EFFECTS OF FOUR SOIL SURFACTANTS ON FOUR SOIL-WATER PROPERTIES IN SAND AND SILT LOAM

By

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Abstract

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Soil surfactants are wetting agents designed to improve infiltration, water distribution, and water retention. This industry-independent study evaluates the effects on soil-water properties of four surfactants commonly used in the Pacific Northwest: Wet-Sol #233 (Schaeffer), WaterMaxx II (Aquatrols/Western Farm Services), Ad-Sort RST (Simplot), and ADVANTAGE Formula One (Wilbur-Ellis). These surfactants were tested on two sifted soils with no water repellency: a Warden silt loam and a Quincy sand. No significant differences were found between any of the surfactants or the control (irrigation water only) in the tests of infiltration rate and volumetric water content. Using a significance level of $\alpha = 0.05$, significant differences were found for the tests of unsaturated hydraulic conductivity ($Pr = 0.0090$) and capillary rise ($Pr = 0.048$) in the sand samples only. Formula One consistently performed best in the hydraulic conductivity and capillary rise tests, and Wet-Sol frequently the worst. However, in the infiltration rate and water holding capacity tests, Formula One was usually the middle performer and Wet-Sol was frequently second or third best. No significant differences were found between any of the surfactant or control treatments in either soil type for the tests of infiltration rate and water holding capacity. Hence, the use of surfactants did not benefit the soil-water movement over the long term (infiltration rate was tested up to 4 hours and water holding

capacity up to 24 hours). Furthermore, the individual surfactants that performed well according to the unsaturated hydraulic conductivity and capillary rise test results were middle or lower performers in the infiltration rate and water holding capacity test results.

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INTRODUCTION

Agricultural surfactants have gained widespread use as "spreaders and stickers" by helping fertilizers, pesticides, and soil conditioners spread through the soil matrix, sorb to soil, or adhere to plant leaves (Ishiguro and Fujii, 2008). Surfactants' potential to improve the movement of water itself in soil has been investigated since the 1960s (DeBano, 2000). Several types of soil surfactants have been applied in fields to improve soil-water problems such as poor water penetration (Feng et al., 2002), preferential flows (Oostindie et al., 2008), runoff and excess channel seepage (Lentz, 2007), and low water use efficiency (Starr et al., 2005; Cooley et al., 2009).

Although the structure and function of the molecules of the wide number of surfactants vary widely, all possess a hydrophilic "head" group and a hydrophobic "tail" group (Karagunduz, 2001). Their head bonds strongly with water, while their tail adsorbs to surfaces such as clay minerals, air molecules in pores, or hydrophobic organic substances in soil (Kuhnt, 1993; Tumeo et al., 1997). The net effect is an apparent lowering of the interfacial tension between air-water and soil-water surfaces (Rosen, 1989; Karagunduz, 2001). This is especially noticeable when the soil particles have hydrophobic, or water repellent, coatings (Doerr et al., 2007; Kostka et al., 2007; Hallett, 2008). Surfactants can thus help some surfaces wet more easily. Surfactants used as wetting agents are both anionic and nonionic, with nonionic surfactants showing stronger and longer-lasting soil sorption (Kuhnt, 1993; Park and Bielefeldt, 2003). Block polymers are a class of nonionic surfactants specially formulated to enhance the surfactant's sorption to soil and remain active in the soil matrix longer than other nonionic surfactants (Schmoka, 1977).

Laboratory tests have shown surfactants to affect infiltration rates and flow patterns. Vertical infiltration rates increased with the concentrations of two commercial soil surfactants applied to water repellent soil (Feng et al., 2002). In horizontal soil columns, flow was induced in direct proportion to surfactant concentration (Henry et al., 1999, 2001; Bashir et al., 2008).

Nonionic AquaGro ® L (Aquatrols Corp.) produced a uniform, 11-cm wetting front in a chamber of mixed sands that previously showed preferential flow paths (Nektarios et al., 2002). Golf-course soil cores treated with an Aquatrols copolymer showed complete wettability over two years, while untreated cores showed significant water repellent regions interspersed with wettable regions (Oostindie et al., 2008).

Researchers have reported both increases and decreases in hydraulic conductivity due to surfactants, and the mechanisms of action have been debated since 1969 (Tumeo, 1997). Researchers have postulated that surfactants either increase or decrease aggregate stability in soils, and hydrophobic coatings on water-repellent soil particles may produce the opposite effect as is seen in hydrophilic soils (Tumeo, 1997). Although the surface tension reduction achieved by surfactants should theoretically increase hydraulic conductivity, decreases in hydraulic conductivity are reported more often in literature. Studies of four anionic and 11 nonionic surfactants showed reductions in hydraulic conductivity of up to 2 orders of magnitude in loamy soils and up to 58% in sand (Allred and Brown, 1994, 1995). After obtaining adsorption isotherms for nonionic Soil Penetrant 3685 and Aqua Gro, researchers concluded that hydraulic conductivities decreased at concentrations near the critical micelle concentration (CMC) in hydrophobic samples, but no changes were observed in hydrophilic samples (Miller et al., 1975).

Direct changes in water content have also been observed after applying surfactants. A higher volumetric water content was observed in soil cores treated with a nonionic copolymer compared to untreated cores (Oostindie et al., 2008). The anionic polymer XPAM increased water retention: seepage rates decreased with increasing XPAM dosages in five soil types (Lentz, 2007). A soil-remediation surfactant formulated to increase drainage, Triton-X, produced the opposite effect of substantially reducing soil water content (Karagunduz et al., 2001). Adding an anionic surfactant to seed-germinating growth media increased the media's total water holding capacity in proportion to surfactant dosage, and the available water increased significantly after adding surfactant (even at the lowest dose) to the media (Urrestarazu et al., 2008).Capillary rise was found to decrease significantly when anionic and nonionic surfactants were tested in sand columns, with the decrease in direct proportion to surfactant concentration (Wiel-Shafran et al., 2006).

Capillary rise significantly decreased in loam and sandy loam columns treated with an anionic surfactant, while the solid-liquid contact angle increased; in the same study, no significant impacts were observed for two nonionic surfactants (Abu-Zrieg et al., 2003). Upward infiltration rates and contact angles were affected differently in different materials when tested with varying concentrations of anionic surfactant (Ishiguro and Fujii, 2008). In hydrophilic sand and glass, the upward infiltration rate decreased with increasing concentration due to surfactant adsorption. In hydrophobic peat moss and polyethylene particles, contact angles decreased with increasing surfactant concentration until they were similar to those of the hydrophilic materials, indicating that the hydrophobic materials grew increasingly wettable; the upward infiltration rates increased as the contact angles became smaller.

In the field, positive results have been seen in hydrophobic turfgrass and potato plots. Severe dry spots were reduced in 36 sand-based golf tees treated with an Aquatrols block polymer (Kostka, 2000). Another Aquatrols surfactant increased soil water uniformity and overall water savings in a putting green (Karcher et al., 2005). Regular monthly applications of surfactants consistently maintained low dry spot levels in turfgrass (Miller, 2002). Pacific Northwest potato yields increased significantly in hydrophobic soil plots treated with an Aquatrols block polymer (O'Neill, 2005). In two Wisconsin studies, nitrate leaching was reduced and water content and yields increased after treating hydrophic sands with surfactants (Kelling et al., 2003; Lowery, 2005).

In contrast, discouraging results were found in several field studies involving other cropping soils. The anionic soil conditioner AgriSci (Four Star Agricultural Services, Inc.) did not significantly improve the hydraulic conductivity, sorptivity, water retention, organic matter content, or 48-hour aeration porosity over two-years of observation in a fallow silt loam plot with incorporated corn residue (Fitch et al., 1989). An Aquatrols and an Advantage surfactant achieved no significant increases in water contents or pinto bean yields in Southwestern sandy loam plots (O'Neill, 2005). Three nonionic wetting agents advertised to improve nutrient availability and crop yield (WEX, Basic H, and Amway Spray Adjuvant) were tested in Wisconsin corn, soybean, and potato plots (silt loam and loamy sand); over several years of study, no significant increases in crop yields, crop protein levels, or foliar nutrient content of N, P, and K were found in surfactant-treated crops (at varying application rates) compared to untreated crops (Wolkowski et al., 1985). Further instances were included in a review of wetting agents in which surfactants did not significantly increase the yield or nutrient content of corn, potatoes, soybeans, wheat, and grain sorghum (McFarland et al., 2005).

While all the field studies in which positive results were found were conducted in problematic hydrophobic soils, the wettability or hydrophobicity of the soils was not found in the other studies. A review of wetting agents for the Cooperative Extension Services of 10 Midwestern states warns growers that surfactant proponents often make "blanket endorsements" in favor of surfactants without discussing the soil conditions or other interfering field conditions that may alter the effectiveness of the agents (Sunderman, 1988). Sunderman (1988) reports two of his own research studies and reviews several other studies in which wetting agents either produced no effect or adversely affected the wetting of hydrophilic soils. Sunderman reasons that the reduction in capillary rise produced by surfactants in normally wettable soils may actually lower the infiltration of water into hydrophilic soil pores.

Many studies of soil surfactant effectiveness are disseminated to the public online and in printed brochures by private and university researchers whose funding is provided by the surfactant manufacturers or distributers. As these studies are not published by peer-reviewed journals, their conclusions do not add to the published body of academic research knowledge and their scientific validity may be called into question by skeptical growers and researchers.

The objective of this study was to evaluate the effects of four commonly marketed and used soil surfactants on infiltration rate, water holding capacity, unsaturated hydraulic conductivity, and capillary rise in two wettable (non-water repellent) soils typically productive for high-value crops in the Pacific Northwest. The null hypothesis (H_o) for these experiments states that the mean values of each test variable will be the same for all surfactants treatments within a given level of significance, while the alternative hypothesis (H_a) predicts a statistically-significant variation in the means:

$$H_o\text{:}\ \mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5$$

$$H_a\text{:}\ \mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4 \neq \mu_5$$

where μ_1 to μ_4 represent the means of the test variables across different sample replicates for each surfactant treatment and μ_5 represents the mean for the control treatment (no added surfactant).

MATERIALS AND METHODS

Soil samples were subjected to five treatments: four different surfactants added to irrigation water and a control treatment of irrigation water without added surfactant. Testing was replicated four times, resulting in 20 samples for each test and each soil type. This study focused on typical soils used to grow high-value crops of potatoes, onions, dry/green beans, and vine/tree fruit in Eastern Washington and Oregon, a Warden Series silt loam and a Quincy Series sand. The soil air-dried for approximately three months (at a mean temperature of 30° C) and was sieved (0.5-cm hole diameter) before all tests. Four agricultural soil surfactants commonly marketed and used in Eastern Washington and Oregon were tested as described in Table 1.

The surfactants were expected to be mixed with water for application to the soil via the regular method of surface, drip, or sprinkler irrigation. To replicate this in the laboratory, an area-equivalent sample volume of the surfactant, *Vs*, was calculated, and then mixed with sufficient irrigation water (161 ml for infiltration rate samples) to penetrate each soil sample to a depth of 1 cm upon application.

To calculate the volume of surfactant added to each sample, *Vs*, the median rate on the product label (volume per acre) was scaled down the equivalent volume per soil-column area. With this reasoning, each soil sample was effectively treated as if it were a small part of a large field receiving the recommended surfactant dosage.

Table 1. Brand names, classification, manufacturers, ingredients, and amounts of the four surfactants applied; V_s, was added to the sample in 161 ml of water, giving a treatment solution concentrations of V_s / 161 ml water after mixing.

Surfactant Applications

Surfactant	Chemical Type	Manufacturer	Active Ingredients	Surfactant Volume, V_s	Concentration % (v/v)
Wet-Sol #233	Nonionic	Schaeffer Manufacturing Co. (St. Louis, MO)	25% Alkylphenyl-hydroxy polyoxyethylene 0.3% Poly dimethyl-siloxane	0.0115 ml	0.007 %
WaterMaxx II	Block polymer	Aquatrols Corp. (Distribut-ed by Western Farm Services (Fresno, CA))	30% Blend of propanediol and glycosides ingredients	0.00766 ml	0.005 %
Ad-Sorb RST	Reverse block polymer	J. R. Simplot Manufacturing Co., Plant Health Technologies (Boise, ID)	10% Alkoxyl-ated polyois 7% Glucoethers	0.00383 ml	0.002 %
ADVANTAGE Formula One	Anionic	Wilbur-Ellis Co. (Fresno, CA)	30% Ammonium alkyl ether sulfate 1% Alkyl aryl polyethoxylates	0.719 µl	0.0004%

Infiltration Rate Experiment

For the infiltration rate experiment, 52 cm of sifted soil was added to each open plexiglass column (14.4-cm diameter). Soil was shaken from a cup and the columns lifted and dropped regularly to ensure uniform settling of soil and consistency across samples. A mesh screen (0.04-cm^2 holes) and filter paper (14.4-cm diameter, 150-mm pore diameter) retained the soil but allowed liquid to drain into a pan beneath the column stand.

Prior to the experiments, 161 ml of treatment solution (water plus surfactant volume V_s or water alone for the control) was sprinkled on top of the dry soil samples and allowed to penetrate 1 cm. Marriotte reservoirs (14.4-cm diameter, 61-cm height) supplied tap water via siphons to the top of the soil columns with ponding heights varying from 1.3 to 3.8 cm, depending on the heights of reservoir air-intake tubes (Figure 1). The reservoir's water levels were recorded every 2 to 10 minutes (more frequently for sand than silt) until drainage began and the siphons were removed. The decline in a reservoir's water level over time matched the rate that water infiltrated the soil. The infiltration rate is theoretically described by the Lewis-Kostiakov equation:

$$i(t) = bkt^{b-1} + f_o \qquad (2)$$

where $i(t)$ is the infiltration rate (m/s) versus intake opportunity time t (s), b and k are empirical parameters, and f_o is the steady state value (m/s) (Sepaskhah and Afshar-Chamanabad, 2002).

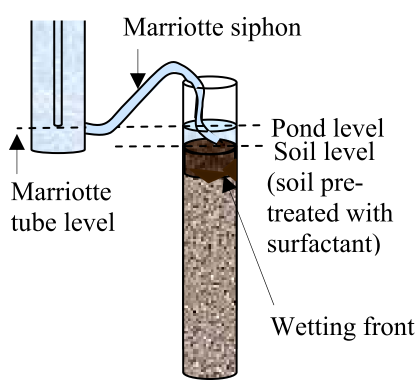

Figure 1. The key elements in the infiltration rate experimental setup.

Water Holding Capacity Experiment

The water holding capacity of the different samples was examined by weighing the columns before and after the infiltration rate experiments. Soil columns were first weighed after treatment with 161 ml of surfactant solution. When the infiltration siphons were removed, the tops of columns were covered with foil to limit evaporation, and the bottoms were covered when drainage ceased. After 48 hours, the coverings were removed, and a second "wet" weight measurement was taken. The difference between the wet and air-dry weights (minus the tare weight of the experimental apparatus and weight of treatment solution) represented the mass of water M_w that the soil retained.

These measurements were used with the soil column volume to calculate the volumetric soil water content achieved after the different treatments.

Unsaturated Hydraulic Conductivity Experiment

Plexiglass columns (14.4-cm diameter) were filled with dry soil up to 8 cm of depth in the same manner as in the previous experiment. No drainage was expected over the experiment time. Mini-disk infiltrometers (Decagon Devices, Inc., 3.18-cm diameter, 100-ml volume) supplied the treatment solution at the concentrations used previously (Table 1), and water levels were recorded every 10 seconds for silt and 5 seconds for sand (Figure 2). Cumulative infiltration was represented by the water level normalized by the infiltrometer's cross-sectional area.

Tension infiltrometers have been used by a number of researchers to calculate hydraulic conductivity from infiltration data (Zhang, 1997; Verbist et al., 2009). Based on the Wooding analysis, the cumulative infiltration $I(t)$ in meters per second is modeled by the following (Zhang, 1997 ; Verbist et al., 2009):

$$I(t) = C_1 t^{1/2} + C_2 t \quad (8)$$

Figure 2. Testing one sample with infiltrometer.

In equation (8), C_1 (m/s) is related to sorptivity and the coefficient C_2 (m/s) is proportional to K (m/s) as follows:

$$K(h_o) = \frac{C_2}{A_2} \tag{9}$$

where h_o (m) is the tension value of the infiltrometer (i.e. matric potential at the disk infiltrometer surface) and dimensionless A_2 depends on van Genuchten parameters under fixed soil conditions (Carsel and Parrish, 1988; Zhang, 1997; Flury, 2007).

Capillary Rise Experiments

Capillary rise heights were measured in open, transparent plastic tubes (30.5-cm height, 3.5-cm diameter) filled with soil to depths of 23 cm by the same filling method used previously. A mesh screen (0.04-cm^2 holes) retained the soil. At the beginning of each test, four replicate columns were placed in a pan (5-cm depth), and a Marriotte bottle containing the treatment solution (at the concentration reported in Table 1) was placed and uncovered in the same pan. The Marriotte reservoir resupplied the pond at the same rate the solution was taken up by the soil (Figure 3). The heights of the rising wetting fronts were recorded over time.

The Washburn Equation characterizes the vertical rise of the wetting front due to capillary action (Ishiguro and Fujii, 2008; Matthews, 2008; Shang et al., 2008). The height of the wetting front in meters, x, is related to contact angle, θ, as follows:

$$x^2 = \frac{R_{eff}\gamma_L \cos\theta}{2\eta} t \qquad (10)$$

where R_{eff} is the effective pore radius of the interparticle capillaries in the porous layer (m), γ_L is the surface tension of the test liquid (J m^{-2}), η is the liquid viscosity (N s m^{-2}), and t is time (s) (Shang et al., 2008). Simplifying this equation to represent the height versus time gives:

$$x = at^{1/2} \qquad (11)$$

where $a = \left(\frac{R_{eff}\gamma_L \cos\theta}{2\eta}\right)^{1/2}$.

In the experiment, columns had to be set in the pan with care and held upward by standing tools. Before the first measurement could be taken, the water had risen in the tube a small distance. To account for the rise height at the time of first recording (t = 0), a second constant term, b (m), was added to the equation:

$$x = at^{1/2} + b\,. \qquad (12)$$

Figure 3. Four replicates undergoing treatment in the capillary rise experiment.

Statistical Analysis

Least-squares error regression was performed to best-fit the equations to the data for each sample replicate of the infiltration rate, unsaturated hydraulic conductivity, and capillary rise tests. The values for $b-1$ (infiltration rate), C_2 (unsaturated hydraulic conductivity) and a (capillary rise) derived from the regression appear in Tables A1, A3, and A4 of Appendix A, along with their associated errors. The calculated values of gravimetric water content, bulk density and volumetric water content are given in Table A2 of Appendix A. Graphs of the raw data with the best-fit curves superimposed appear in Figures B1 through B6 of Appendix B. All four replicates are graphed together for each treatment.

To determine whether the differences among treatments were significant, one-way analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$ was performed on the derived values and the volumetric water content using Statistical Analysis Software (SAS) 9.1.3 (SAS Institute Inc., Cary, NC). The *Pr*-values from the ANOVA appear in Table 2. The complete SAS input and response files appear in Appendix C.

RESULTS AND DISCUSSION

No significant differences were found for the tests of infiltration rate and volumetric water content. A strong significant difference was seen among the treatment variables in the unsaturated hydraulic conductivity test in sand with $Pr = 0.009$, while the results were not significant in silt loam ($Pr = 0.083$). Similarly, results were significant in sand samples for the capillary rise test ($Pr = 0.049$), but not significant for capillary rise in silt loam ($Pr = 0.082$).

ANOVA also determined the significance of each treatment with respect to each other treatment (see section 4, "Least Squares Means for Effect Treatment," in each SAS file in Appendix C). For the unsaturated hydraulic conductivity test in sand, the Wet-Sol results were significantly different from every other surfactant and the control. The mean value of C_2 for the Wet-Sol replicates was lower than all other treatment means. Formula One had the highest

Table 2. Statistical results from the SAS ANOVA across treatments for each experiment.

Statistical Significances

Experiment	Treatment variables	Overall *Pr*, Silt Loam	Overall *Pr*, Sand
Infiltration rate	Power constant $b–1$ for Lewis-Kostiakov curve, $i(t) = bk\, t^{b-1} + f_o$	0.50	0.52
	Slope constant bk for Lewis-Kostiakov curve, $i(t) = bk\, t^{b-1} + f_o$	0.54	0.81
Water holding capacity	Volumetric water content, θ_v	0.059	0.10
Unsaturated hydraulic conductivity	C_2 in cumulative infiltration curve, $I(t) = C_1\, t^{½} + C_2\, t$	0.083	0.0090*
Capillary rise	Slope constant a in Washburn equation, $x = a\, t^{½} + b$.	0.082	0.049*

* Results with an asterix are statistically significant.

mean value of C_2, and its performance was significantly different from Wet-Sol, Ad-Sorb, and the control, but not compared to WaterMaxx. No other C_2 differences were significant in sand.

Although ANOVA indicated an overall insignificant response for C_2 in silt loam, individual surfactants did perform significantly differently from each other ($Pr \leq 0.05$). Both Formula One and Wet-Sol were significantly different from the control and from each other. Formula One again had the highest mean value of C_2, and Wet-Sol had the second-to-lowest mean. WaterMaxx had the lowest mean in silt loam (significantly different from Ad-Sorb, the control, and Formula One, but not Wet-Sol), while it was second-to-lowest in sand.

For capillary rise, the mean value of *a* in the Washburn equation was significantly higher for the control than for all the surfactants in sand. In silt loam, the mean of *a* was significantly higher for the control than for Formula One, WaterMaxx, and Wet-Sol. Formula One had the lowest *a* mean in both sand and silt loam, but the difference was significant only compared to the control in sand and compared to the control and Ad-Sorb in silt loam. Ad-Sorb had the second lowest *a* mean in sand, but the second highest in silt. Wet-Sol had the second highest *a* mean in sand, but the second lowest in silt loam (significantly different from the control and Ad-Sorb).

For all other tests, no significant differences were found among treatment means. In the infiltration rate test, the mean value of the exponent $b-1$ was often opposite for the different surfactants in sand compared to silt. The $b-1$ mean became increasingly negative in this order for sand: Ad-Sorb > WaterMaxx > Formula One > Wet-Sol > control. In silt loam, the order was WaterMaxx > control > Formula One > Wet-Sol > Ad-Sorb. However, the data curves (Appendix B) clearly showed that the value of $b-1$ alone did not determine which surfactant performed best: bk and f_o also affected the shape of the infiltration rate curve. Considering the mean values of all three parameters, which all together determined the fastest-falling infiltration rate curves and lowest steady-state infiltration rate values, the control samples performed better than all surfactants in both silt loam and sand. Likewise, the control was the best performer in the water holding capacity test. The mean volumetric water content was highest to lowest in the following orders: Control > Formula One > Wet-Sol > WaterMaxx > Ad-Sorb for silt, and control > Ad-Sorb > Formula One > WaterMaxx > Wet-Sol for sand.

A concern could be that critical micelle concentrations for these surfactants are not reported. Surfactants may perform differently below and above the CMC, the point at which surfactants arrange themselves in micelles in soil-water (Karagunduz et al., 2001; Abu-Zreig et al., 2003). Adsorption isotherms show that surface tension falls slowly as surfactant concentration increases toward the CMC, and near the CMC, surface tension drops rapidly and shortly thereafter remains constant (Valoras et al., 1969; Tsujii, 1998). The argument might be made that at concentrations below the CMC, the surfactant monomers might adhere to the surfaces of air molecules either in solution or at the air-water interface of a water table. If such adsorption to air occurred in the infiltrometer used to test hydraulic conductivity or in the open pan used to test capillary rise, then the surfactant solutions could not have reached the samples until the very ends of these two tests.

This potential problem was not discussed in numerous previous articles (Fitch et al., 1989; Kuhnt, 1993; Tumeo 1997; Henry et al., 1999; Bauters et al., 2000; Feng et al., 2002; Wiel-Shafran et al., 2006; Kostka et al., 2000; Lentz, 2007; Bashir et al., 2008; Oostindie et al., 2008; Urrestarazu et al., 2008). Other researchers have applied surfactant solution in setups similar to those used in this study for finding cumulative infiltration and capillary rise (Abu-Zrieg, 2003; Wiel-Shafran, 2006). In addition, surfactants have even been observed to affect sorption, water content, and capillary rise at concentrations below the CMC (Miller et al., 1975; Karagunduz et al., 2001; Park and Bielefeldt, 2003; Ishiguro and Fujii, 2008).

CMC data is not often available to the public for commercial soil surfactants, but rather the manufacturers recommend the concentrations that users should apply. Manufacturers also recommend soil surfactants for all types of irrigation systems, and many are recommended for spraying directly on standing water. Hence, the labeled rates may represent concentrations at which surfactant-air interactions will not present problems.

In this study, we applied the surfactants at the labeled rates that customers would also use in the field. The significant differences found among the surfactant treatments in the unsaturated hydraulic conductivity and capillary rise tests seemed to indicate that surfactants (not just water) were being tested in these setups.

CONCLUSIONS

Although the surfactants significantly affected spreading and capillary action in tests that lasted from a few minutes to an hour, no significant differences were found in the longer-lasting tests of infiltration rate and water holding capacity. Hence, over several hours and several days, the surfactants did not produce significantly different effects in the hydrophilic soils that were tested. Additionally, the surfactants did not behave the same in all the tests or in both soil types, so that the best performer could not be clearly determined.

In totality, our results did not lead to a strong recommendation to use a surfactant. Rather, the results underscore the theory soil surfactants may not be profitable for healthy soils (Miller et al., 1975; McFarland et al., 2005). Structurally, surfactants interact well with problem conditions such as hydrophobicity or dense surface clods (Kuhnt, 1993). The soil conditions in an advertisement may be ideal for a product's action, but if a buyer's field does not have these the same conditions, the same results should not be expected.

This study is limited to a single application of surfactant. Different results may be achieved if the soil is conditioned by several applications of surfactant, as reported by Feng (2002) and Miller (2002). The surfactants with strongest adsorption might remain in the soil matrix and affect the soil-water properties over time.

In addition to testing the residual effects of these surfactants, this same set of experiments should be conducted in hydrophobic, compacted, or crusty soils to present a full picture of the possible effectiveness of these wetting agents. In problem soils, differences might emerge between the anionic, nonionic and block polymer surfactants due to their different mechanisms of soil sorption and soil-water movement.

BIBLIOGRAPHY

Abu-Zreig, M., Rudrak, R. P., Dickinson, W. T. 2003. Effect of application of surfactants on hydraulic properties of soils. Biosystems Engineering 84(3): 363–372.

Allred, B. and Brown, G. O. 1994. Surfactant-induced reductions in soil hydraulic conductivity. Groundwater Monitoring and Remediation 14(2): 174–184.

Allred, B. and Brown, G. O. 1995. Surfactant-induced reductions of saturated hydraulic conductivity and unsaturated diffusivity. Surfactant-Enhanced Subsurface Remediation — Emerging Technologies. ACS Symposium Series 594: 216–230.

Bashir, R., Smith, J. E., Stolle, D. F. 2008. Surfactant-induced unsaturated flow: Instrumented horizontal flow experiment and hysteretic modeling. Soil Science Society of America Journal 72 (6): 1510–1519.

Carsel, R. F. and Parrish, R. S. 1988. Developing joint probability distributions of soil water retention curves. Water Resources Research 24: 755–769.

Cooley, E. T., Lowery, B., Kelling, K. A., Speth, P. E., Madison, F. W., Bland, W. L., and Tapsieva, A. 2009. Surfactant use to improve soil water distribution and reduce nitrate leaching in potatoes. Soil Science 174: 321-329.

DeBano, L.F. 2000. Water repellency in soils: a historical overview. Journal of Hydrology 231–232: 4–32.

Doerr, S. H., Ritsema, C. J., Dekker, L. W., Scott, D. F., and Carter, D. 2007. Water repellence of soils: new insights and emerging research needs. Hydrological Processes 21: 2223–2228.

Feng, G. L., Letey, J., and Wu, L. 2002. The influence of two surfactants on infiltration into a water-repellent soil. Soil Science Society of America Journal 66: 361–367.

Fitch, B. C., Chong, S. K., Arosemena, J., Theseira, G. W. 1989. Effects of a conditioner on soil physical properties. Soil Science Society of America Journal 53: 1536–1539.

Flury, M. 2007. Soil Physics Laboratory Manual. Washington State University, Pullman, WA. Unpublished.

Hallett, P. D. 2008. A brief overview of the causes, impacts, and amelioration of soil water repellency. Soil and Water Resources 3: S21–S29.

Henry, E. J., Smith, J. E., Warrick, A. W. 1999. Solubility effects on surfactant-induced unsaturated flow through porous media. Journal of Hydrology 223: 164–174.

Henry, E. J., Smith, J. E., Warrick, A. W. 2001. Surfactant effects on unsaturated flow in porous media with hysteresis: horizontal column experiments and numerical modeling. Journal of Hydrology 245: 73–88.

Ishiguro, M. and Fujii, T. 2008. Upward infiltration into porous media as affected by wettability and anionic surfactants. Soil Science Society of America Journal 72(3): 741–749.

Karagunduz, A., Pennell, K. D. and Young, M. H. 2001. Influence of a Nonionic Surfactant on the Water Retention Properties of Unsaturated Soils. Soil Science Society of America Journal 65: 1392–1399.

Karcher, D., Miller, J., Richardson, M. and Leinauer, B. 2005. Irrigation frequency and soil surfactant effects on a sand-based putting green. University of Arkansas Research and Extension Center. Accessed 2 April 2010. http://147.213.145.2/biohydrology/abstracts/Karcher_S3.doc

Kelling, K. A., Speth, P. E., Arriaga, F. J. and Lowery, B. 2003. Use of a nonionic surfactant to improve nitrogen use efficiency of potato. Acta Horticulturae, International Society for Horticultural Science 619: 225–232.

Kostka, S. J. 2000. Amelioration of water repellency in highly managed soils and the enhancement of turfgrass performance through the systematic application of surfactants. Journal of Hydrology 231–232: 359–368.

Kostka, S. J., Schuermann, G. and Franklin, M. 2007. Alkyl-capped block copolymer surfactants for remediation of soil water repellency and heterogenous rootzone moisture. Journal of ASTM International 4(7): 1–8.

Kuhnt, G. 1993. Behavior and fate of surfactants in soil. Environmental Toxicology and Chemistry 12: 1813–1820.

Lentz, R. D. 2003. Inhibiting water infiltration with polyacrylamide and surfactants: Applications for irrigated agriculture. Journal of Soil and Water Conservation 58(5): 290–300.

Lentz, R. D. 2007. Inhibiting water infiltration into soils with cross-linked polyacrylamide: Seepage reduction for irrigated agriculture. Soil Science Society of America Journal 71: 1352–1362.

Lowery, B., Speth, P., and Kelling, K. 2005. Use of surfactant to increase water and nitrogen use efficiency in potato production in hydrophobic sandy soil in Wisconsin, USA. Geophysical Research Abstracts 7: 00490.

Matthews, G.P., Watts, C. W., Powlson, D. S., Price, J. C., and Whalley, W. R. 2008. Wetting of agricultural soil measured by a simplified capillary rise technique. European Journal of Soil Science 59: 817–823.

McFarland, M. L., Stichler, C., and Lemon, R. G. 2005. Non-traditional soil additives: Can they improve crop production? Forages. Texas A&M University System AgriLife Extension. Accessed 2 April 2010.
http://forages.tamu.edu/pubs.html

Miller, C. 2002. Timing soil surfactant applications: Their effect on soil water repellency. TurfGrass Trends. Accessed 2 April 2010.
http://www.golfdom.com/irrigation-systems/timing-soil-surfactant-applications?page_id=1

Miller, W. W., Valoras, N., and Letey, J. 1975. Movement of two Nonionic Surfactants in Wettable and Water-Repellent Soils. Soil Science Society of America Proceedings 39: 11–16.

Nektarios, P.A., Petrovic, A.M., and Steenhuis, T.S.   2002. Effect of surfactant on fingered flow in laboratory golf greens. Soil Science 167 (9): 572–579.

O'Neill, M., Heyduck, R., and Prior, N. 2005. Soil surfactants for improved soil moisture and nutrient use efficiency in pinto beans. New Mexico State University 2005 Annual Progress Report: 133–137. Accessed 2 April 2010.
http://cahe.nmsu.edu/aes/farm/projects--results.html

Oostindie, K. Dekker, L. W., Wesseling J. G., and Ritsema, C. J. 2008. Soil surfactant stops water repellency and preferential flow paths. Soil Use and Management 24: 409–415.

Park, S. and Bielefeldt, A. R. 2003. Aqueous chemistry and interactive effects on non-ionic surfactant and pentachlorophenol sorption to soil. Water Research 37: 4663–4672.

Rosen, M. J. 1989. Surfactants and Interfacial Phenomena. John Wiley and Sons. New York, New York.

Sepaskhah, A.R. and Afshar-Chamanabad, H. 2002.   Determination of infiltration rate for every-other furrow irrigation. Biosystems Engineering 82 (4): 479–484.

Shang, J., Flury, M., Harsh, J. B., Zollars, R. L. 2008. Comparison of different methods to measure contact angles of soil colloids. Journal of Colloid and Interface Science 328: 299–307.

Schmoka, I. R. 1977. A Review of Block Polymer Surfactants. Journal of the American Oil Chemists' Society 54: 110–116.

Starr, G. C., Cooley, E. T., Lowery, B., and Kelling, K. 2005. Soil water fluctuations in a loamy sand under irrigated potato. Soil Science 170(2): 77–89.

Sunderman, H.D. 1988. Soil wetting agents: Their use in crop production. North Central Regional Extension Publication 190. Cooperative Extension Service, Kansas State University, Manhattan, Kansas.

Tsujii, K. Surface Activity: Principles, Phenomena, and Applications. Academic Press, San Diego, CA, pp. 44–46, 83–100.

Tumeo, M. A. 1997. A survey of the causes of surfactant-induced changes in hydraulic conductivity. Ground Water Monitoring Review: 138–134.

Urrestarazu, M., Guillén C., Mazuela, P. C., Carrasco, G. 2008. Wetting agent effect on physical properties of new and reused rockwool and coconut coir waste. Scientia Horticulturae 116: 104–108.

Valoras, N., Letey, J., and Osborn, J. F. 1969. Adsorption on nonionic surfactants by soil materials. Soil Science Society of America Proceedings 33: 345–348.

Verbist, K., Baetens, J., Torres, C., and Soto, G. 2009. Hydraulic conductivity as influenced by stoniness in degraded drylands of Chile. Soil Science Society of America Journal 73: 471–484.

Wiel-Shafran, A., Ronen, Z., Weisbrod, N., Adar, E., Gross, A. 2006. Potential changes in soil properties following irrigation with surfactant-rich greywater. Ecological Engineering 26: 348–354.

Wolkowski, R. P., Kelling, K. A., Oplinger, E. S. 1985. Evaluation of three wetting agents as soil additives for improving crop yield and nutrient availability. Agronomy Journal 77: 695–698.

Zhang, R. 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Science Society of America Journal 61: 1024–1030.

APPENDIX A: DATA TABLES

Table A1. The values derived from regression that fit the Lewis-Kostiakov equation $i(t) = bk\, t^{\,b-1} + f_o$ (equation 2) to the data are given for the four replicates (R1 through R4), along with the associated sum of squared error (SSE) for each fit.

Lewis-Kostiakov Infiltration Rate Constants with Regression Errors

		bk	$b-1$	f_o (cm/s)	SSE	bk	$b-1$	f_o (cm/s)	SSE
		Silt Loam Samples				Sand Samples			
Wet-Sol #233	R1	10.6	−1.40	0.064	0.35	2.2	−0.78	0.18	0.015
	R2	0.94	−0.60	0.016	0.0074	9.2	−1.08	0	1.20
	R3	0.96	−0.64	0.018	0.0014	4.4	−1.60	0.43	0.064
	R4	0.41	−0.41	0.024	0.0013	2.7	−0.54	0	0.14
WaterMaxx II	R1	0.61	−0.42	0	0.096	2.03	−0.55	0.11	0.22
	R2	0.54	−0.42	0	0.0056	3.7	−1.06	0.40	0.17
	R3	0.82	−0.71	0.036	0.0055	1.8	−0.52	0.025	0.11
	R4	0.68	−0.47	0	0.013	6.7	−1.10	0.20	0.019
Ad-Sorb RST	R1	1.20	−0.69	0.032	0.0091	1.5	−0.66	0.19	0.12
	R2	0.93	−0.53	0	0.027	4.9	−0.77	0	0.070
	R3	0.59	−0.40	0	0.023	2.4	−0.58	0	0.030
	R4	8.40	−1.40	0.054	0.0032	3.0	−0.95	0.3	0.026
Formula One	R1	1.40	−0.78	0.040	0.0069	2.7	−1.00	0.24	0.007
	R2	0.82	−0.50	0	0.022	6.0	−1.07	0.25	0.042
	R3	0.77	−0.58	0.022	0.016	1.3	−0.27	0	1.00
	R4	0.68	−0.48	0	0.0082	4.8	−1.30	0.29	0.0053
Control	R1	0.62	−0.47	0	0.0064	6.7	−1.70	0.36	0.037
	R2	0.34	−0.34	0	0.0046	2.4	−0.95	0.25	0.046
	R3	0.86	−0.52	0	0.048	6.8	−1.40	0.40	0.0019
	R4	0.73	−0.54	0	0.048	2.8	−0.71	0.22	0.0012

Table A2 . Calculated values of gravimetric water content θ_m, volumetric water content θ_v, and bulk density P_b for sample replicates R1 through R4.

Water Contents and Bulk Densities After Surfactant Treatments

		θ_m (g/g)	θ_v (cm^3/cm^3)	P_b (kg/m^3)	θ_m (g/g)	θ_v (cm^3/cm^3)	P_b (kg/m^3)
		Silt Loam Samples			Sand Samples		
Wet-Sol #233	R1	0.280	0.399	1425	0.146	0.246	1690
	R2	0.267	0.385	1439	0.154	0.258	1678
	R3	0.246	0.360	1455	0.153	0.258	1687
	R4	0.233	0.345	1479	0.162	0.272	1675
WaterMaxx II	R1	0.277	0.397	1429	0.140	0.237	1692
	R2	0.279	0.399	1427	0.147	0.246	1678
	R3	0.257	0.376	1458	0.141	0.239	1689
	R4	0.288	0.408	1418	0.150	0.254	1682
Ad-Sorb RST	R1	0.282	0.399	1409	0.142	0.241	1701
	R2	0.280	0.399	1422	0.157	0.265	1682
	R3	0.306	0.422	1379	0.152	0.254	1672
	R4	0.243	0.355	1457	0.162	0.272	1675
Formula One	R1	0.274	0.397	1446	0.146	0.247	1689
	R2	0.283	0.406	1432	0.165	0.275	1661
	R3	0.282	0.403	1425	0.159	0.268	1678
	R4	0.272	0.392	1441	0.161	0.270	1678
Control	R1	0.268	0.390	1450	0.146	0.249	1697
	R2	0.295	0.420	1420	0.161	0.272	1685
	R3	0.322	0.448	1392	0.161	0.270	1675
	R4	0.306	0.432	1408	0.158	0.264	1670

Table A3. Calculated values of C_1 and C_2 that best fit the cumulative infiltration equation (8), $I(t) = C_1 t^{1/2} + C_2 t$, to the data with associated sums of squared errors for the unsaturated hydraulic conductivity test.

Cumulative Infiltration Constants with Regression Errors

		C_1 (cm/s$^{1/2}$)	C_2 (cm/s)	*SSE*	C_1 (cm/s$^{1/2}$)	C_2 (cm/s)	*SSE*
		Silt Loam Samples			Sand Samples		
Wet-Sol #233	R1	0.368	0.018	0.80	0.793	0.068	0.68
	R2	0.371	0.030	0.10	0.183	0.230	0.61
	R3	0.343	0.035	0.07	0.245	0.188	0.35
	R4	0.342	0.027	0.41	0.211	0.171	0.25
WaterMaxx II	R1	0.329	0.021	0.58	0.026	0.292	0.34
	R2	0.328	0.020	0.48	0.385	0.182	0.50
	R3	0.321	0.040	0.13	0.275	0.231	0.86
	R4	0.374	0.022	0.53	0.067	0.298	0.52
Ad-Sorb RST	R1	0.281	0.037	0.08	0.186	0.290	0.26
	R2	0.292	0.029	0.53	0.268	0.210	0.25
	R3	0.333	0.041	0.14	0.133	0.292	0.23
	R4	0.344	0.034	0.28	0.190	0.293	0.12
Formula One	R1	0.338	0.040	0.06	0.323	0.323	0.11
	R2	0.388	0.039	0.44	0.264	0.302	0.11
	R3	0.309	0.038	0.17	0	0.399	0.02
	R4	0.291	0.033	0.11	0.085	0.334	0.17
Control	R1	0.349	0.030	1.16	0.067	0.296	0.92
	R2	0.316	0.031	0.46	0.117	0.158	1.08
	R3	0.313	0.041	0.14	0.153	0.272	0.06
	R4	0.328	0.046	0.10	0.221	0.295	0.07

Table A4. Derived values of *a* and *b* that best fit the Washburn equation (12), $x = a\, t^{1/2} + b$, to the data, along with the sums of squared errors from the regression.

Constants for Capillary Rise Height Equations with Regression Errors

		Silt Loam Samples			Sand Samples		
		a (cm/s$^{1/2}$)	*b* (cm)	*SSE*	*a* (cm/s$^{1/2}$)	*b* (cm)	*SSE*
Wet-Sol #233	R1	2.32	2.83	9.76	3.67	3.10	13.1
	R2	2.39	2.89	7.11	3.19	3.80	7.95
	R3	2.72	1.03	7.59	3.01	5.18	8.96
	R4	2.39	3.70	9.10	3.31	5.04	14.0
WaterMaxx II	R1	2.60	0.52	12.0	3.25	2.80	5.30
	R2	2.83	0	15.2	3.09	4.00	4.31
	R3	2.25	5.11	0.42	3.24	5.31	13.6
	R4	2.35	5.41	1.17	2.90	5.01	3.75
Ad-Sorb RST	R1	2.77	0	14.7	3.25	3.87	29.3
	R2	2.60	1.07	6.68	3.30	3.90	12.7
	R3	2.58	0.64	7.93	2.97	4.77	7.61
	R4	2.84	0.05	11.6	2.80	5.28	9.67
Advantage Formula One	R1	2.54	1.98	5.15	3.19	5.40	5.20
	R2	2.29	5.21	5.56	3.02	5.86	7.22
	R3	2.52	1.67	11.4	3.18	4.65	2.98
	R4	2.44	0.72	3.89	2.93	6.72	6.18
Control	R1	2.65	0.62	2.90	3.76	1.19	13.1
	R2	2.76	0	7.29	3.68	4.40	35.6
	R3	2.74	0.60	6.20	4.00	2.01	31.6
	R4	2.70	0.13	4.83	3.04	6.49	9.74

APPENDIX B: DATA CURVES

For each surfactant treatment, the data and best-fit curves for the four sample replicates are plotted in the following graphs. A total of ten graphs — five for silt loam and five for sand columns — appear for each of the experiments of infiltration rate, unsaturated hydraulic conductivity, and capillary rise.

Data Curves for Infiltration Rate Test in Silt Loam

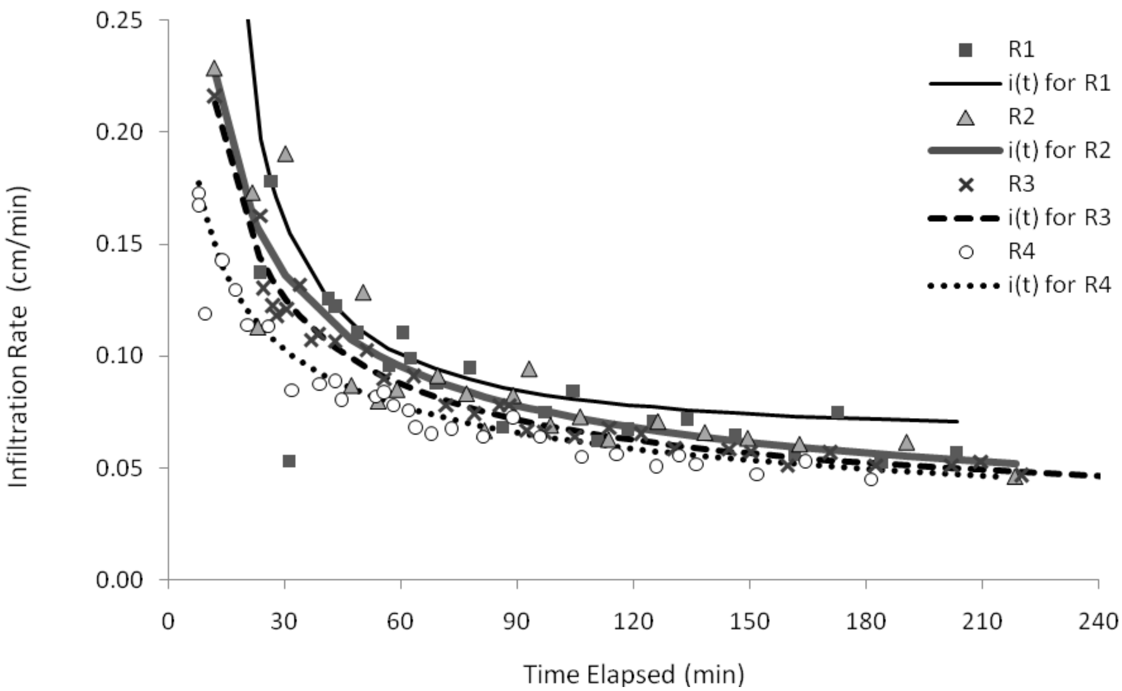

Figure B1(a). Infiltration rate versus time for all silt loam replicates treated with Wet-Sol #233.

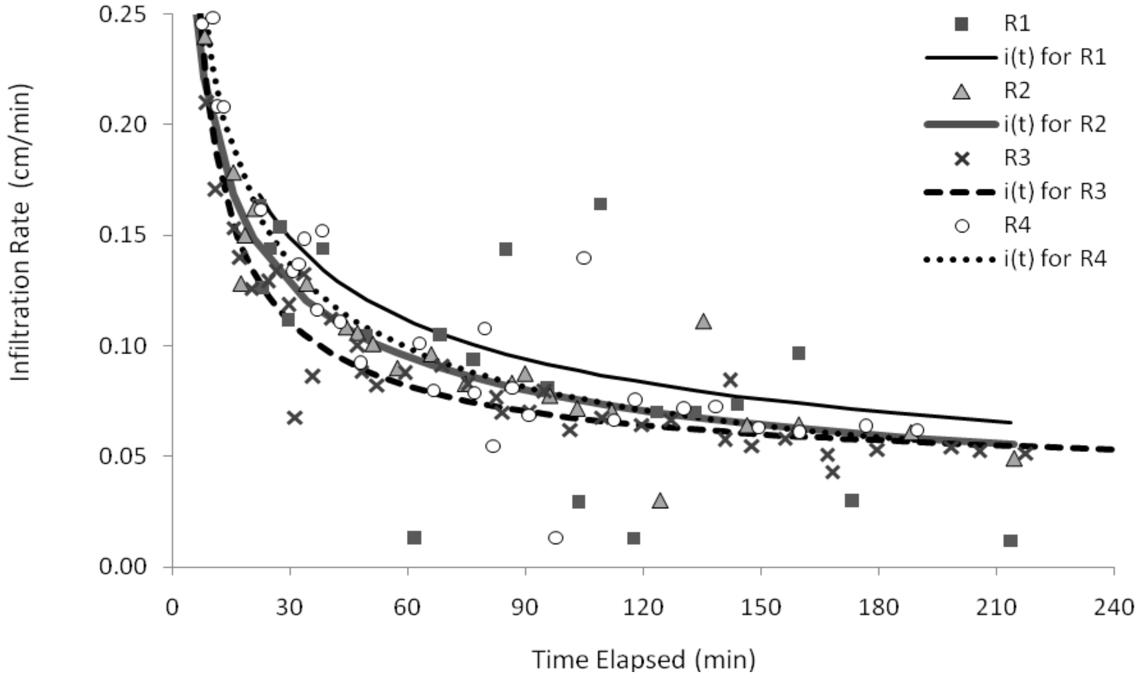

Figure B1(b). Infiltration rate versus time for all silt loam replicates treated with WaterMaxx II.

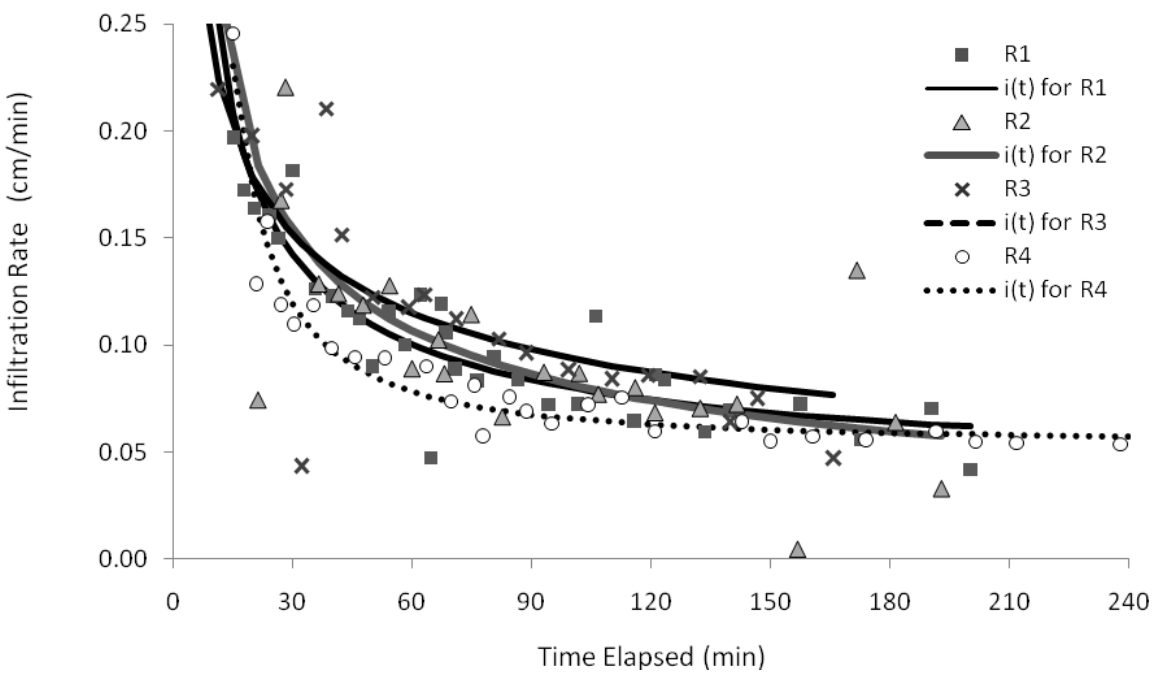

Figure B1(c). Infiltration rate versus time for all silt loam replicates treated with Ad-Sorb RST.

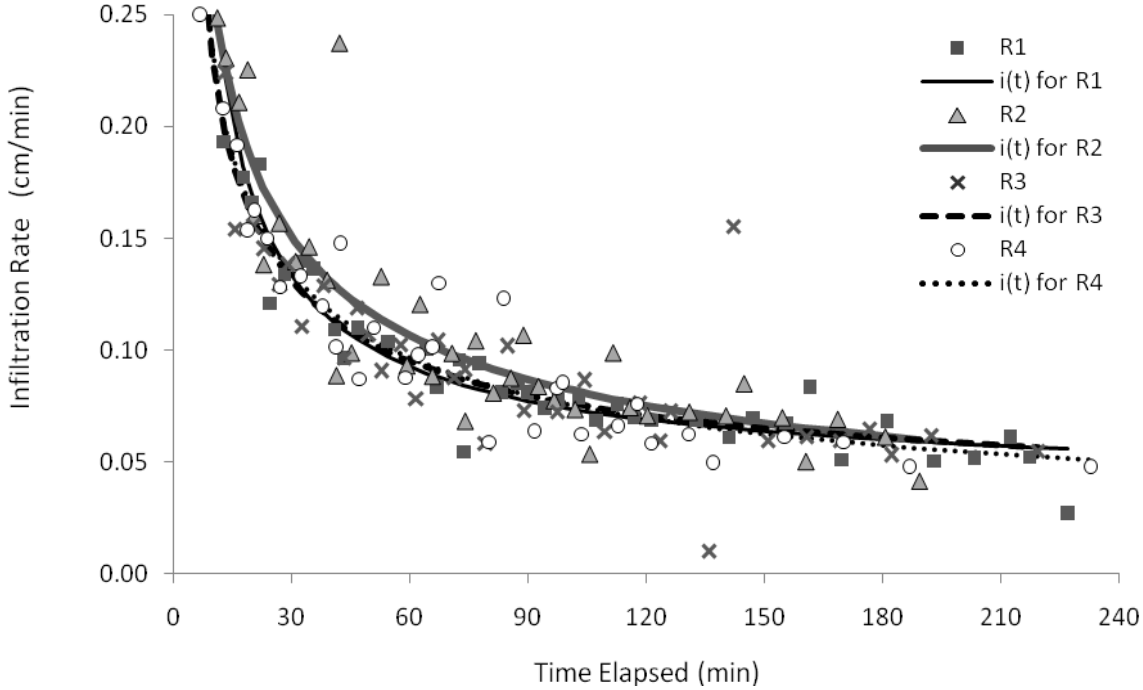

Figure B1(d). Infiltration rate versus time for all silt loam replicates treated with ADVANTAGE Formula One.

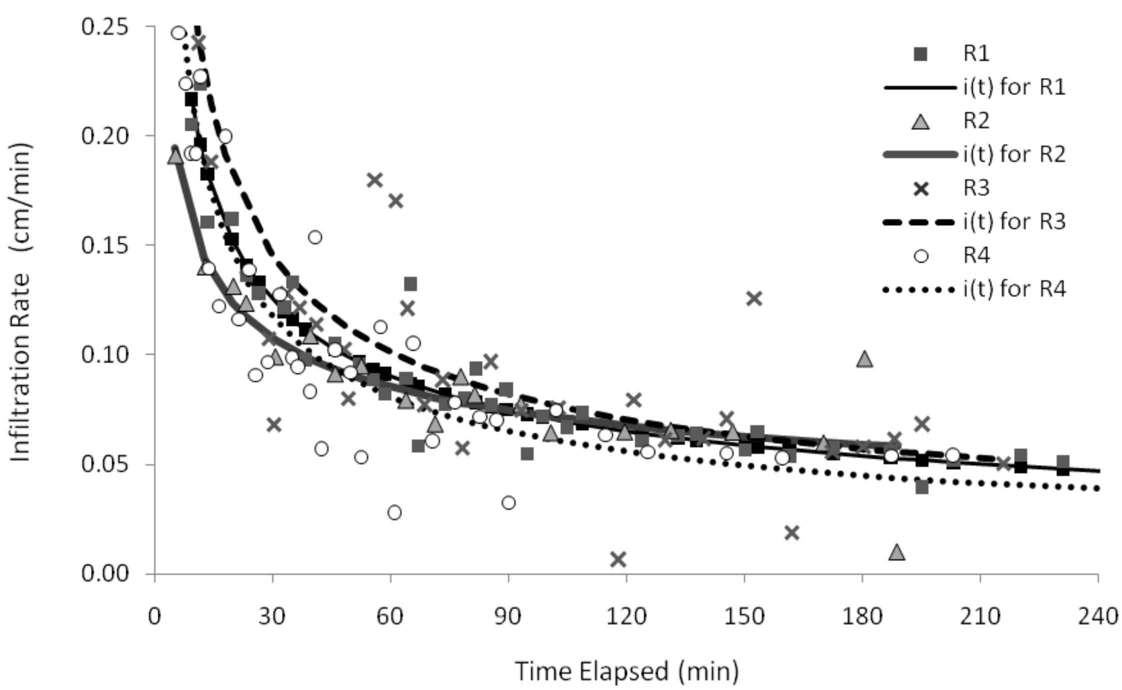

Figure B1(e). Infiltration rate versus time for all silt loam replicates under the control treatment.

Data Curves for Infiltration Rate Test in Sand

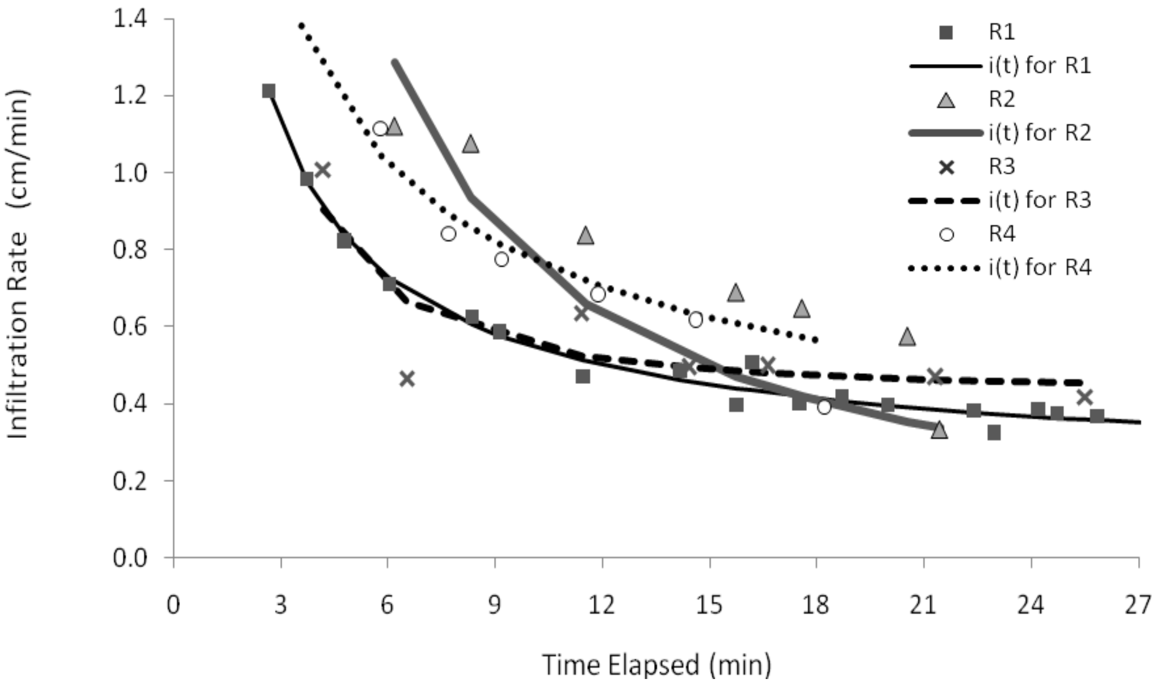

Figure B2(a). Infiltration rate versus time for all sand replicates treated with Wet-Sol #233.

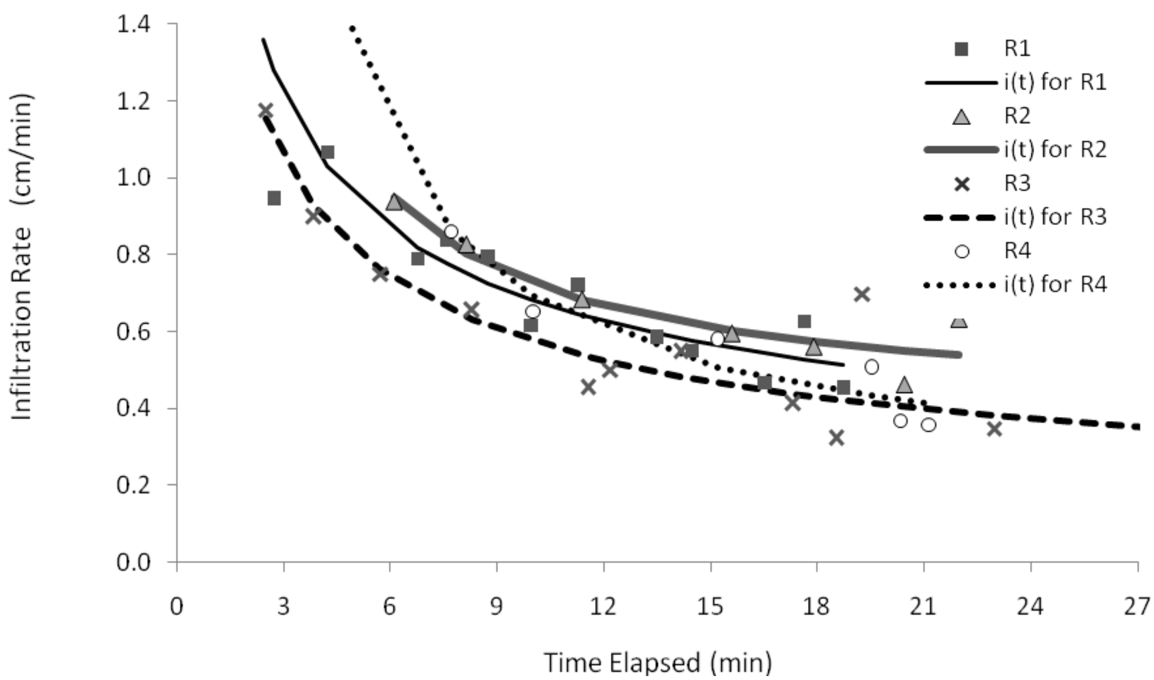

Figure B2(b). Infiltration rate versus time for sand replicates treated with WaterMaxx II.

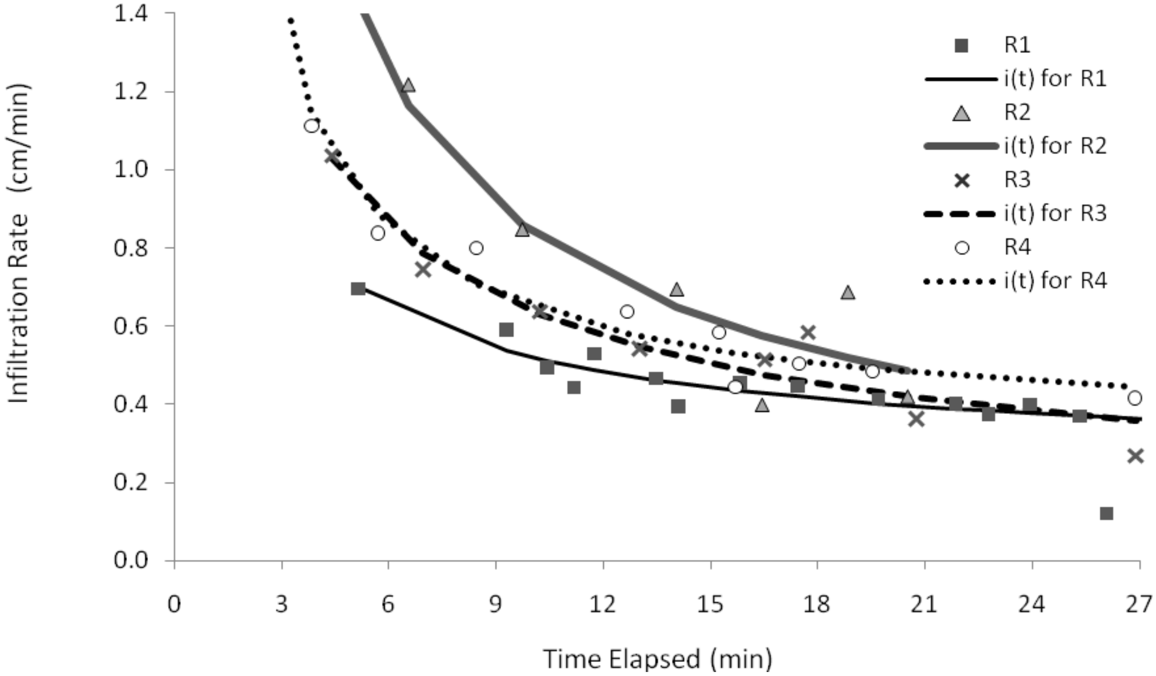

Figure B2(c). Infiltration rate versus time for all sand replicates treated with Ad-Sorb RST.

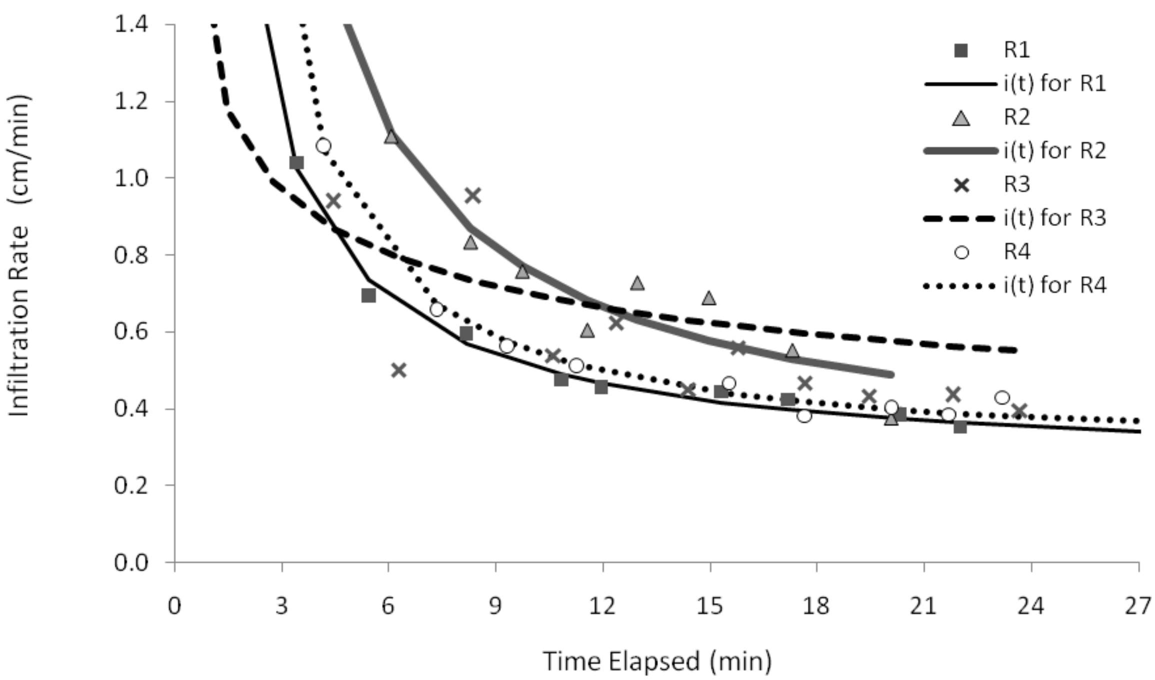

Figure B2(d). Infiltration rate versus time for all sand replicates treated with ADVANTAGE Formula One.

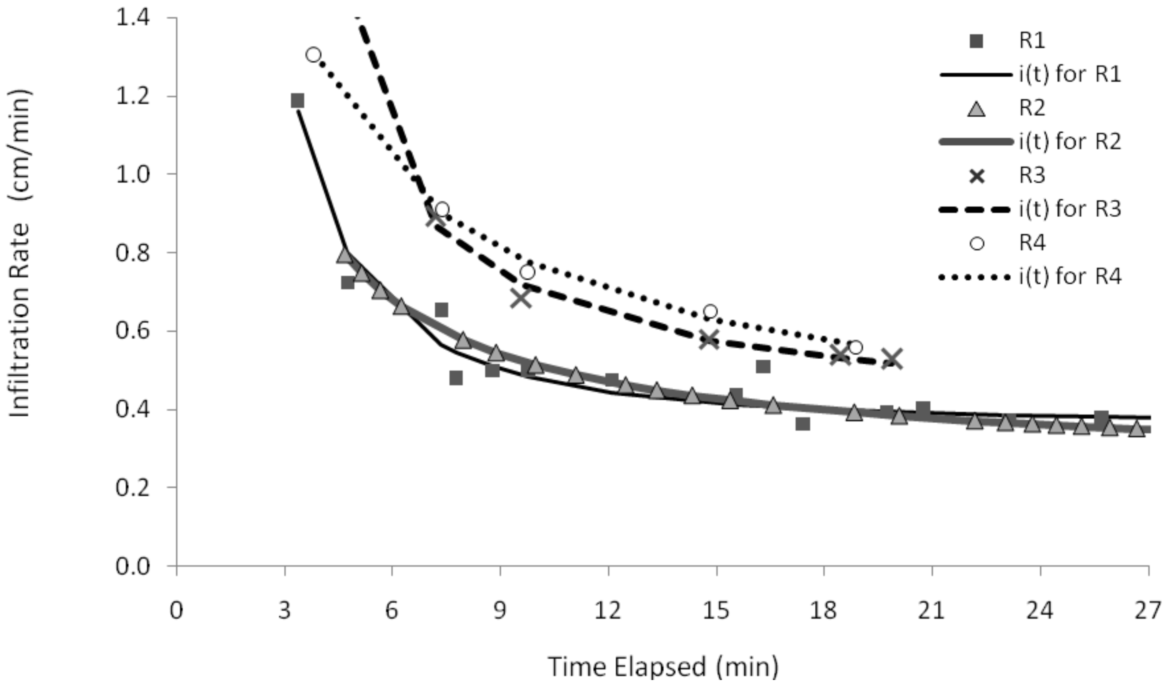

Figure B2(e). Infiltration rate versus time for all sand replicates under the control treatment.

Data Curves for Unsaturated Hydraulic Conductivity Test in Silt Loam

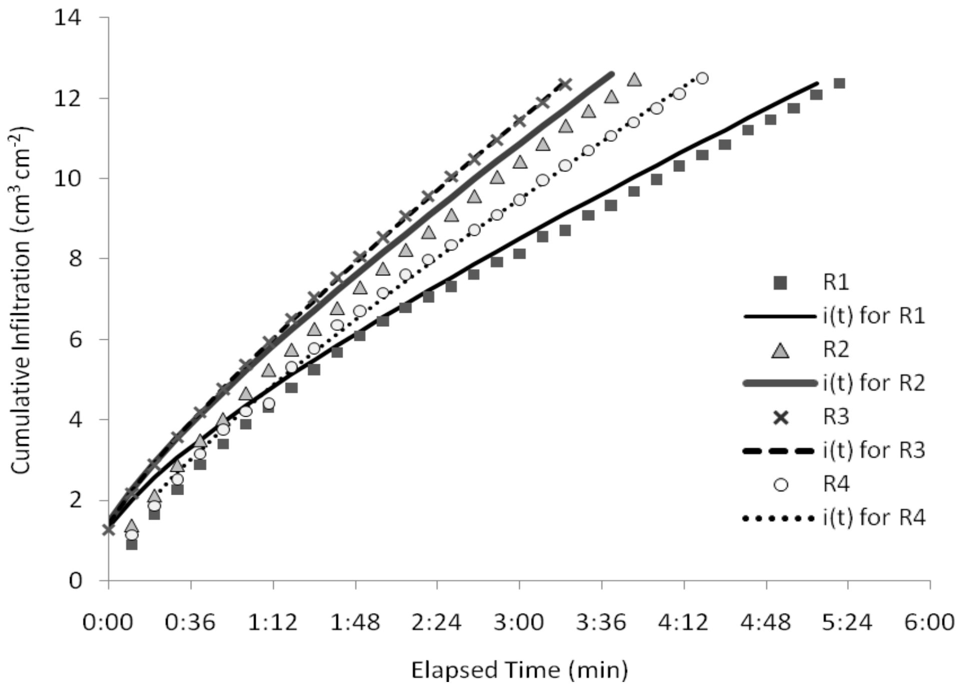

Figure B3(a). Cumulative infiltration versus time for all silt loam replicates treated with Wet-Sol #233.

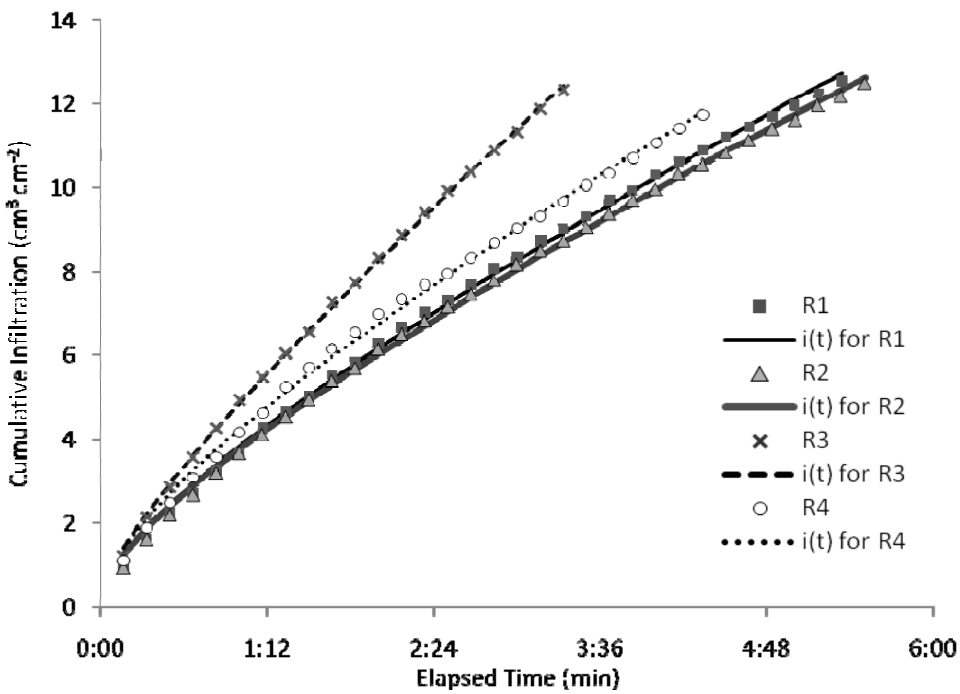

Figure B3(b). Cumulative infiltration versus time for all silt loam replicates treated with WaterMaxx II.

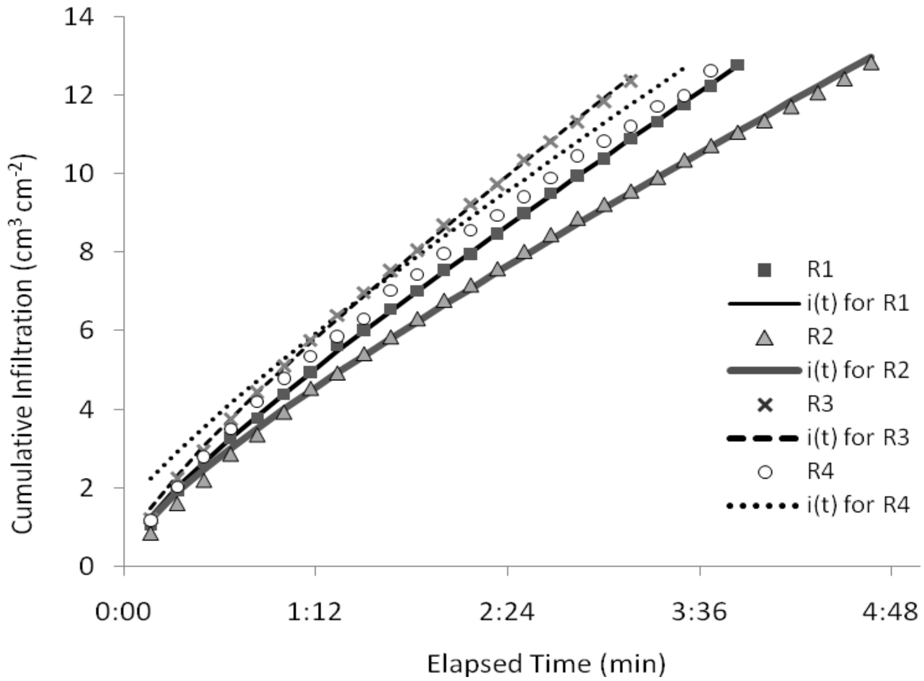

Figure B3(c). Cumulative infiltration versus time for all silt loam replicates treated with Ad-Sorb RST.

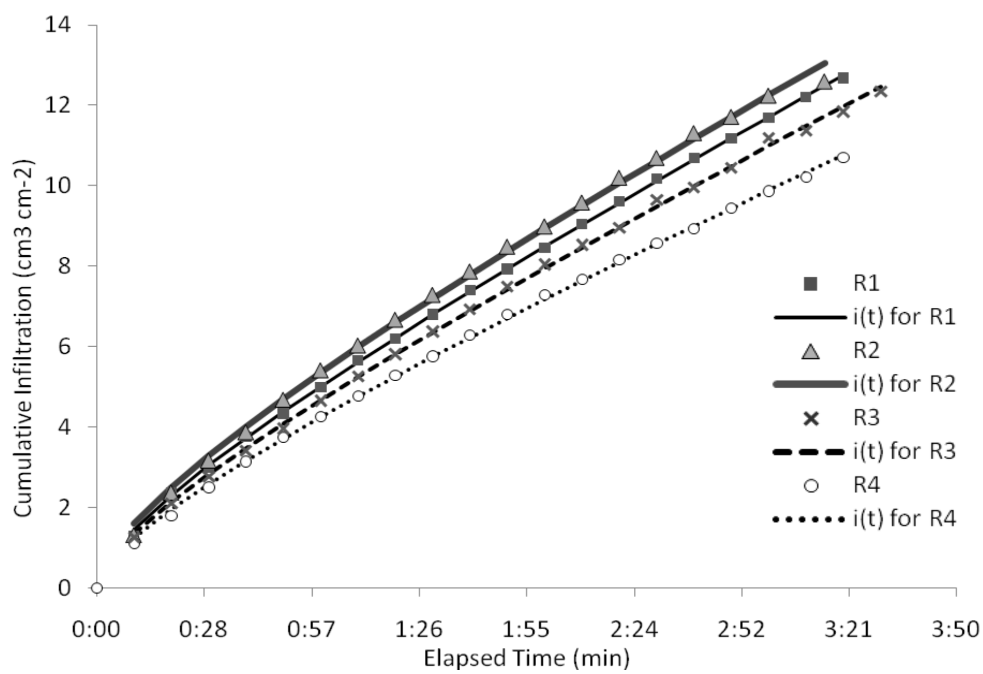

Figure B3(d). Cumulative infiltration versus time for all silt loam replicates treated with ADVANTAGE Formula One.

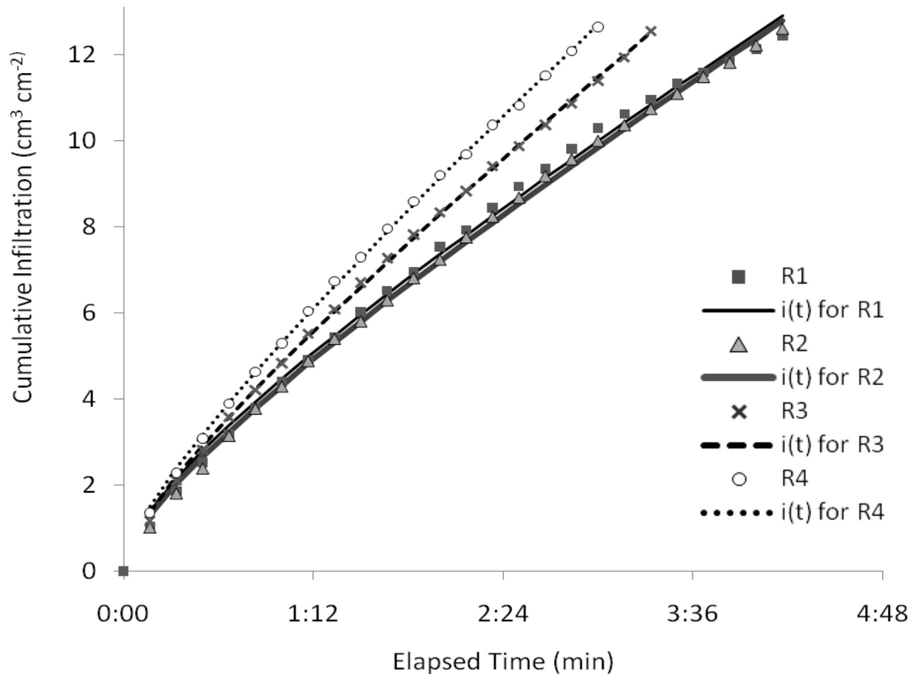

Figure B3(e). Cumulative infiltration versus time for all silt loam replicates under the control treatment.

Data curves for the Unsaturated Hydraulic Conductivity Test in Sand

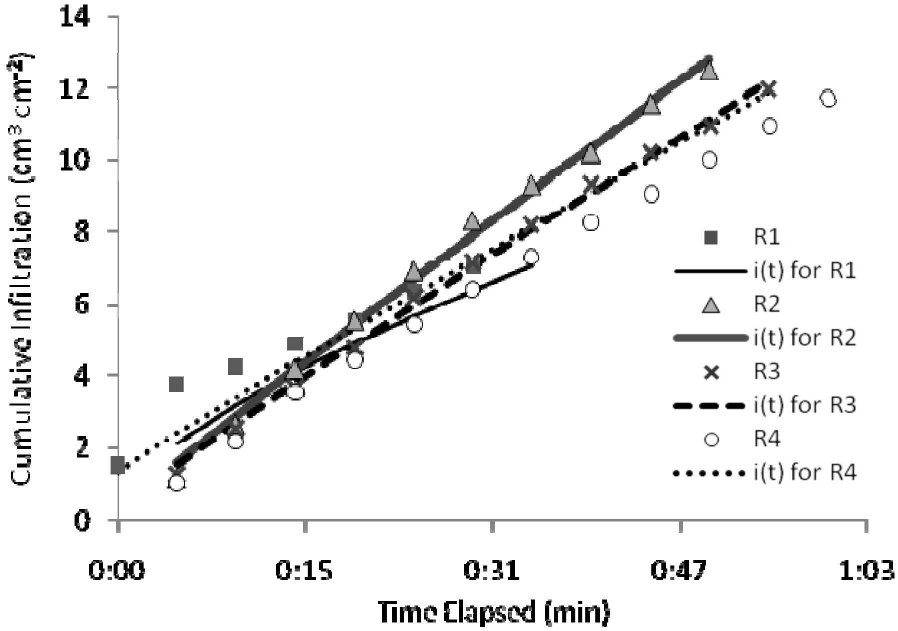

Figure B4(a). Cumulative infiltration versus time for all sand replicates treated with Wet-Sol #233.

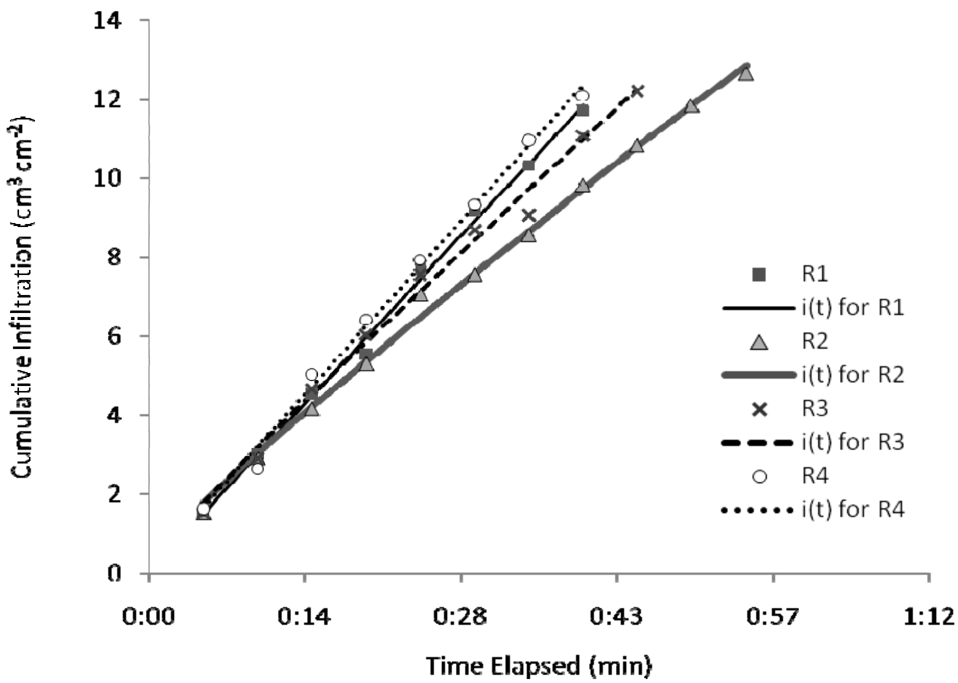

Figure B4(b). Cumulative infiltration versus time for all sand replicates treated with WaterMaxx II.

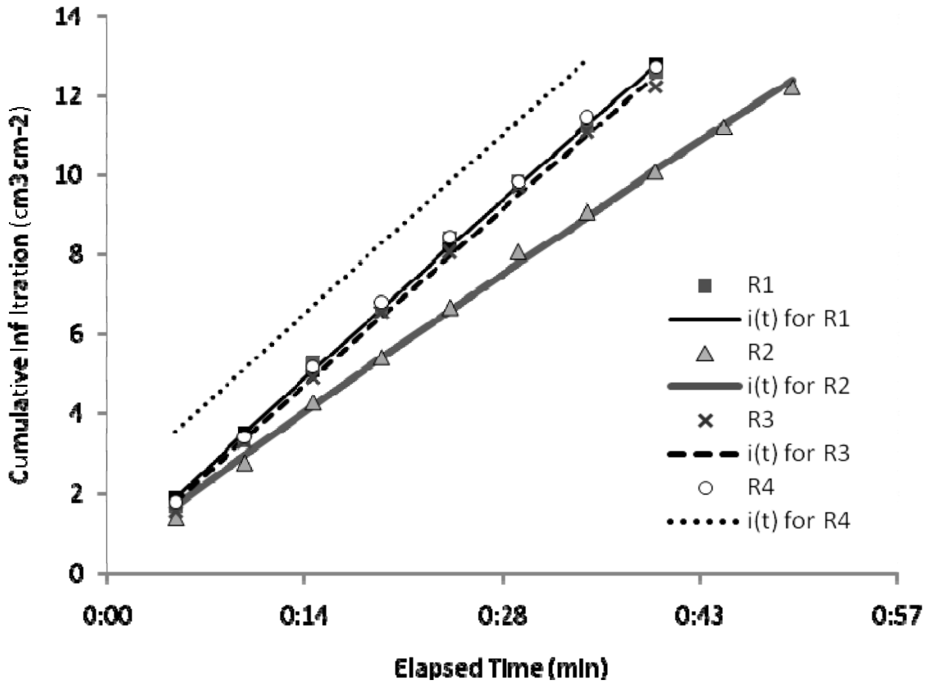

Figure B4(c). Cumulative infiltration versus time for all sand replicates treated with Ad-Sorb RST.

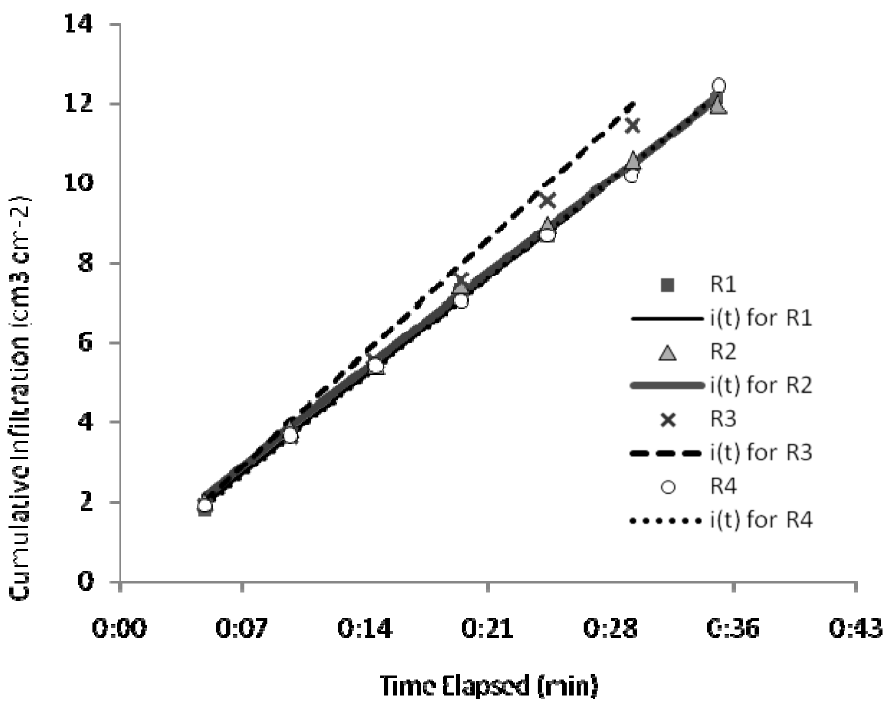

Figure B4(d). Cumulative infiltration versus time for all sand replicates treated with ADVANTAGE Formula One.

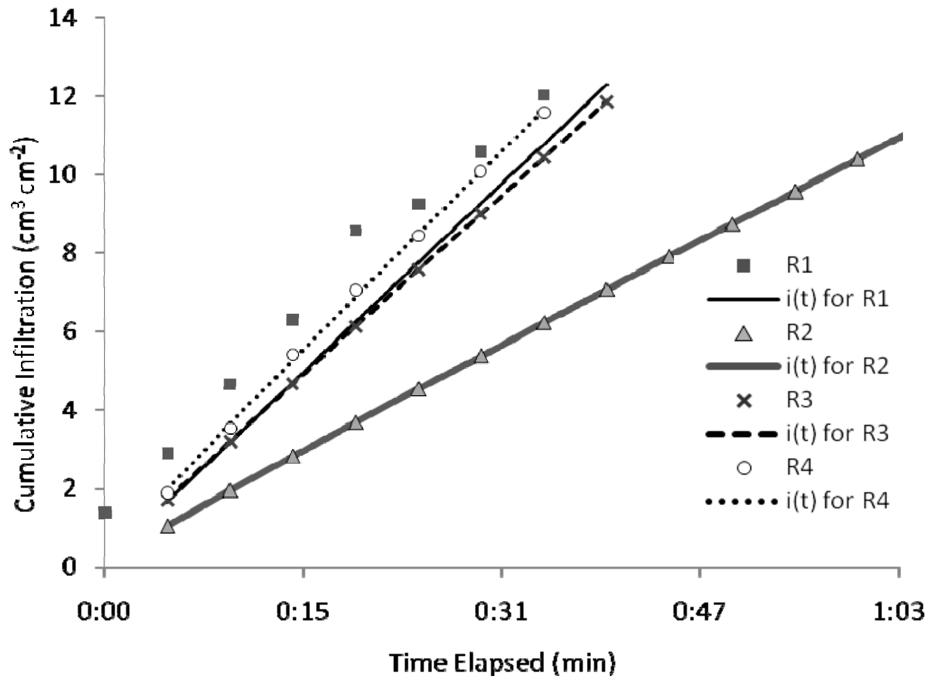

Figure B4(e). Cumulative infiltration versus time for all sand replicates under the control treatment.

Data Curves for Capillary Rise Test in Silt Loam

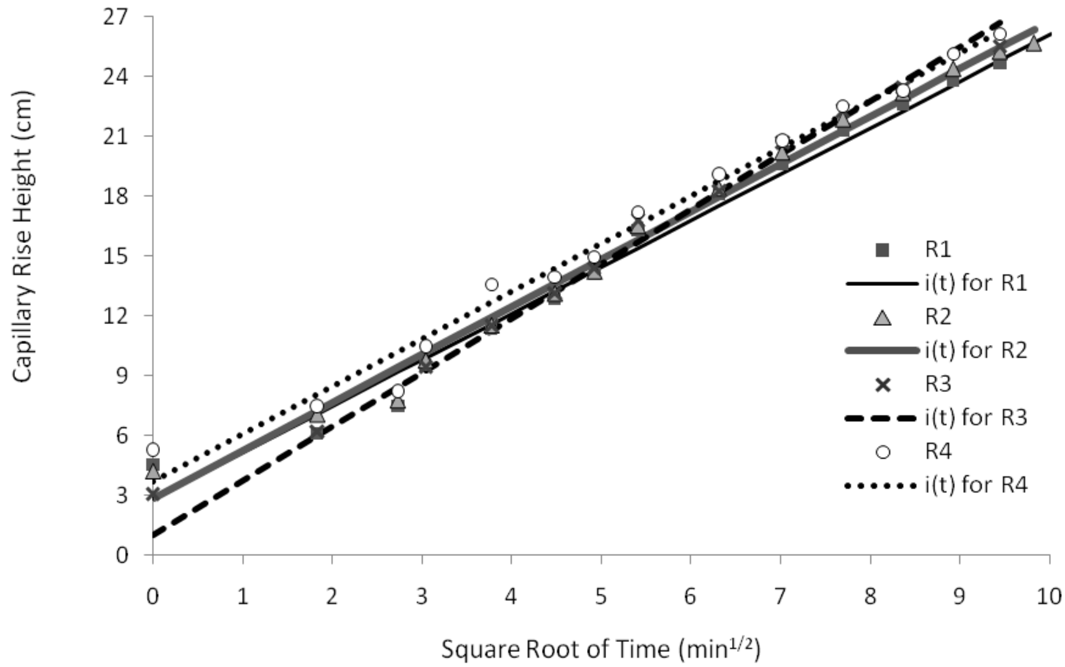

Figure B5(a). The vertical rise in the wetting front versus the square root of time for all silt loam replicates treated with Wet-Sol #233.

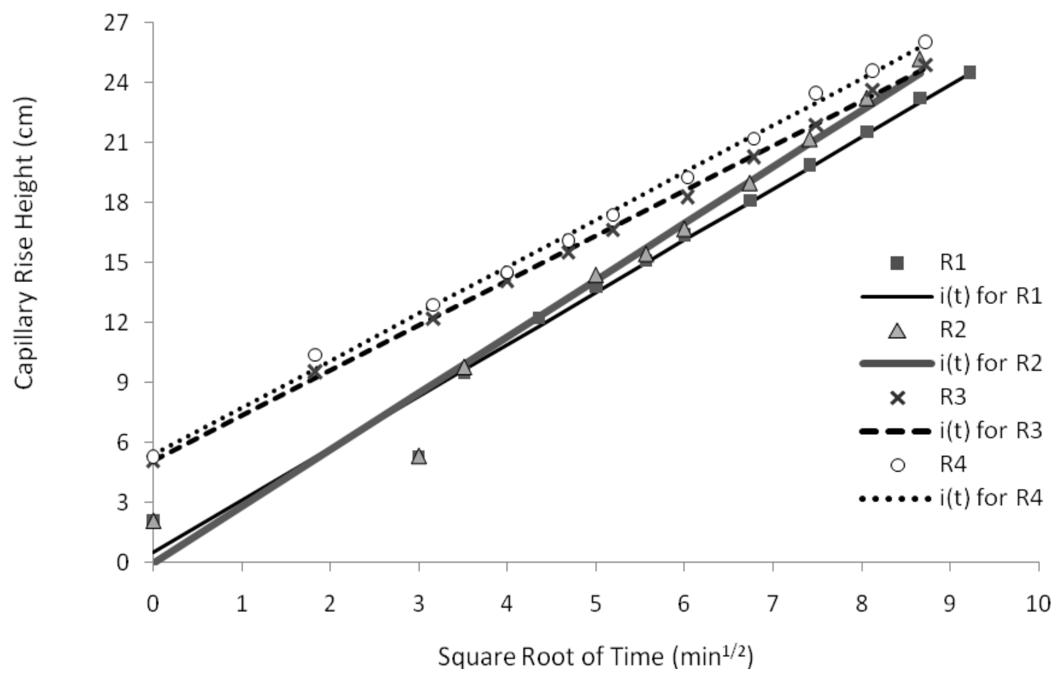

Figure B5(b). The vertical rise in the wetting front versus the square root of time for all silt loam replicates treated with WaterMaxx II.

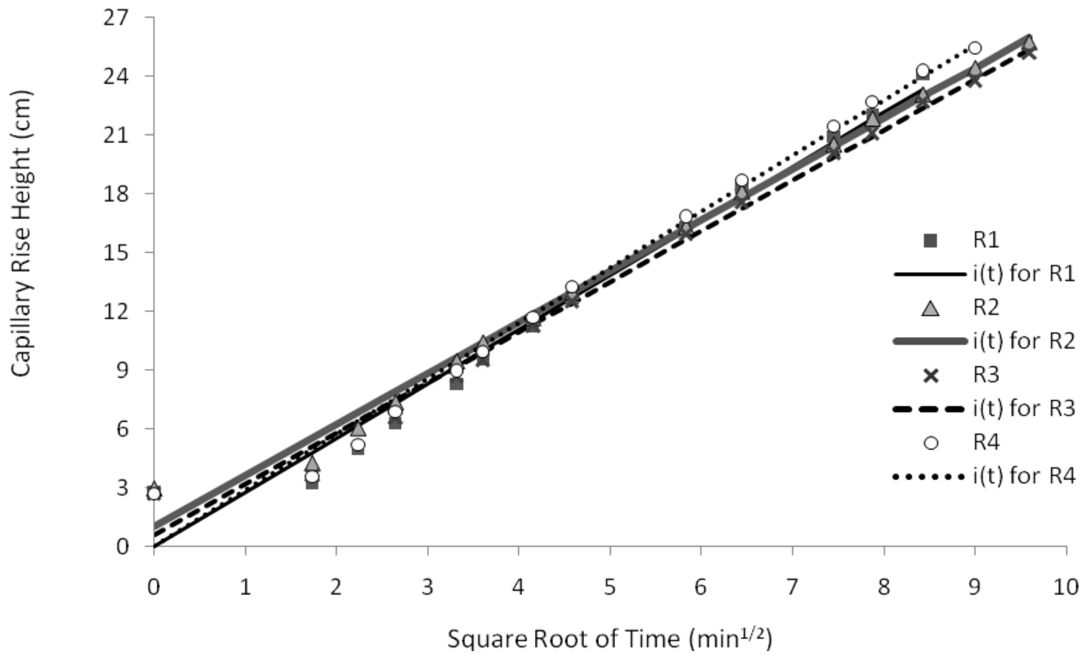

Figure B5(c). The vertical rise in the wetting front versus the square root of time for all silt loam replicates treated with Ad-Sorb RST.

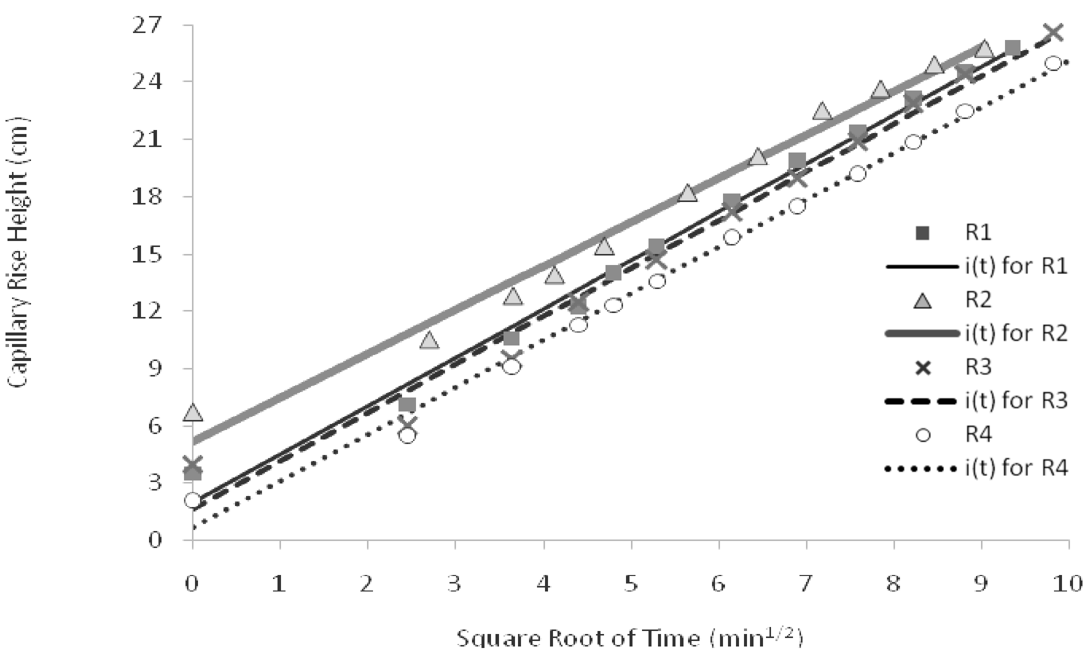

Figure B5(d). The vertical rise in the wetting front versus the square root of time for all silt loam replicates treated with ADVANTAGE Formula One.

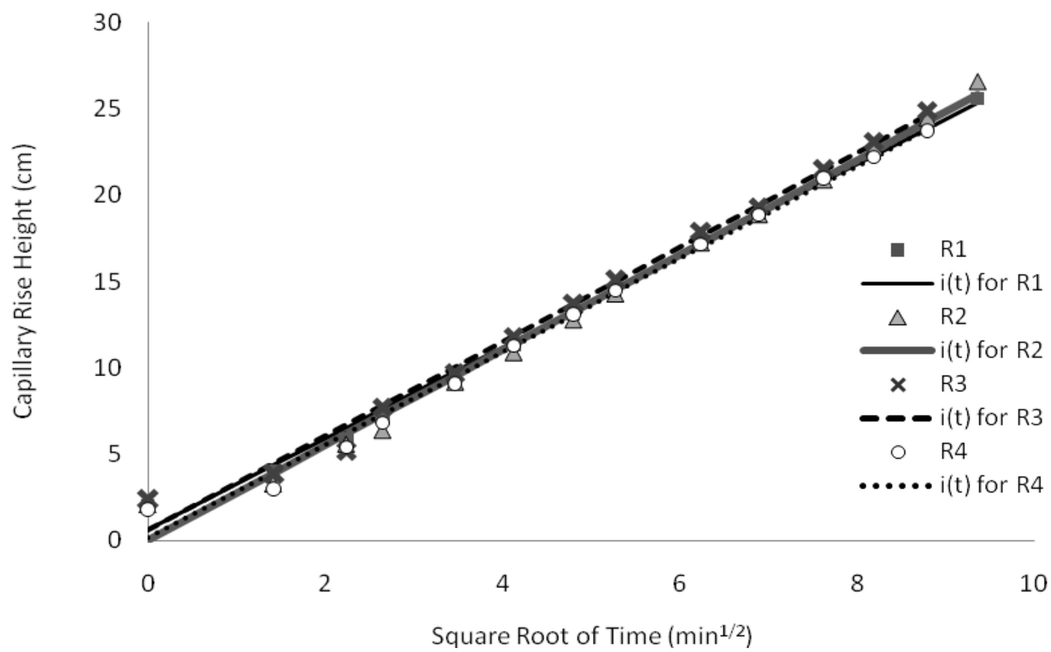

Figure B5(e). The vertical rise in the wetting front versus the square root of time for all silt loam replicates under the control treatment.

Data Curves for Capillary Rise Test in Sand

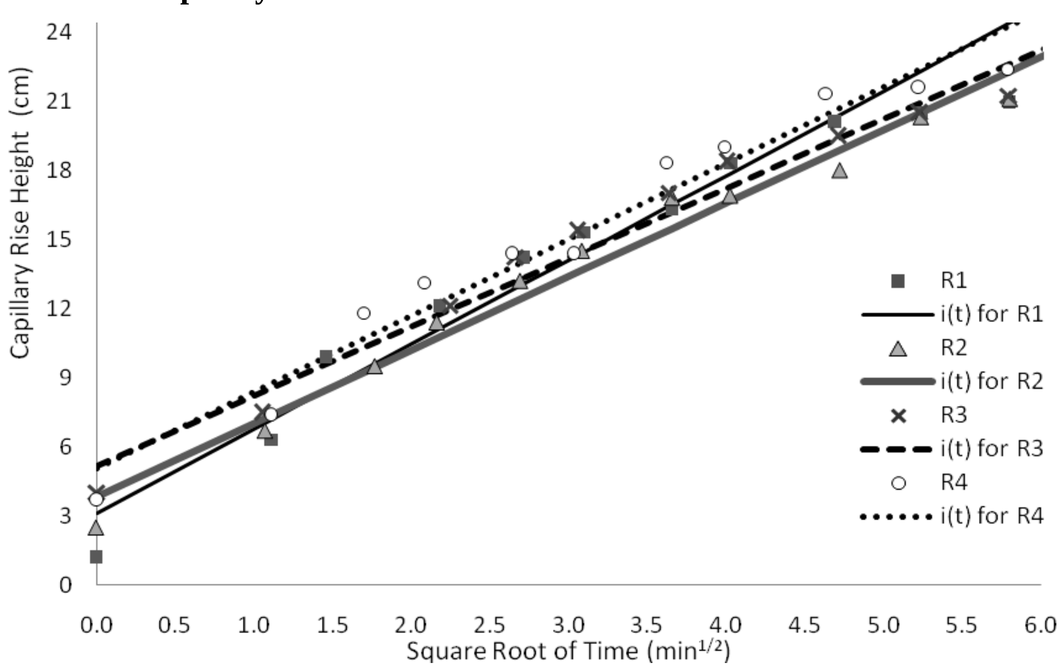

Figure B6(a). The vertical rise in the wetting front versus the square root of time for all sand replicates treated with Wet-Sol #233.

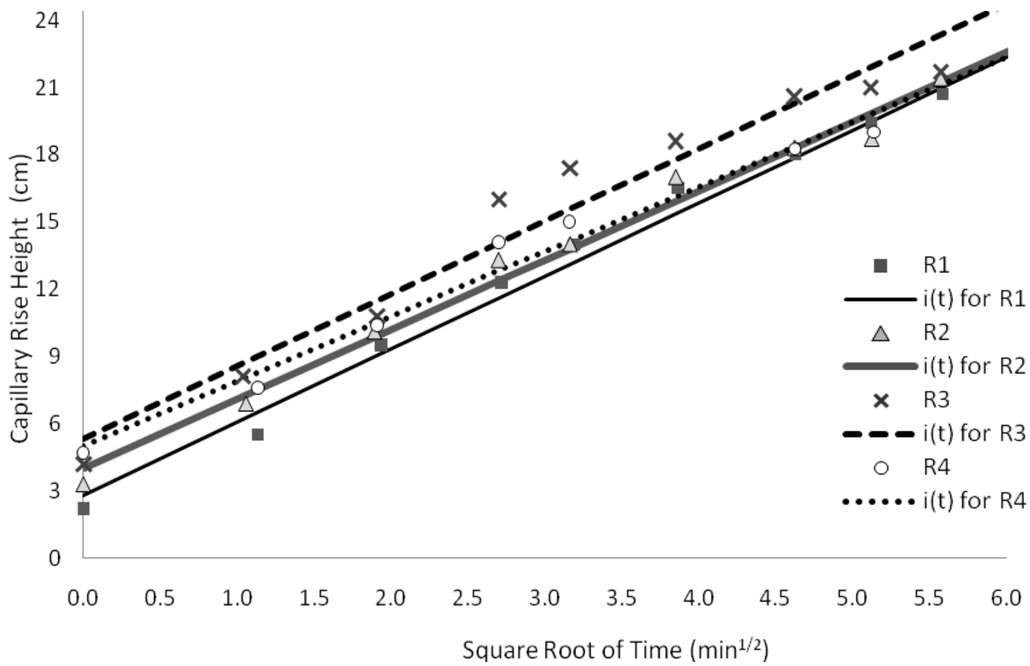

Figure B6(b). The vertical rise in the wetting front versus the square root of time for all sand replicates treated with WaterMaxx II.

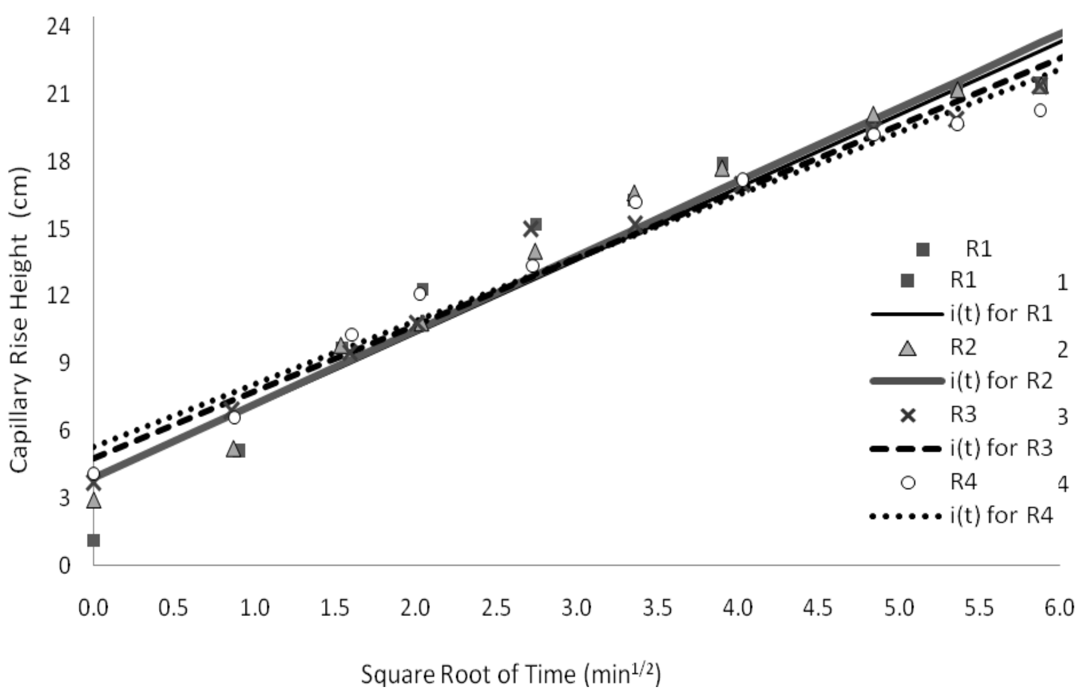

Figure B6(c). The vertical rise in the wetting front versus the square root of time for all sand replicates treated with Ad-Sorb RST.

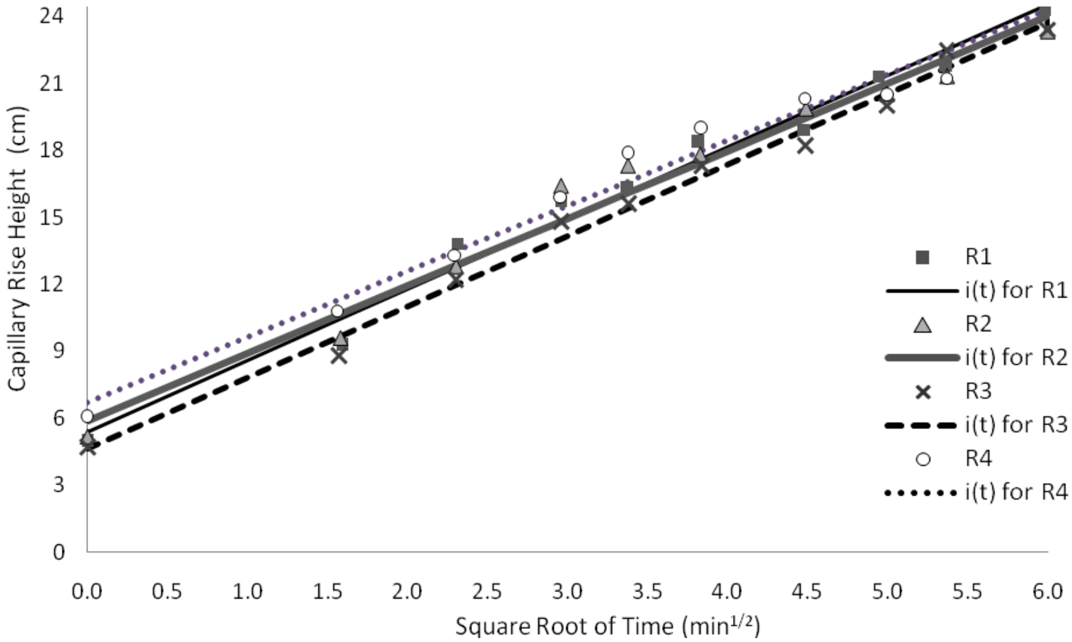

Figure B6(d). The vertical rise in the wetting front versus the square root of time for all sand replicates treated with ADVANTAGE Formula One.

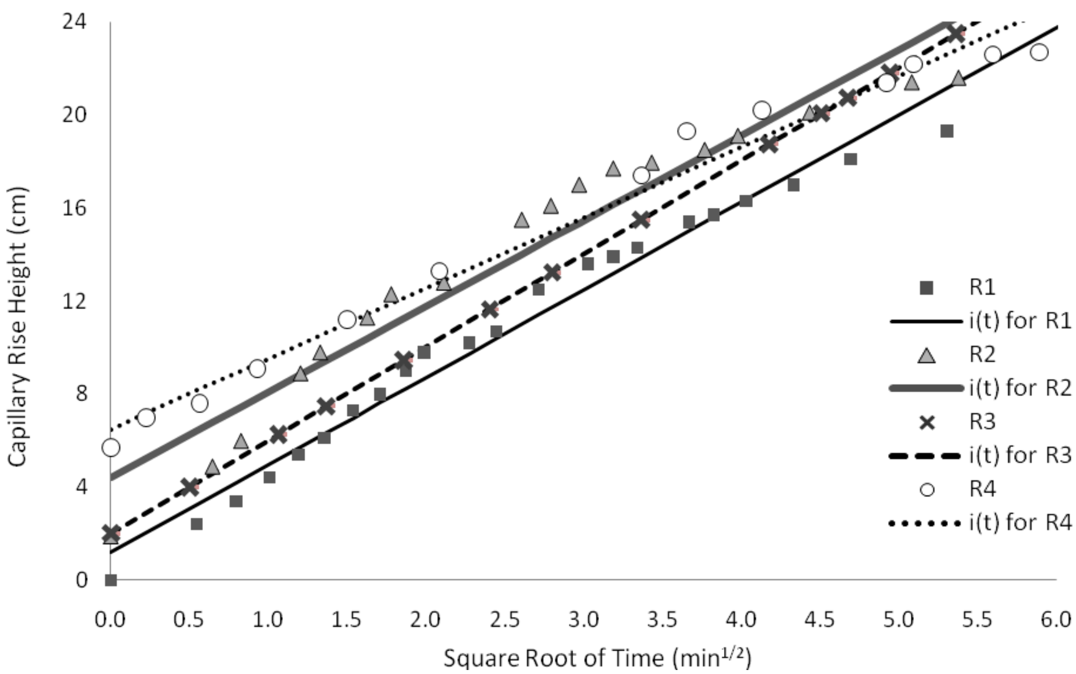

Figure B5(e). The vertical rise in the wetting front versus the square root of time for all sand replicates under the control treatment.

APPENDIX C: SAS FILES

SAS Input

The following is just one of the SAS input program files used to perform the ANOVA, which can be taken as an example of all the input files. (Note that line numbers were added for the reader's convenience and are not part of the program.) In other files, the treatment variables (the last three data cards listed on line 5) associated with each particular test replaced the treatment variables of *bk*, *x* (representing the exponent $b-1$), and f_o shown below in lines 7 through 26. Similarly, "Silt" was used as the Soil card in some input files, while "Sand" was used in others. All the data cards can be seen in the SAS output files (next chapter of Appendix C).

The treatment variable named on line 33 ("*x*" in the example below) was the variable analyzed in the SAS run. The program was run separately for each treatment variable of interest.

SAS Input Program for Infiltration Rate Experiment in Silt Loam Columns

```
 1  options pageno = 1;
 2  title "Surfactant Infiltration Rate ANOVA for Silt
 3  Loam";
 4  data flow;
 5  input Soil $ Treatment $  Replicate  bk  x  fo;
 6  cards;
 7  Silt  WetSol      1  10.5563  -1.38214  0.0638
 8  Silt  WetSol      2   0.9418  -0.60312  0.0156
 9  Silt  WetSol      3   0.9577  -0.64037  0.0179
10  Silt  WetSol      4   0.4078  -0.4050   0
11  Silt  WaterMaxx   1   0.6138  -0.41707  0
12  Silt  WaterMaxx   2   0.5374  -0.42347  0
13  Silt  WaterMaxx   3   0.8233  -0.70630  0.0361
14  Silt  WaterMaxx   4   0.6825  -0.47244  0
15  Silt  AdSorb      1   1.1504  -0.69155  0.0325
16  Silt  AdSorb      2   0.9253  -0.52750  0
17  Silt  AdSorb      3   0.5877  -0.39830  0
18  Silt  AdSorb      4   8.4456  -1.42860  0.0539
19  Silt  FormulaOne  1   1.3751  -0.77852  0.0359
20  Silt  FormulaOne  2   0.8211  -0.49890  0
21  Silt  FormulaOne  3   0.7742  -0.57672  0.022
22  Silt  FormulaOne  4   0.6762  -0.47522  0
```

```
Silt  Control     1   0.6207  -0.47060  0
Silt  Control     2   0.3375  -0.33560  0
Silt  Control     3   0.8601  -0.52204  0
Silt  Control     4   0.7277  -0.53634  0
;
run;
proc print data = flow;
run;
proc glm data = flow;
  class Treatment;
  model x = Treatment;
  lsmeans Treatment / pdiff stderr;
  output out = diagn p = predicted r = residuals;
run;
proc univariate data = diagn normal;
  var residuals;
run;
proc plot data = diagn;
  plot residuals*predicted;
run;
```

SAS Ouput Responses

Below are shortened versions of the output files that SAS generated in response to ANOVA for most of the treatment variables listed in Table 2. The sections showing the behavior of residuals are not included.

SAS Response for Infiltration Rate Variable "*x*" (i.e. "*b*–1") in Silt Loam Columns

```
                Surfactant Infiltration Rate ANOVA for Silt Loam
1                                                  18:18 Tuesday, January 12, 2010

Obs    Soil    Treatment    Replicate       a           x          Fo

1    Silt    WetSol          1        10.5563    -1.38214    0.0638
2    Silt    WetSol          2         0.9418    -0.60312    0.0156
3    Silt    WetSol          3         0.9577    -0.64037    0.0179
4    Silt    WetSol          4         0.4078    -0.40500    0.0000
5    Silt    WaterMax        1         0.6138    -0.41707    0.0000
6    Silt    WaterMax        2         0.5374    -0.42347    0.0000
7    Silt    WaterMax        3         0.8233    -0.70630    0.0361
8    Silt    WaterMax        4         0.6825    -0.47244    0.0000
9    Silt    AdSorb          1         1.1504    -0.69155    0.0325
10    Silt    AdSorb          2         0.9253    -0.52750    0.000
11    Silt    AdSorb          3         0.5877    -0.39830    0.0000
12    Silt    AdSorb          4         8.4456    -1.42860    0.0539
13    Silt    FormulaO        1         1.3751    -0.77852    0.0359
14    Silt    FormulaO        2         0.8211    -0.49890    0.0000
15    Silt    FormulaO        3         0.7742    -0.57672    0.0220
16    Silt    FormulaO        4         0.6762    -0.47522    0.0000
17    Silt    Control         1         0.6207    -0.47060    0.0000
18    Silt    Control         2         0.3375    -0.33560    0.0000
19    Silt    Control         3         0.8601    -0.52204    0.0000
20    Silt    Control         4         0.7277    -0.53634    0.0000

                Surfactant Infiltration Rate ANOVA for Silt Loam
2
                                 GLM Procedure
                            Class Level Information

Class          Levels    Values
Treatment           5    AdSorb Control FormulaO WaterMax WetSol

Number of Observations Read          20
Number of Observations Used          20
```

Surfactant Infiltration Rate ANOVA for Silt Loam

3

The GLM Procedure

Dependent Variable: x

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.30869027	0.07717257	0.87	0.5031
Error	15	1.32659863	0.08843991		
Corrected Total	19	1.63528891			

R-Square	Coeff Var	Root MSE	x Mean
0.188768	-48.39598	0.297388	-0.614490

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Treatment	4	0.30869027	0.07717257	0.87	0.5031

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	4	0.30869027	0.07717257	0.87	0.5031

Surfactant Infiltration Rate ANOVA for Silt Loam

4

The GLM Procedure

Least Squares Means

Treatment	x LSMEAN	Standard Error	Pr > |t|	Number
AdSorb	-0.76148750	0.14869424	0.0001	1
Control	-0.46614500	0.14869424	0.0068	2
FormulaO	-0.58234000	0.14869424	0.0014	3
WaterMax	-0.50482000	0.14869424	0.0040	4
WetSol	-0.75765750	0.14869424	0.0001	5

Least Squares Means for effect Treatment

Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: x

i/j	1	2	3	4	5
1		0.1805	0.4077	0.2411	0.9857
2	0.1805		0.5887	0.8565	0.1859
3	0.4077	0.5887		0.7175	0.4175
4	0.2411	0.8565	0.7175		0.2479
5	0.9857	0.1859	0.4175	0.2479	

SAS Response for Infiltration Rate Parameter “*x*” (i.e. “*b*–1”) in Sand Columns

Surfactant Infiltration Rate ANOVA for Sand

1 18:18 Tuesday, January 12, 2010

Obs	Soil	Treatment	Rep	a	x	Fo
1	Sand	WetSol	1	2.21431	-0.78082	0.18232
2	Sand	WetSol	2	9.15177	-1.07688	0.00000
3	Sand	WetSol	3	4.41703	-1.55707	0.42538
4	Sand	WetSol	4	2.69217	-0.54015	0.00000
5	Sand	WaterMax	1	2.03289	-0.55037	0.10955
6	Sand	WaterMax	2	3.73548	-1.05880	0.39753
7	Sand	WaterMax	3	1.81909	-0.51938	0.02490
8	Sand	WaterMax	4	6.68404	-1.13511	0.20339
9	Sand	AdSorb	1	1.49490	-0.66048	0.19373
10	Sand	AdSorb	2	4.91296	-0.76660	0.00000
11	Sand	AdSorb	3	2.44141	-0.58348	0.00000
12	Sand	AdSorb	4	2.98072	-0.94488	0.30993
13	Sand	FormulaO	1	2.66573	-0.99506	0.24064
14	Sand	FormulaO	2	5.99476	-1.07128	0.24667
15	Sand	FormulaO	3	1.30597	-0.27266	0.00000
16	Sand	FormulaO	4	4.79277	-1.27367	0.29440
17	Sand	Control	1	6.66521	-1.74239	0.03664
18	Sand	Control	2	2.39316	-0.95281	0.24608
19	Sand	Control	3	6.81503	-1.35417	0.39907
20	Sand	Control	4	2.81129	-0.71051	0.21751

Surfactant Infiltration Rate ANOVA for Sand

2

The GLM Procedure

Class Level Information

Class	Levels	Values
Treatment	5	AdSorb Control FormulaO WaterMax WetSol

Number of Observations Read 20

Number of Observations Used 20

Surfactant Infiltration Rate ANOVA for Sand

3

The GLM Procedure

Dependent Variable: x

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.48507634	0.12126908	0.84	0.5194
Error	15	2.15784219	0.14385615		
Corrected Total	19	2.64291852			

R-Square	Coeff Var	Root MSE	x Mean
0.183538	-40.90065	0.379284	-0.927329

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Treatment	4	0.48507634	0.12126908	0.84	0.5194

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	4	0.48507634	0.12126908	0.84	0.5194

Surfactant Infiltration Rate ANOVA for Sand

4

The GLM Procedure

Least Squares Means

<table>
<tr><th>Treatment</th><th>x LSMEAN</th><th>Standard Error</th><th>Pr > |t|</th><th>Number</th></tr>
<tr><td>AdSorb</td><td>-0.73885907</td><td>0.18964186</td><td>0.0014</td><td>1</td></tr>
<tr><td>Control</td><td>-1.18997179</td><td>0.18964186</td><td><.0001</td><td>2</td></tr>
<tr><td>FormulaO</td><td>-0.90316881</td><td>0.18964186</td><td>0.0003</td><td>3</td></tr>
<tr><td>WaterMax</td><td>-0.81591549</td><td>0.18964186</td><td>0.0006</td><td>4</td></tr>
<tr><td>WetSol</td><td>-0.98873136</td><td>0.18964186</td><td>0.0001</td><td>5</td></tr>
</table>

Least Squares Means for effect Treatment

Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: x

i/j	1	2	3	4	5
1		0.1133	0.5493	0.7778	0.3663
2	0.1133		0.3018	0.1834	0.4646
3	0.5493	0.3018		0.7494	0.7541
4	0.7778	0.1834	0.7494		0.5291
5	0.3663	0.4646	0.7541	0.5291	

SAS Response for Volumetric Water Content in Silt Loam Columns

Surfactant Volumetric Water Content ANOVA for Silt Loam

1 16:35 Friday, April 16, 2010

Obs	Soil	Treatment	Replicate	Pb	Theta_m	Theta_v
1	Silt	WetSol	1	1424.69	0.27962	0.39909
2	Silt	WetSol	2	1438.75	0.26712	0.38500
3	Silt	WetSol	3	1455.15	0.24639	0.35918
4	Silt	WetSol	4	1478.59	0.23298	0.34509
5	Silt	WaterMax	1	1429.38	0.27707	0.39674
6	Silt	WaterMax	2	1427.03	0.27916	0.39909
7	Silt	WaterMax	3	1457.50	0.25725	0.37561
8	Silt	WaterMax	4	1417.66	0.28762	0.40848
9	Silt	AdSorb	1	1408.68	0.28194	0.39788
10	Silt	AdSorb	2	1422.35	0.28008	0.3990
11	Silt	AdSorb	3	1378.79	0.30576	0.42234
12	Silt	AdSorb	4	1457.50	0.24278	0.35448
13	Silt	FormulaO	1	1445.78	0.27392	0.39674
14	Silt	FormulaO	2	1431.72	0.28316	0.40613
15	Silt	FormulaO	3	1425.03	0.28198	0.40256
16	Silt	FormulaO	4	1441.09	0.27156	0.39205
17	Silt	Control	1	1450.47	0.26819	0.38970
18	Silt	Control	2	1420.00	0.29540	0.42022
19	Silt	Control	3	1391.88	0.32157	0.44839
20	Silt	Control	4	1408.29	0.30617	0.43195

Surfactant Volumetric Water Content ANOVA for Silt Loam

2

The GLM Procedure

Class Level Information

Class	Levels	Values
Treatment	5	AdSorb Control FormulaO WaterMax WetSol

Number of Observations Read 20

Number of Observations Used 20

Surfactant Volumetric Water Content ANOVA for Silt Loam

3

The GLM Procedure

Dependent Variable: Theta_v

Source	DF	Squares	Sum of Mean Square	F Value	Pr > F
Model	4	0.00517998	0.00129499	2.89	0.0589
Error	15	0.00672968	0.00044865		
Corrected Total	19	0.01190965			

R-Square	Coeff Var	Root MSE	Theta_v Mean
0.434939	5.342186	0.021181	0.396490

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Treatment	4	0.00517998	0.00129499	2.89	0.0589

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	4	0.00517998	0.00129499	2.89	0.0589

Surfactant Volumetric Water Content ANOVA for Silt Loam

4

The GLM Procedure

Least Squares Means

Treatment	Theta_v LSMEAN	Standard Error	LSMEAN Pr > |t|	Number
AdSorb	0.39344635	0.01059062	<.0001	1
Control	0.42256437	0.01059062	<.0001	2
FormulaO	0.39936864	0.01059062	<.0001	3
WaterMax	0.39498031	0.01059062	<.0001	4
WetSol	0.37209140	0.01059062	<.0001	5

Least Squares Means for effect Treatment

Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: Theta_v

i/j	1	2	3	4	5
1		0.0709	0.6981	0.9198	0.1744
2	0.0709		0.1423	0.0854	0.0042
3	0.6981	0.1423		0.7735	0.0886
4	0.9198	0.0854	0.7735		0.1473
5	0.1744	0.0042	0.0886	0.1473	

SAS Response for Volumetric Water Content in Sand Columns

Surfactant Water Holding Capacity ANOVA for Sand

1

16:32 Friday, April 16, 2010

Obs	Soil	Treatment	Replicate	Pb	Theta_m	Theta_v
1	Sand	WetSol	1	1689.49	0.14564	0.24650
2	Sand	WetSol	2	1677.78	0.15364	0.25823
3	Sand	WetSol	3	1687.15	0.15279	0.25823
4	Sand	WetSol	4	1675.43	0.16225	0.27232
5	Sand	WaterMax	1	1691.84	0.13990	0.23711
6	Sand	WaterMax	2	1677.78	0.14666	0.24650
7	Sand	WaterMax	3	1689.49	0.14148	0.23945
8	Sand	WaterMax	4	1682.46	0.15043	0.25354
9	Sand	AdSorb	1	1700.71	0.14149	0.24107
10	Sand	AdSorb	2	1672.27	0.15182	0.25434
11	Sand	AdSorb	3	1672.27	0.15182	0.25434
12	Sand	AdSorb	4	1675.43	0.16225	0.27232
13	Sand	FormulaO	1	1688.57	0.14621	0.24734
14	Sand	FormulaO	2	1661.37	0.16503	0.27467
15	Sand	FormulaO	3	1677.78	0.15923	0.26762
16	Sand	FormulaO	4	1677.78	0.16062	0.26997
17	Sand	Control	1	1696.52	0.14642	0.24884
18	Sand	Control	2	1684.81	0.16134	0.27232
19	Sand	Control	3	1675.43	0.16085	0.26997
20	Sand	Control	4	1669.94	0.15761	0.26367

Surfactant Water Holding Capacity ANOVA for Sand

2

16:32 Friday, April 16, 2010

The GLM Procedure

Class Level Information

Class	Levels	Values
Treatment	5	AdSorb Control FormulaO WaterMax WetSol

Number of Observations Read 20

Number of Observations Used 20

Surfactant Water Holding Capacity ANOVA for Sand

3

16:32 Friday, April 16, 2010

The GLM Procedure

Dependent Variable: Theta_v

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.00110848	0.00027712	2.35	0.1007
Error	15	0.00176549	0.00011770		
Corrected Total	19	0.00287396			

R-Square	Coeff Var	Root MSE	Theta_v Mean
0.385696	4.214537	0.010849	0.257417

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Treatment	4	0.00110848	0.00027712	2.35	0.1007

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	4	0.00110848	0.00027712	2.35	0.1007

Surfactant Water Holding Capacity ANOVA for Sand

4

The GLM Procedure

Least Squares Means

Treatment	Theta_v LSMEAN	Standard Error	Pr > |t|	Number
AdSorb	0.25551375	0.00542446	<.0001	1
Control	0.26370075	0.00542446	<.0001	2
FormulaO	0.26489950	0.00542446	<.0001	3
WaterMax	0.24414850	0.00542446	<.0001	4
WetSol	0.25882075	0.00542446	<.0001	5

Least Squares Means for effect Treatment

Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: Theta_v

i/j	1	2	3	4	5
1		0.3027	0.2400	0.1592	0.6725
2	0.3027		0.8779	0.0223	0.5343
3	0.2400	0.8779		0.0163	0.4405
4	0.1592	0.0223	0.0163		0.0751
5	0.6725	0.5343	0.4405	0.0751	

SAS Response for C_2 of Unsaturated Hydraulic Conductivity Test in Silt Loam Columns

Surfactant Unsaturated Hydraulic Conductivity ANOVA for Silt Loam
1
16:54 Monday, March 22, 2010

Obs	Soil	Treatment	Replicate	C2
1	Silt	WetSol	1	0.018025
2	Silt	WetSol	2	0.030281
3	Silt	WetSol	3	0.035418
4	Silt	WetSol	4	0.027226
5	Silt	WaterMax	1	0.021444
6	Silt	WaterMax	2	0.020242
7	Silt	WaterMax	3	0.039510
8	Silt	WaterMax	4	0.022258
9	Silt	AdSorb	1	0.036845
10	Silt	AdSorb	2	0.028893
11	Silt	AdSorb	3	0.041385
12	Silt	AdSorb	4	0.034402
13	Silt	FormulaO	1	0.039848
14	Silt	FormulaO	2	0.039082
15	Silt	FormulaO	3	0.038045
16	Silt	FormulaO	4	0.033222
17	Silt	Control	1	0.029553
18	Silt	Control	2	0.031227
19	Silt	Control	3	0.040484
20	Silt	Control	4	0.046118

Surfactant Unsaturated Hydraulic Conductivity ANOVA for Silt Loam
2
The GLM Procedure
Class Level Information

Class	Levels	Values
Treatment	5	AdSorb Control FormulaO WaterMax WetSol

Number of Observations Read 20
Number of Observations Used 20

Surfactant Unsaturated Hydraulic Conductivity ANOVA for Silt Loam
3
The GLM Procedure
Dependent Variable: C2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.00047700	0.00011925	2.55	0.0827
Error	15	0.00070224	0.00004682		
Corrected Total	19	0.00117924			

R-Square	Coeff Var	Root MSE	C2 Mean
0.404498	20.94006	0.006842	0.032675

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Treatment	4	0.00047700	0.00011925	2.55	0.0827

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	4	0.00047700	0.00011925	2.55	0.0827

Surfactant Unsaturated Hydraulic Conductivity ANOVA for Silt Loam
4

The GLM Procedure
Least Squares Means

Treatment	C2 LSMEAN	Standard Error	Pr > |t|	Number
AdSorb	0.03538122	0.00342111	<.0001	1
Control	0.03684550	0.00342111	<.0001	2
FormulaO	0.03754901	0.00342111	<.0001	3
WaterMax	0.02586342	0.00342111	<.0001	4
WetSol	0.02773739	0.00342111	<.0001	5

Least Squares Means for effect Treatment
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: C2

i/j	1	2	3	4	5
1		0.7663	0.6605	0.0679	0.1350
2	0.7663		0.8863	0.0384	0.0793
3	0.6605	0.8863		0.0289	0.0607
4	0.0679	0.0384	0.0289		0.7040
5	0.1350	0.0793	0.0607	0.7040	

SAS Response for C_2 of Unsaturated Hydraulic Conductivity Test in Sand Columns

Surfactant Unsaturated Hydraulic Conductivity ANOVA for Sand

1

17:01 Monday, March 22, 2010

Obs	Soil	Treatment	Replicate	C2
1	Sand	WetSol	1	0.06765
2	Sand	WetSol	2	0.23038
3	Sand	WetSol	3	0.18848
4	Sand	WetSol	4	0.17064
5	Sand	WaterMax	1	0.29214
6	Sand	WaterMax	2	0.18211
7	Sand	WaterMax	3	0.23087
8	Sand	WaterMax	4	0.29815
9	Sand	AdSorb	1	0.29017
10	Sand	AdSorb	2	0.21021
11	Sand	AdSorb	3	0.29181
12	Sand	AdSorb	4	0.29270
13	Sand	FormulaO	1	0.32278
14	Sand	FormulaO	2	0.30182
15	Sand	FormulaO	3	0.39916
16	Sand	FormulaO	4	0.33400
17	Sand	Control	1	0.29639
18	Sand	Control	2	0.15799
19	Sand	Control	3	0.27217
20	Sand	Control	4	0.29530

Surfactant Unsaturated Hydraulic Conductivity ANOVA for Sand

2

17:01 Monday, March 22, 2010

The GLM Procedure

Class Level Information

Class	Levels	Values
Treatment	5	AdSorb Control FormulaO WaterMax WetSol

Number of Observations Read	20
Number of Observations Used	20

Surfactant Unsaturated Hydraulic Conductivity ANOVA for Sand

3

17:01 Monday, March 22, 2010

The GLM Procedure

Dependent Variable: C2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.06253062	0.01563265	5.02	0.0090
Error	15	0.04669785	0.00311319		
Corrected Total	19	0.10922847			

R-Square	Coeff Var	Root MSE	C2 Mean
0.572475	21.77437	0.055796	0.256246

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Treatment	4	0.06253062	0.01563265	5.02	0.0090

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	4	0.06253062	0.01563265	5.02	0.0090

Surfactant Unsaturated Hydraulic Conductivity ANOVA for Sand
4
17:01 Monday, March 22, 2010

The GLM Procedure
Least Squares Means

Treatment	C2 LSMEAN	Standard Error	Pr > |t|	Number
AdSorb	0.27122282	0.02789798	<.0001	1
Control	0.25546090	0.02789798	<.0001	2
FormulaO	0.33944302	0.02789798	<.0001	3
WaterMax	0.25081675	0.02789798	<.0001	4
WetSol	0.16428670	0.02789798	<.0001	5

Least Squares Means for effect Treatment
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: C2

i/j	1	2	3	4	5
1		0.6952	0.1043	0.6125	0.0161
2	0.6952		0.0503	0.9079	0.0355
3	0.1043	0.0503		0.0402	0.0005
4	0.6125	0.9079	0.0402		0.0445
5	0.0161	0.0355	0.0005	0.0445	

SAS Response for Capillary Rise Test Parameter "*a*" in Silt Loam Columns

Surfactant Capillary Rise ANOVA for Silt Loam

1

15:36 Friday, January 29, 2010

Obs	Soil	Treatment	Replicate	a
1	Silt	WetSol	1	2.32477
2	Silt	WetSol	2	2.38822
3	Silt	WetSol	3	2.71908
4	Silt	WetSol	4	2.38510
5	Silt	WaterMax	1	2.59790
6	Silt	WaterMax	2	2.82584
7	Silt	WaterMax	3	2.24838
8	Silt	WaterMax	4	2.35069
9	Silt	AdSorb	1	2.77017
10	Silt	AdSorb	2	2.59651
11	Silt	AdSorb	3	2.57750
12	Silt	AdSorb	4	2.83997
13	Silt	FormulaO	1	2.54244
14	Silt	FormulaO	2	2.29471
15	Silt	FormulaO	3	2.52008
16	Silt	FormulaO	4	2.44336
17	Silt	Control	1	2.64729
18	Silt	Control	2	2.75778
19	Silt	Control	3	2.73340
20	Silt	Control	4	2.69603

Surfactant Capillary Rise ANOVA for Silt Loam

2

The GLM Procedure

Class Level Information

Class	Levels	Values
Treatment	5	AdSorb Control FormulaO WaterMax WetSol

Number of Observations Read	20
Number of Observations Used	20

Surfactant Capillary Rise ANOVA for Silt Loam

3

The GLM Procedure

Dependent Variable: a

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.26696429	0.06674107	2.55	0.0821
Error	15	0.39200851	0.02613390		
Corrected Total	19	0.65897280			

SAS Response for Capillary Rise Test Parameter "*a*" in Sand Columns

```
                    Surfactant Capillary Rise ANOVA for Sand
1
                                                    15:47 Friday, January 29, 2010

                         Obs    Soil    Treatment    Replicate       a

1    Sand    WetSol          1        3.66291
2    Sand    WetSol          2        3.18530
3    Sand    WetSol          3        3.00544
4    Sand    WetSol          4        3.31113
5    Sand    WaterMax        1        3.25376
6    Sand    WaterMax        2        3.09388
7    Sand    WaterMax        3        3.23631
8    Sand    WaterMax        4        2.89249
9    Sand    AdSorb          1        3.25120
10    Sand    AdSorb          2        3.30239
11    Sand    AdSorb          3        2.97466
12    Sand    AdSorb          4        2.80841
13    Sand    FormulaO        1        3.18519
14    Sand    FormulaO        2        3.02116
15    Sand    FormulaO        3        3.17699
16    Sand    FormulaO        4        2.92862
17    Sand    Control         1        3.76350
18    Sand    Control         2        3.68111
19    Sand    Control         3        4.00447
20    Sand    Control         4        3.03684

                              Surfactant Capillary Rise ANOVA for Sand
2

                                The GLM Procedure
                             Class Level Information

Class          Levels    Values
Treatment           5    AdSorb Control FormulaO WaterMax WetSol

                   Number of Observations Read          20
                   Number of Observations Used          20

                   Surfactant Capillary Rise ANOVA for Sand
3
                                The GLM Procedure

                             Dependent Variable: a

                                                   Sum of
Source          DF         Squares     Mean Square    F Value    Pr > F
 Model           4      0.85315261      0.21328815       3.08    0.0487
Error           15      1.03789405      0.06919294
Corrected Total 19      1.89104666

              R-Square     Coeff Var      Root MSE        a Mean
              0.451154      8.121727      0.263046      3.238788

Source         DF       Type I SS     Mean Square    F Value    Pr > F
```

Treatment	4	0.85315261	0.21328815	3.08	0.0487

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	4	0.85315261	0.21328815	3.08	0.0487

Surfactant Capillary Rise ANOVA for Sand

4

The GLM Procedure

Least Squares Means

Treatment	a LSMEAN	Standard Error	Pr > |t|	Number
AdSorb	3.08416423	0.13152275	<.0001	1
Control	3.62148120	0.13152275	<.0001	2
FormulaO	3.07798941	0.13152275	<.0001	3
WaterMax	3.11910983	0.13152275	<.0001	4
WetSol	3.29119510	0.13152275	<.0001	5

Least Squares Means for effect Treatment

Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: a

i/j	1	2	3	4	5
1		0.0112	0.9740	0.8535	0.2832
2	0.0112		0.0105	0.0164	0.0961
3	0.9740	0.0105		0.8280	0.2696
4	0.8535	0.0164	0.8280		0.3695
5	0.2832	0.0961	0.2696	0.3695	

R-Square	Coeff Var	Root MSE	a Mean
0.405122	6.307543	0.161660	2.562960

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Treatment	4	0.26696429	0.06674107	2.55	0.0821

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	4	0.26696429	0.06674107	2.55	0.0821

Surfactant Capillary Rise ANOVA for Silt Loam

4

The GLM Procedure
Least Squares Means

Treatment	a LSMEAN	Standard Error	Pr > |t|	Number
AdSorb	2.69603523	0.08082992	<.0001	1
Control	2.70862460	0.08082992	<.0001	2
FormulaO	2.45014906	0.08082992	<.0001	3
WaterMax	2.50570405	0.08082992	<.0001	4
WetSol	2.45428927	0.08082992	<.0001	5

Least Squares Means for effect Treatment
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: a

i/j	1	2	3	4	5
1		0.9138	0.0482	0.1166	0.0516
2	0.9138		0.0390	0.0962	0.0419
3	0.0482	0.0390		0.6340	0.9716
4	0.1166	0.0962	0.6340		0.6593
5	0.0516	0.0419	0.9716	0.6593	