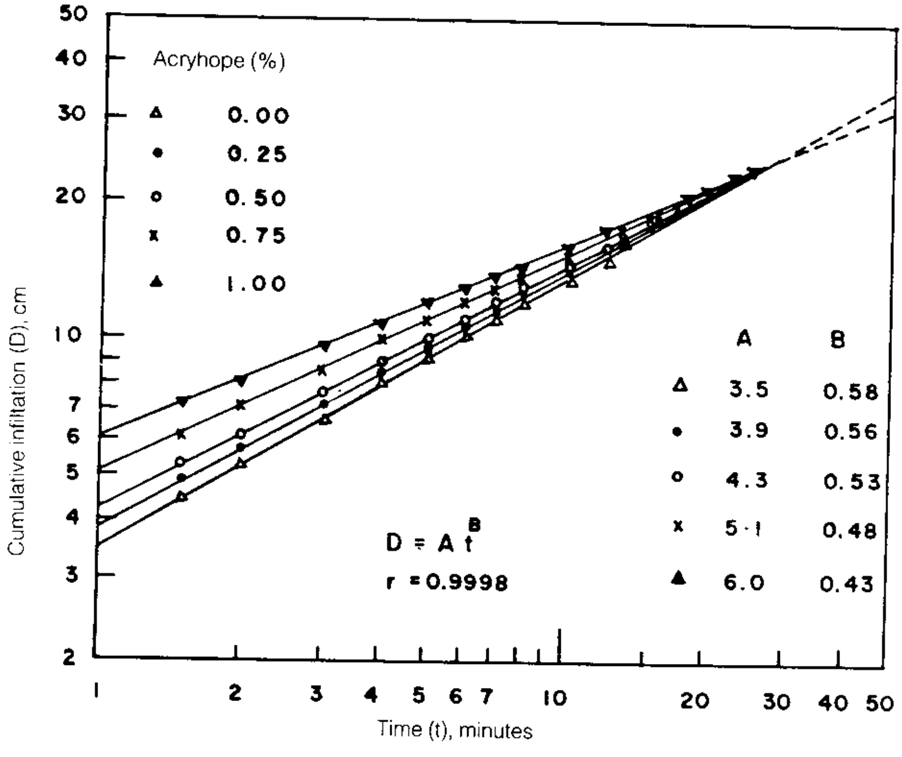

Fig. 4. Cumulative infiltration as influenced by Acryhope added to the upper layer (10-cm depth) of sandy soil.

The swelling of gel particles associated with soil expansion resulted in a peculiar bulk density distribution (Fig. 5). The bulk density (D_b) of the surface layer was greatly influenced by Acryhope concentration (C). The higher C, the lowest the resultant D_b of the surface layer. However at each value of C, D_b was increasing with depth and eventually approached the initial value of D_b for sandy soil. The values of

D_b (Fig. 5) were then implemented to convert the water content on weight basis (W) to volumetric water content (θ) for each corresponding depth. It can be noticed from the data depicted in Fig. 5 that a value 0.5% was the least C required to obtain θ less than W at the upper 5 cm depth. However, to achieve such condition (θ<W) for the subsequent layer (5 - 10 cm depth), 0.75% of C was needed. For example, W was 95% for C = 0.75% but the corresponding θ would be 66.5% since the resultant D_b was 0.7g cm^{-3} for each layer.

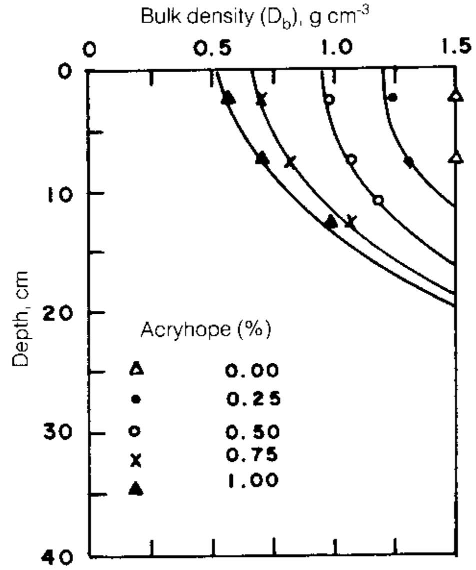

Fig. 5. Effect of Acryhope concentration at the upper layer (10-cm depth) on soil bulk density profile in sandy soil under ponded infiltration .

There were two main zones in the water distribution profile obtained after the cessation of infiltration (Fig. 6). The first zone was greatly influenced by C and was characterized by higher water content (θ). The higher C, the heigher the resultant θ and the length of the first zone. However, the first zone did not extend more than 20 cm depth for any value of C (up to 1%). It might be mentioned here that El-Shafei *et al.* [27] obtained a similar result even when the whole soil profile was uniformly treated with Acryhope. Below the first zone, there existed a relatively lengthening zone with a uniform water content regardless of the value of C. This second main zone was followed by a wetting zone where the water content gently decreased with depth. Apparently, Fig. 6 indicates that the water content in the untreated lower

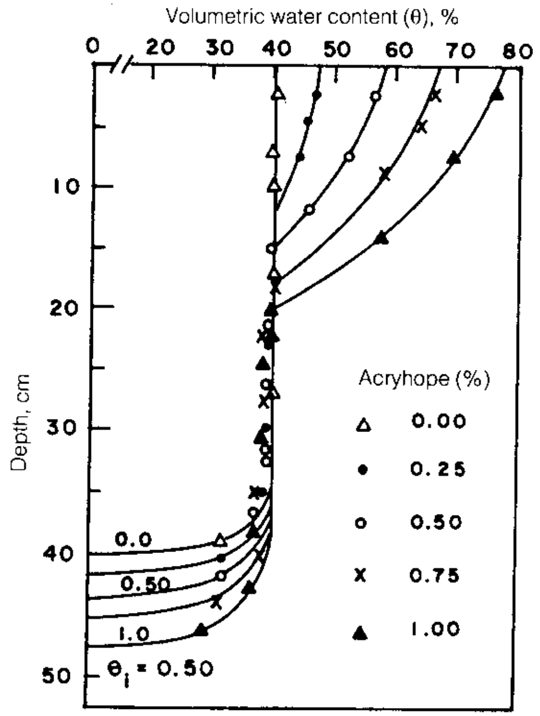

Fig. 6. **Effect of Acryhope concentration at the upper layer (10-cm depth) on water distribution profile of sandy soil under ponded infiltration.**

layer was unaffected by the Acryhope application to upper layer. It can be concluded that if the Acryhope treated soil overlies the untreated sandy soil, water content in the lower layer will be consistently the same at corresponding depths in untreated uniform profile under ponded infiltration. The average water content (θ) of the surface layer (0-10 cm depth) was increased by approximately 12, 33, 54, and 79%, with corresponding C: 0.25, 0.50, 0.75, and 1%, respectively.

The evaporation experiment under a constant temperature 22.5°C revealed that adding Acryhope to the surface layer (10 cm depth) was highly effective in reducing evaporation loss from sandy soil (Fig. 7). The higher the Acryhope concentration (C) the lowest the resultant evaporation rate. Although water was initially under 10 kPa matric suction for all the t, the cumulative evaporation ($\dot{E}$) as a function of time (T) was pronouncedly decreased by Acryhope application. For example an evaporation loss of 20 mm required a time of approximately 7, 9, and 14 days for corresponding

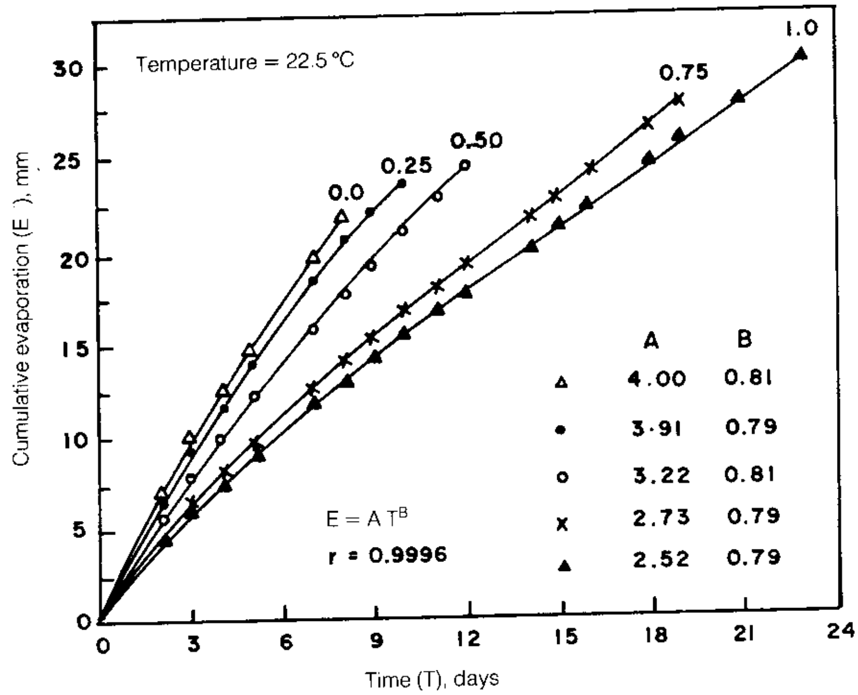

Fig. 7. **Effect of Acryhope concentration at the upper layer (10-cm depth) on evaporation loss from sandy soil, initially was at 10 kPa suction, under a constant temperature. Numbers by the curves are percentages of Acryhope concentration .**

C: 0, 0.5, and 1%, respectively. The relationship between E (mm) and T (days) was also found to be power type equation (7) with r = 0.9996 for all Acryhope treatments.

$$E = A\,T^{B} \tag{7}$$

The exponent (B) had approximately a constant value of 0.80, while the computed power regression intercept (A) was decreasing with increase of C (Fig. 7). It might be stated here that the reduction in evaporation rate was due to the large retention nature of Acryhope which tied up the water in a gel form and resulted in a very viscous liquid. Since the factor A is dependent on C, Equation 7 can be written as:

$$E = 2.52\,C^{-0.32}\,T^{0.80} \qquad \text{for } 0.25 \leqslant C \geqslant 1 \tag{7a}$$

Figure 8 illustrates how the capillary rise was influenced by Acryhope application to the upper layer (10 cm depth) of sandy soil. The bottom of the soil column was

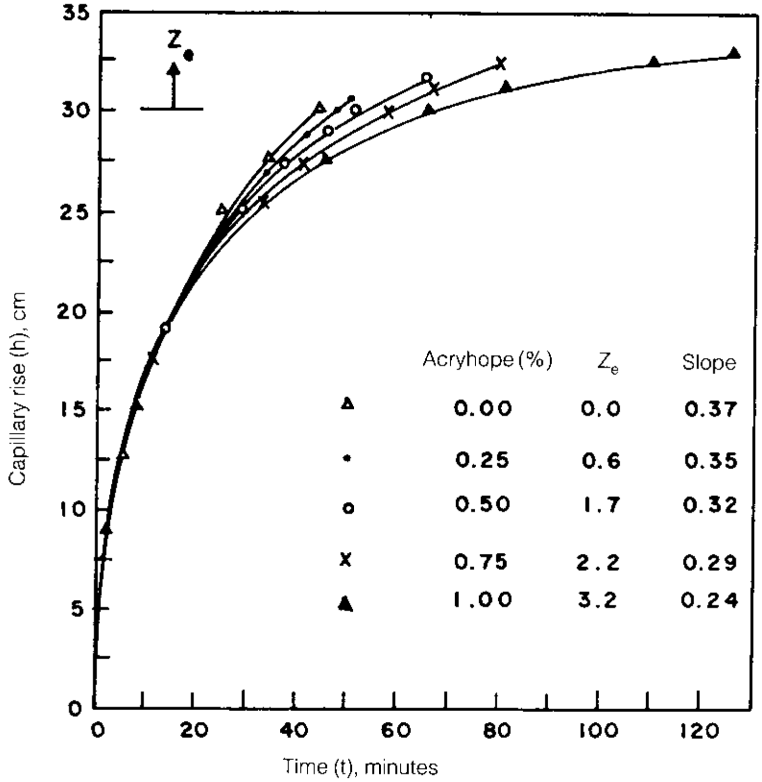

Fig. 8. Capillary rise of water in columns of layered sandy soil where the upper layer (10-cm depth) was treated with Acryhope. Z_e is the absolute expansion (cm) and the slope refers to the rate of Capillary rise (dh/dt) through the upper layer

taken as datum line, i.e. h=0.0. The results indicated that the rate of capillary rise was identical up to h equal to approximately 20 cm for all the treatments. The rate of capillary rise (dh/dt) started to deviate from the 20 cm height, at the interface, where water began to penetrate the upper treated layer. This deviation of (dh/dt) was lowered with the increase of C at the upper layer. The rates of capillary rise through the upper layer were 0.37, 0.35, 0.32, 0.29, and 0.24 for the corresponding C: 0.0, 0.25, 0.50, 0.75, and 1%, respectively. However, the treatment of C = 1% was the most effective in controlling capillary rise of water. While the capillary rise achieved the soil surface at elapsed time of 43 min for the control, the time have increased to as high as 126 min for C = 1%. The decrease in the rate of capillary rise in soil columns produced change in wet ability of sandy soil as can be noticed from the result depicted in Fig. 9. The water distribution profile resulted from capillary rise consisted of two main zones (Fig. 9). The first zone extended upward from the bottom of soil column

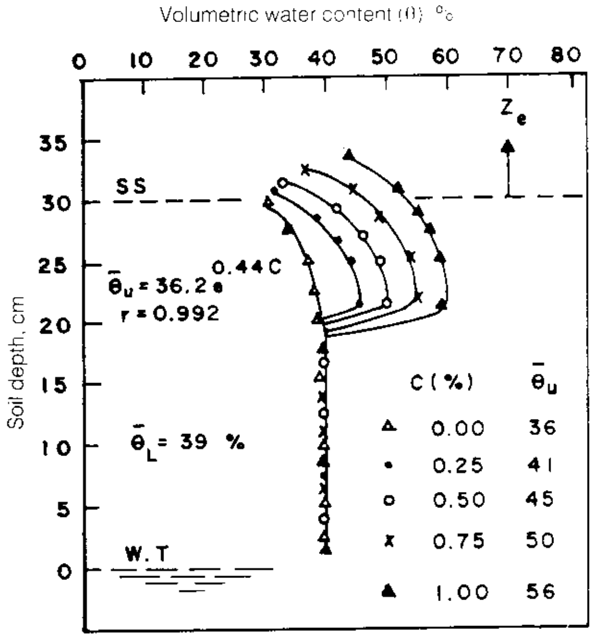

Fig. 9. Effect of Acryhope concentration (C) at the upper layer (10-cm depth) on water distribution profile of sandy soil under capillary rise. θ_u and θ_L are the average water contents for the upper and lower layers, respectively. W.T. referes to static water table.

up to 20 cm high and was characterized by a uniform water content (θ_L) which was not affected by Acryhope treatment at the upper layer. Above this zone, there was the second zone extended from the interface up to the erected soil surface and was characterized by higher water content depending on C. It can be concluded that if the Acryhope treated soil overlies the untreated sandy soil, water content in the lower layer will be consistently the same as in uniform soil profile under capillary rise. The results depicted in Fig. 9 indicate that the higher Acryhope concentration (C) at the upper layer, the higher the resultant average water content in that layer (θ_u). For example, the values of θ_u were 36, 45, and 56 % for the corresponding C: 0.0, 0.50, and 1%, respectively. The relationship between θ_u and C was exponentially type equation with r = 0.992.

$$\theta_u = 36.2\, e^{0.44C} \tag{8}$$

It is evident that increasing the Acryhope concentration at the upper layer (10 cm depth) caused increasing in displacement of water distribution curve to the right without significant change in the general slope of the curve (Fig. 9).

Further laboratory studies on the use of Acryhope conditioner on layered sandy soil in conjunction with sprinker (rain) infiltration are being carried out.

Conclusions

The gel-froming conditioner (Acryhope) exhibited a superabsorbing power for water and high water retention. When Acryhope is added to the upper layer of sandy soil, its gel particles are swollen upon water absorption causing soil expansion associated with upward displacement of the initial soil surface and consequently decreasing the bulk density of this layer. The highest value of absolute expansion (surface displacement) was 7.5 cm conjugated with the lowest bulk density of 0.6 g cm^{-3} for Acryhope concentration 1%, under ponded infiltration.

Acryhope was beneficial in increasing water content at the upper treated layer and decreasing rate of wetting front advance under ponded infiltration, and reducing evaporation loss. The conditioner was also effective in decreasing the rate of capillary rise through the upper treated layer resulting high water contents.

Those hydrophysical effects were more pronounced when Acryhope concentration at the upper treated layer (10 cm depth) ranged from 0.75 to 1%. However, present cost-benefit analysis may limit the use of soil gel-conditioners at the concentrations suggested by this study and others especially field application in a wide scale. Thus, it might be recommended to apply Acryhope conditioner to the upper layer of sandy soil and adjacent to the plant at concentration ranging from 0.50 to 0.75% for both the benefit of soil water management and economical consideration.

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تأثير أحد المحسنات الجيلاتينية عالية الانتفاخ (أكري هوب Acryhope) على الخواص الهيدروفيزيائية للترب الرملية الطبقية

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ملخص البحث. أجريت دراسة معملية على أعمدة تربة رملية طبقية لمعرفة تأثير أحد المحسنات الجلاتينية عديدة الأكريلات (أكري هوب Acryhope) على احتفاظية الماء وسريانه. وقد أضيفت خمسة تركيزات (C) من الأكري هوب تراوحت من صفر إلى ١٪ (على أساس الوزن الجاف) إلى الطبقة العليا (١٠سم) كحبيبات جافة. وقد انتفخت حبيبات المحسن الجيلاتيني عند امتصاص الماء مما نتج عنه تمددًا كبيرًا للتربة. وقدرت الكثافة الظاهرية للتربة واستخدمت في تقدير المحتوى الرطوبي الحجمي (θ)، وقيست أيضًا الزيادة في ارتفاع سطح التربة. ووجد أن كمية الماء التي احتفظت بها التربة عند مص (شد) ١٠ و١٥٠٠ كيلوباسكال قد زادت أسيا مع زيادة C (r = ٠,٩٩٩). وأدت زيادة C في الطبقة العليا المعاملة إلى نقص جوهري في معدل تقدم جبهة الابتلال خلال قطاع التربة وإلى زيادة θ للعمق ٢٠سم العلوي وذلك تحت التسرب الغمري. وبالرغم من أن التمدد النسبي (L_r) زاد مع زيادة C بالطبقة العليا، فإن قيمة L_r لكل تركيز ظلت ثابتة تقريبًا خلال التسرب الغمري، وكذلك وجدت علاقة لوغاريتمية بين L_r وC (r = ٠,٩٧٢). وقد قل فقد البخر بصورة فعالة نتيجةً لإضافة الأكري هوب إلى الطبقة العليا. كما أدت زيادة تركيز الـ C في الطبقة العليا المعاملة إلى خفض جوهري في معدل الصعود الشعري وإلى زيادة المحتوى الرطوبي لهذه الطبقة. وقد وجد ارتباط أسي بين متوسط المحتوى الرطوبي بالطبقة العليا (θ_a) والـ C (r = ٠,٩٩٢). وعمومًا كانت تأثيرات الأكري هوب أكثر وضوحًا عندما تراوحت قيمة الـ C بالطبقة العليا المعاملة (١٠سم) للتربة الرملية من ٠,٧٥ إلى ١٪. ولذلك فإنه من الممكن النصح بإضافة محسن الأكري هوب إلى الطبقة العليا للتربة الرملية وملاصقةً لجذور النبات بتركيز يتراوح من ٠,٥ إلى ٠,٧٥٪ وذلك لاعتبارات المردود الاقتصادي.