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Some benefits of treating a sandy soil with a cross-linked type polyacrylamide

S. Sivapalan

School of Agricultural and Veterinary Sciences, Charles Sturt University, Locked Bag 588, Wagga Wagga, NSW 2678, Australia.

Current address: School of Urban Development, Queensland University of Technology, GPO Box 2434, Brisbane QLD 4001, Australia, s.sivapalan@qut.edu.au

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Abstract. The productivity of sandy soils is mostly limited by their low water holding capacity and excessive deep percolation losses, which reduce the efficiency of water and fertiliser use, by plants. The effect of a cross-linked type polyacrylamide, ALCOSORB® 400, on water holding capacity of a sandy soil, Siliceous Sands, was studied under the laboratory and glasshouse conditions. Water holding capacity of the soil exposed to 0.01 MPa pressure increased by 23 and 95% by adding 0.03 and 0.07% of polyacrylamide to the soil, respectively. This indicated that the soil treated with polyacrylamide was able to store more water compared with untreated soil, thereby reducing the potential losses due to deep percolation in sandy soils. However, the soil treated with polyacrylamide did not significantly increase the quantity of water released from the soil by increasing the pressure from 0.01 to 1.5 MPa. The results from the first glasshouse experiment demonstrated that the excess amount of water stored in the soil by polyacrylamide was available to plants and resulted in their higher water use and grain production. Consequently, there were 12 and 18 times increase in water use efficiency of soybean plants grown in soils treated with 0.03 and 0.07% polyacrylamide, respectively. The results from the second glasshouse experiment demonstrated that the increasing amounts of polyacrylamides in a sandy soil can extend the irrigation interval without any adverse effect on the grain yield of soybeans.

Additional keywords: soil water holding capacity, plant water use efficiency, irrigation interval.

Introduction

Use of polyacrylamides as soil conditioner in many countries increased after the introduction of Krilium in 1951 (De Boodt 1972). Krilium is a trade name used by the Monsanto Chemical Company for a polymer formulated from vinyl acetate maleic acid and clay extenders (Nelson 1997). New generation polyacrylamides have high molecular weights and require low application rates. They also have important environment, soil conservation and irrigation efficiency benefits for general agriculture, making their use economically feasible (Sojka and Lentz 1994). The properties of different types of polyacrylamides have been described by Bouranis (1997). The effect of cross-linked polyacrylamides on physical and chemical properties of sandy soils has been described by Al-Omran and Al-Harbi (1997).

The use of cross-linked polyacrylamides has been tested to increase the water holding capacity of sandy soils (Stewart 1975; Taylor and Halfacre 1986; Silberbush *et al*. 1993). Polyacrylamides in soil were also able to reduce the amount of water lost from the soil through evaporation (Al-Omran and Al-Harbi 1997).

The productivity of sandy soils is mostly limited by their low water holding capacity and excessive deep percolation losses. Thus the management of these soils must aim at increasing their water holding capacity and reducing losses due to deep percolation. The water holding capacity of sandy soils can be improved with the addition of soil conditioners. Soil conditioners, primarily the cross-linked type polyacrylamides, can absorb water and swell up to many times of their dry weight.

Absorption of deionised water by polyacrylamides under laboratory conditions can vary between products in the range from 20-1000 per g. Johnson and Veltkamp (1985) observed that the maximum time required by the product with the slowest water absorption rate to reach equilibrium was 2 h. However, the expansion of polyacrylamides in soil can be limited by soil physical conditions and other factors. Johnson (1984*a*) reported that the water storage properties of these products were significantly affected by the nature and concentrations of dissolved salts in irrigation water.

Johnson and Veltkamp (1985) described that the storage of water by these high expansion polyacrylamides is affected in two ways. The greater proportion (80-85%) is stored within the vacuoles as numerous minute reservoirs and the remaining (15-20%) is bound with greater tenacity but is still available to plants. The polymer bridges provide a physical resistance to outflow of water from the gel. This structural barrier is probably responsible for reduced evaporation losses from soils treated with such polyacrylamides.

As irrigation water is becoming increasingly limited in south-eastern Australia, it is vital to improve the water use efficiency of crops grown under irrigated conditions in this region. The use of water retaining polyacrylamides in sandy soils has potential not only to improve crop production but also to minimise percolation and evaporation losses of irrigation water. However, the feasibility of treating sandy soils with water absorbing polyacrylamides to improve the water use efficiency of crops in general agriculture has not been adequately exploited in the past under Australian conditions. Therefore this study was undertaken to quantify some of the benefits that could be realised from this type of soil treatments using laboratory and glasshouse experiments.

Materials and methods

Polyacrylamide

A synthetic anionic acrylic copolymer (cross-linked type polyacrylamide) manufactured by the Allied Colloids Pty Ltd and marketed in Australia by the Ciba Specialty Chemicals Pty Ltd under the trade name of 'ALCOSORB® 400' was used in this study. It is a white granular powder with 90% active ingredient, 75-1000 µm particle size, 0.60 g/cm^3 bulk density and it swells to form a gel in water. The synthesis of cross-linked polyacrylamides has been described by Bouranis (1997).

Soil description

A sandy soil (Great soil group – Siliceous Sand, and Australian soil classification – Tenosol) containing 86% sand, 8% silt and 6% clay in the upper 27 cm layer with negligible amount of organic matter, obtained from Currawarna in NSW, was used in this study. Some selected physical and chemical properties of the soil are given in Table 1. The soil was air-dried, sieved through 2 mm sieve, and the soil fractions of less than 2 mm were used for further study.

(Table 1 about here)

Soil pretreatments used in experiments

Soil fractions of less than 2 mm were mixed with polyacrylamide at the rates of 0, 0.03, and 0.07 % by weight and the treated soils were used for the laboratory study and the glasshouse experiment 1. In the second glasshouse experiments, polyacrylamide at 5 rates (0, 0.05, 0.1, 0.2 and 0.3% by weight) was mixed with the sand.

Laboratory study. The objective of this study was to assess the water holding capacity of the soil treated with 3 rates (0, 0.03 and 0.07 % by weight) of polyacrylamide. The soil water holding capacity of treated soils was studied using a pressure plate apparatus at 0.01, 0.08, 0.2, 0.5 and 1.5 MPa pressures. The results from this laboratory study are reported here as the averages of 3 samples for each treatment at each pressure level.

Glasshouse experiment 1. The objective of this experiment was to assess the effect of polyacrylamide on grain yield and water use efficiency of soybeans. A pot experiment with soybean (*Glycine max*; cv Stephens) was conducted in the glasshouse at the Charles Sturt University, Wagga Wagga during the period from December 1999 to April 2000 using the above treated soils in a randomised complete block design with 3 replicates. Each pot (5 L) was filled with 4.5 kg of the treated soil to achieve a bulk density of 1.5 g/cm^3. Three seeds were planted in each pot and later thinned to 2 plants per pot to achieve a plant density of 30-40 plants/square metre under the irrigated conditions. An irrigation interval of 5 days was imposed and the pots were weighed before and after the addition of water. At each irrigation event, enough water was allowed to be absorbed by the soil in each pot through the bottom of the pot from a saucer filled with water. After 6 h, the saucers were removed and the pots were allowed for drainage of excess water for approximately 30 min, the maximum time required for the pots to show negligible drainage from bottom of the pots, before weighing them. The changes in the weight of the plants were ignored. The pots were rotated at each irrigation event, within the glasshouse, to ensure uniform distribution of light and air to the plants. An all purpose soluble fertiliser (Thrive™ with NPK 27-5.5-9) was mixed with irrigation water at 30 days after planting. At maturity, pods were harvested manually and seeds were separated from the pods before drying them in the oven at

80˚C for 72 h. The weight of oven dried grain was determined for each pot at harvest. Water use efficiency was calculated from the weight of grain and the evapotranspiration from planting to harvest.

Glasshouse experiment 2. The objective of this experiment was to assess the effect of polyacrylamide and irrigation interval on grain yield of soybeans. A pot experiment with soybean (*Glycine max*; cv Stephens) was conducted in the glasshouse at the Charles Sturt University, Wagga Wagga during the period from December 2000 to April 2001. Two seeds were planted in each pot (1 L) containing 800 g of treated soil at a bulk density of 1.5 g/cm^3 and later thinned to one plant per pot to achieve a plant density of 30-40 $plants/m^2$ under the irrigated conditions. Irrigation intervals of 3, 4, 5, 6 and 7 days were imposed on each of the above soil treatments separately. All the treatments had 3 replicates arranged in a split plot design. A similar procedure as described in the previous section for *Glasshouse experiment 1* was followed here. Pots were not weighed in this experiment. Thrive™ was mixed with irrigation water at 15, 30, 50 and 65 days after planting. Yield of oven dried grains at harvest was determined for each treatment.

Statistical analyses

Data from the laboratory study and glasshouse experiment 1 were analysed by 1-way ANOVA and the treatment means were separated by Duncan's multiple range test ($P = 0.05$). Data from the glasshouse experiment 2 were analysed by 2-way ANOVA.

In general, data are presented as means with the relevant least significance difference (P = 0.05).

Results and discussion

Soil water holding capacity

The water holding capacity of Siliceous Sand treated with different polyacrylamide rates and subjected to different pressures is shown in Fig. 1. Generally, at any given pressure, the water holding capacity of the soil increased with increasing amounts of polyacrylamide in the soil. However, the water holding capacity of the soil at any applied pressure did not increase linearly with increasing amounts of polyacrylamide in the soil (Fig. 2). For example, the water holding capacity of the soil at 0.01 MPa pressure was significantly (P = 0.05) increased by 23 and 95% with the addition of 0.03 and 0.07% polyacrylamide, respectively (Fig. 2). This indicated that 0.03 and 0.07% polyacrylamide in the soil held an additional amount of water equivalent to 29 and 61 times of their own weight, respectively. This increase in water holding capacity can potentially reduce the amount of water otherwise lost by deep percolation.

(Fig. 1 and Fig. 2 about here)

As expected, the water holding capacity of the soil decreased with increasing amount of applied pressure (Fig. 1). But the rate of decrease is different for control when compared to polyacrylamide treated soils. The decrease in water holding capacity of each soil by increasing the pressure from 0.01 to 1.5 MPa was about the same quantity for all treatments (Fig. 2). Similar results were also reported by Al-Omran and Al-Harbi (1997) when Broadleaf P4 was mixed with a sandy soil at 0, 0.2, 0.4 and 0.6 concentrations. However, there was significant amount of water still held by the soil treated with 0.03 and 0.07% polyacrylamide even at 1.5 MPa pressure compared with that in the control soil. About 92% of the water removed by increasing the pressure from 0.01 to 1.5 MPa in the control soil was, in fact, removed from the soil at 0.08 MPa pressure. However, this was only about 26 and 27% for soils treated with 0.03 and 0.07% polyacrylamide, respectively.

The difference in soil water holding capacity at 0.01 and 1.5 MPa pressures was calculated for the soils treated with 0, 0.03 and 0.07% polyacrylamide and the results are shown in Fig. 3. Even though 0.03 and 0.07% polyacrylamide enabled the soil to hold more water, the difference in soil water holding capacity at 0.01 and 1.5 MPa pressures was not significantly ($P = 0.05$) changed by the polyacrylamide treatment. In other words, the extra water held by the soil at 0.01 MPa pressure due to 0.03 and 0.07% polyacrylamide was, in fact, not removed from the soil by applying 1.5 MPa pressure. This raises the question that whether plants can extract this extra water stored in soil by the polyacrylamide. This aspect was verified by a pot trial reported here as glasshouse experiment 1 using soybean plants.

(Fig. 3 about here)

Water use efficiency of soybeans

The amount of water lost from the soil between two irrigations gradually increased with time for all treatments (Fig. 4). Up to about 35 days after planting (DAP), more water was lost from the control soil than from the polyacrylamide treated soils. This trend was reversed after about 40 DAP. After 40 DAP, the excess water retained by the polyacrylamide must have been utilised by the plants. Due to insufficient available water in the control soil, plants suffered from some moisture stress after 45 DAP and hence showed somewhat reduced growth rate which subsequently reduced the amount of water intake by plants to some extent until they gradually recovered. On the other hand, the plants in soils treated with polyacrylamide at the rate of 0.07% showed better growth than in the control soil or with 0.03% polyacrylamide in soil.

(Fig. 4 about here)

The results from this glasshouse experiment 1 also showed that the excess amount of water stored in the soil due to the presence of polyacrylamide was, in fact, utilised by the soybean plants. The dry polyacrylamide granules form a gel upon absorbing water and the gel may probably be resistant to release water by increasing pressure in the chamber. Pressure plate apparatus is effective as long as there are continuous pores saturated with water between the saturated plate and the polymer granules. When the water column is interrupted by air, there is no flow of water from the granules to the saturated plate. However, soybean plants grew healthier in soils treated with polyacrylamide than in control soil and this indicated that the excess water stored in polyacrylamide was freely available to these plants. During early stages of the crop, much of the water was lost by evaporation from the soil due to lack of ground cover. The results from this experiment showed that the polyacrylamide in soil was able to reduce the amount of water lost from the soil through evaporation. According to Johnson and Veltkamp (1985), the cross-linking bridges in the polyacrylamide can act as a structural barrier and provide a physical resistance for the water stored in the vacuoles to escape by evaporation. Al-Omran and Al-Harbi (1997) also reported that the cumulative evaporation of distilled water was significantly reduced by different commercial gel conditioners (Hydrogel, Stawet and Jalma).

In terms of cumulative amount of water lost during the 75 days of measurement, more water was lost from the soils treated with polyacrylamide than from control (Table 2). However, the plants grown in soils treated with polyacrylamide produced more grain than by the plants grown in the control soil. This resulted in significant ($P = 0.05$) increase in water use efficiency for plants grown in soils treated with polyacrylamide. Soil treated with 0.03 and 0.07% polyacrylamide increased the water use efficiency of soybeans by about 12 and 18 times, respectively.

(Table 2 about here)

The results from the glasshouse experiment 1 demonstrated a significant ($P = 0.05$) increase in water use efficiency of soybean plants grown in soils treated with polyacrylamide. This increase in water use efficiency was, in fact, due to increased production of grains by plants grown in soil treated with polyacrylamide. Better growth of plants in soils treated with polyacrylamide than that in control soil increased the total amount of water lost from the soil treated with polyacrylamide by evaporation and transpiration. This indicated that the irrigation interval for this soil without polymer should be reduced lower than 5 days after the plants have reached full canopy. On the other hand, excess water stored in soils treated with polyacrylamide enabled the plants to grow without suffering any moisture stress for 5 days until the next irrigation even at full canopy development.

Johnson (1984*b*) found that at least 95% of the moisture held by the polyacrylamide at full expansion was stored at tensions within the range of 0.01 to 1.48 MPa and was therefore available to plants. Johnson and Veltkamp (1985) reported that over 40% of the limited available moisture pool in sand was released at tensions <0.015 MPa and over 55% at tensions <0.05 MPa. They also found that only 10% of the much higher available water pool in the polyacrylamide was released at tensions <0.015 MPa. Therefore plants will use water stored in polyacrylamide more efficiently as compared to that held between soil mineral particles. However, it should be noted that Johnson (1984*b*) used a sand-suction table to create the 0.01 MPa suction pressure and a pressure membrane cell for the 1.48 MPa pressure while Johnson and Veltkamp (1985) used polyacrylamides alone without mixing them with soil on a pressure membrane apparatus at moderate and higher tensions.

Irrigation interval

The average grain yield at harvest from each plant under different soil and irrigation treatments (glasshouse experiment 2) is shown in Fig. 5. Some plants, especially those grown in soils with little or no polyacrylamide under higher irrigation intervals failed to produce any grain. Two-way analysis of variance indicated a significant ($P = 0.05$) difference between different soil and irrigation treatments. The grand mean of grain yield was 0.74 g/plant. A highest grain yield of about 2.89 g/plant was achieved with 0.2% polyacrylamide in soil and 3-days of irrigation interval. The grain yields obtained from this experiment were lower than that obtained from the glasshouse experiment 1 due to restricted volume of soil in each pot used for this trial. Grain yields were higher with increasing amounts of polyacrylamide in soil and decreasing intervals between 2 irrigations.

(Fig. 5 about here)

A comparison of grain production of plants grown in soil with no polyacrylamide (control) under different irrigation intervals revealed that the grain yield was the highest (0.21 g/plant) under the 3-days of irrigation interval (Fig. 5). This yield was progressively increased by about 6, 9 and 14 times by incorporating 0.05, 0.1 and 0.2% polyacrylamide with the soil, respectively. Further increase in polyacrylamide (0.3%) in soil failed to increase the grain yield achieved with 0.2% polyacrylamide in soil. The amount of water stored in soil treated with 0.2% polyacrylamide must be adequate to meet the evapotranspiration requirements of plants grown under 3-days of irrigation interval. Further increase in polyacrylamide in soil would retain more water than required by the plants and in fact, this could pose a threat to the ideal environment in the root zone. This trend was also shown by better grain production of plants grown in soil treated with 0.3% polyacrylamide under 4-days of irrigation interval than that under 3-days of irrigation interval. This meant that the water stored in this soil was adequate to meet the evapotranspiration requirements of plants during a 4-days irrigation interval.

A comparison of the interval between 2 consecutive irrigations showed that the grain production of plants grown in soil with no polyacrylamide under 3-days of irrigation interval could be achieved with 0.05% polyacrylamide in soil and 4-days of irrigation interval or 0.1% polyacrylamide in soil and 5-days of irrigation interval. However, if the maximum grain production is targeted, then plants grown in soils treated with 0.2% polyacrylamide under 3-days of irrigation interval or plants grown in soils treated with 0.3% polyacrylamide under 4-days of irrigation interval seems ideal for this purpose.

This glasshouse experiment 2 demonstrated that the large quantity of water retained by polyacrylamides provided extra water to the plants. This facilitated better plant growth while reducing the losses due to deep percolation and evaporation. More water also meant less frequent watering or irrigation.

In a greenhouse experiment, Taylor and Halfacre (1986) observed that wax tree, Compactum, in water absorbing (hydrophilic) polymer amended media in containers required irrigation less frequently than plants in non-amended medium. Baasiri *et al.* (1986) demonstrated that the cucumber grown in polyacrylamide (Aquastock) treated sandy loam soil achieved significantly higher fruit yield while reducing the number of irrigations required under greenhouse conditions. In field trials, Silberbush *et al.* (1993*a,b*) showed that corn and cabbage yields were increased with increasing amounts of polyacrylamide (Agrosoak) in sand dunes.

Conclusions

The results from this study have demonstrated that ALCOSORB®400 has the ability to increase the water holding capacity of sandy soils while suppressing the evaporation loss of absorbed water from the vacuoles. Crops like soybeans are able to utilise the stored water in polyacrylamide. Consequently, this type of cross-linked polyacrylamides can reduce the frequency and amount of irrigation, leading to an increase in water use efficiency by plants. It should be noted that the soil mixtures in the pots in these studies were saturated from below to make sure enough water was absorbed by the soil in each pot. In the field, if the soil is wetted from above, polyacrylamides may not get enough water to swell to their full capacity.

The implication of these results, if they can be repeated under field conditions, is that it could save time, money and energy spent on high frequent irrigations. Currently (2004), the cost of polyacrylamide is A$8/kg and the farm gate value of soybean seeds is about A$600/t. At the rates of application of polyacrylamide tested in this study, it may not be economical to treat the entire soil volumes within the root zone of a crop such as soybeans. However, the polyacrylamide treatment seems to be cost effective if applied as a band in the crop row, instead of whole field application. Such a band application technique will minimise the amount of polyacrylamide required for large areas but provides a source of water storage closer to the root zone of the crop. This aspect is currently being investigated.

Acknowledgments

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TABLES

Table 1. Some selected physical and chemical properties of the soil (<2mm)

(Source: S Black 2004, pers. comm., 29 July)

Property	Depth of soil (cm)				
	0-27	27-35	35-65	65-90	90-100
Clay (%)	6	7	6	7	9
Silt (%)	8	5	5	5	4
Fine sand (%)	43	38	41	42	38
Coarse sand (%)	43	50	48	46	49
Exch. Mg^{++} (meq/100g soil)	0.53	0.45	0.45	0.37	0.45
Exch. K^{+} (meq/100g soil)	0.24	0.24	0.27	0.27	0.29
Exch. Na^{+} (meq/100g soil)	0.20	0.17	0.17	0.31	0.48
Exch. Mn^{++} (meq/100g soil)	0.16	0.13	0.09	0.07	0.05
Exch. Ca^{++} (meq/100g soil)	3.10	0.70	0.58	0.48	0.95

Table 2. Amount of water used, weight of grain harvested and calculated water use efficiency of soybean plants grown in soils treated with polyacrylamide

Values in a column followed by different letters are significantly different at $P = 0.05$

Amount of polyacrylamide	Amount of water used in 75 days	Weight of grain harvested	Water use efficiency (g/L)

in soil (%)	(L/pot)	(g/pot)	
0.00	7.350a	0.14a	0.0190a
0.03	7.987b	1.91b	0.2391b
0.07	8.269b	3.04c	0.3676c
l.s.d. (*P* = 0.05)	0.311	1.01	0.0013

FIGURES

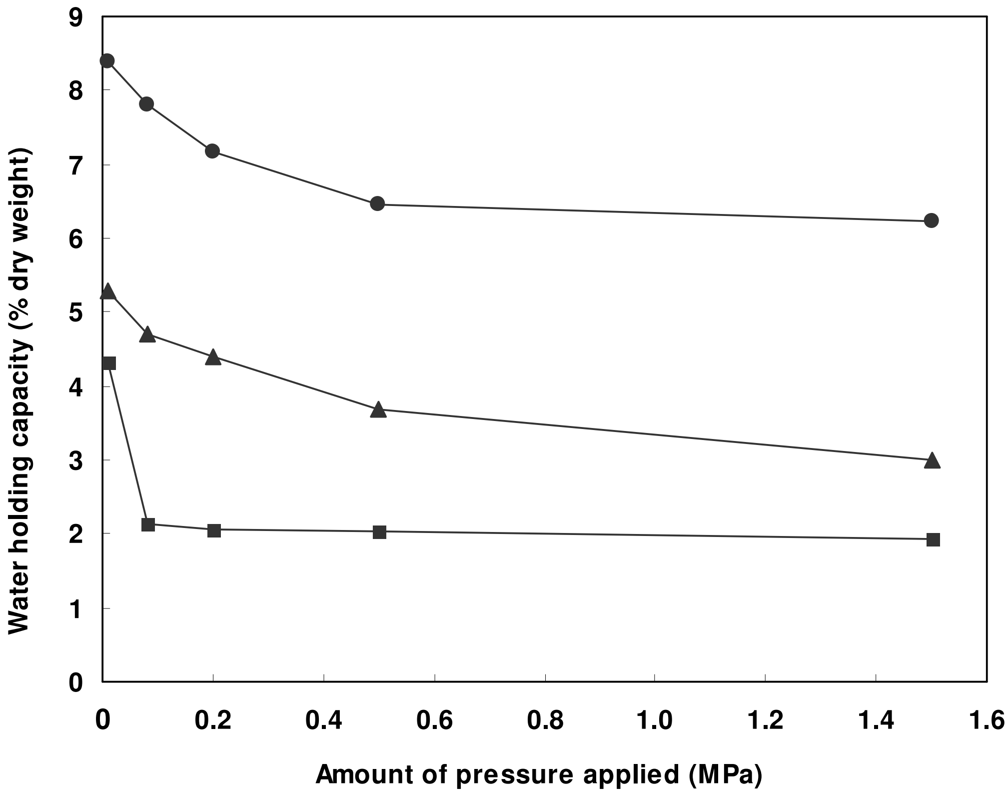

Figure 1. Water holding capacity of soils treated with different rates of polyacrylamide and subjected to different pressures. ■ 0.00% polyacrylamide (control); ▲ 0.03% polyacrylamide; ● 0.07% polyacrylamide.

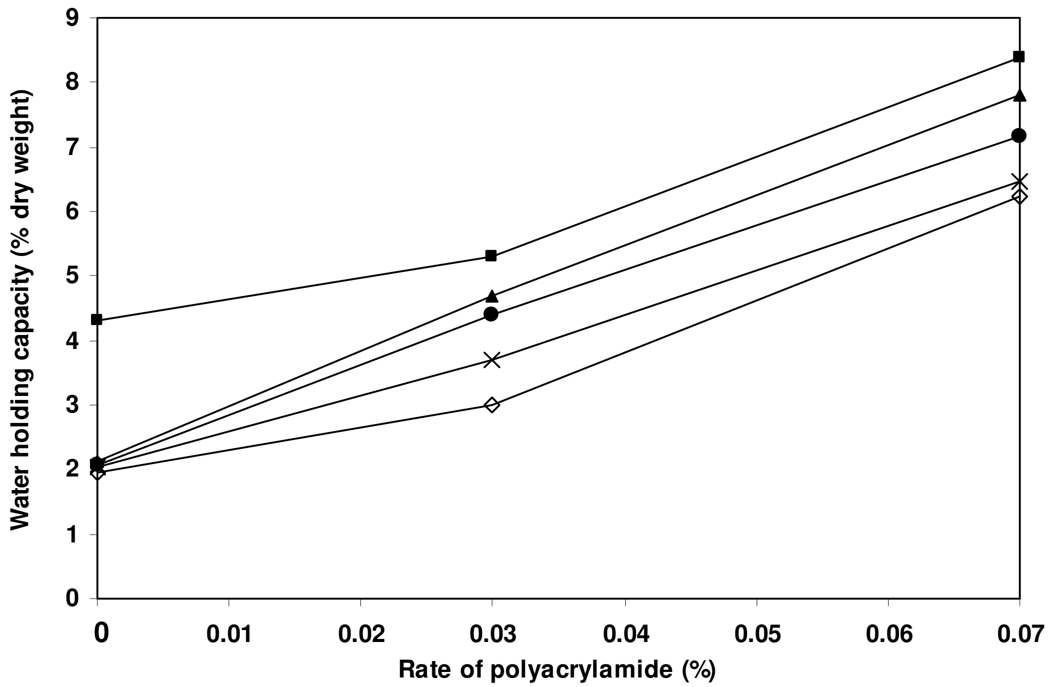

Figure 2. Increase in water holding capacity of the soil at different applied pressure with increasing amounts of polyacrylamide in the soil. ■ 0.01 MPa; ▲ 0.08 MPa; ● 0.20 MPa; × 0.50 MPa; (1.50 MPa.

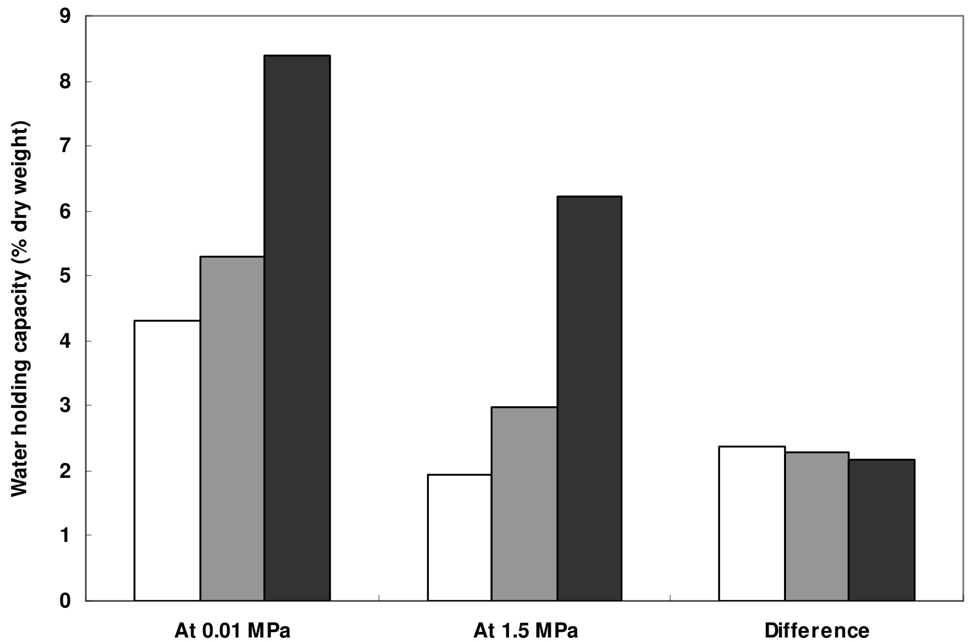

Figure 3. Water holding capacity at 0.01 and 1.5 MPa pressures and their difference for soils treated with 0.00% poyacrylamide (unshaded bars), 0.03% polyacrylamide (lightly shaded bars) and 0.07% polyacrylamide (darkly shaded bars). l.s.d. (P = 0.05) for 0.01 MPa pressure, 0.827; 1.5 MPa pressure, 1.463; difference, 2.129.

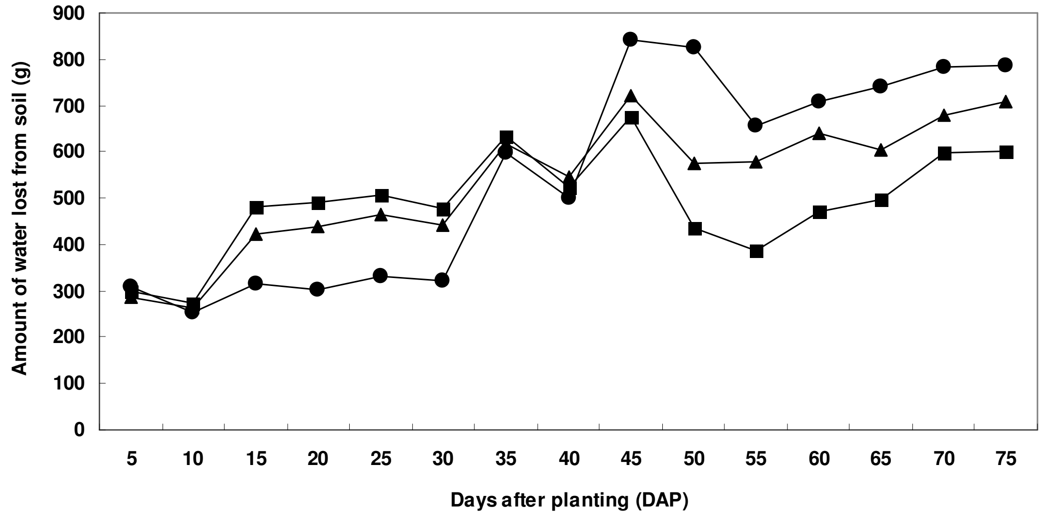

Figure 4. Amount of water lost from soil between 2 consecutive irrigations. ■ 0.00% polyacrylamide; ▲ 0.03% polyacrylamide; ● 0.07% polyacrylamide.

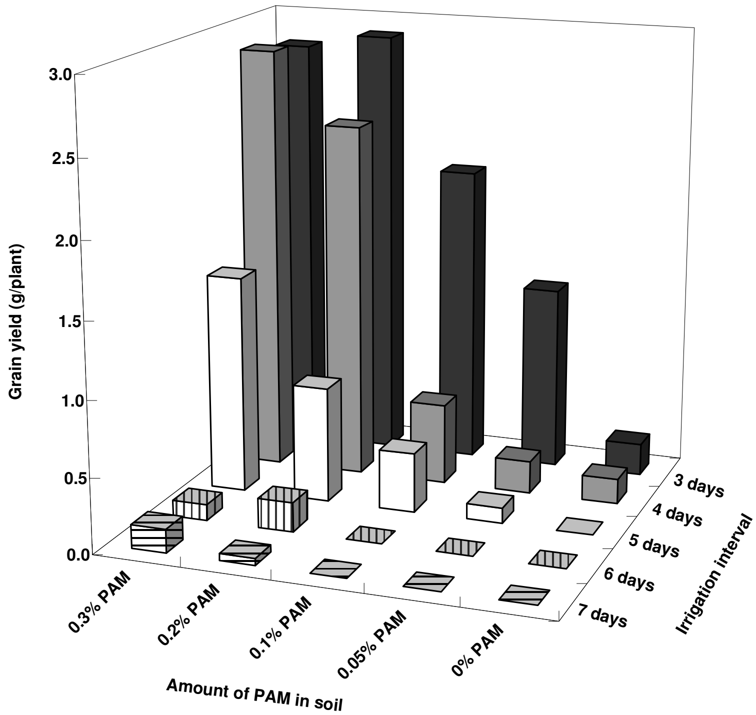

Figure 5. Grain yield of soybean plants at harvest under different soil and irrigation treatments. Irrigation intervals are 3 days (darkly shaded bars), 4 days (lightly shaded bars), 5 days (unshaded bars), 6 days (vertical stripe bars), 7 days (horizontal stripe bars).