Water Release from Cross-linked Polyacrylamide

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Abstract. Cross-linked polyacrylamide (CLP) has a number of well-established industrial and household uses due to its high water absorbency. Industry has promoted the usage of CLP as a soil water conservation amendment and as a reservoir for plant available water that is helpful in alleviating plant stress during periods of drought. The purpose of this research is to verify that the absorbed water is, in fact, plant available. Following a single drying cycle, and its structural sensitivity to dilute salt solutions, the changes in CLP's water absorption capacity may be serious impediments to its usefulness in field applications. A field study using CLP banded at the recommended rate and 20 times this rate were performed to test the robustness of CLP to enhance drought tolerance in legumes. The addition of CLP did not sustain yields with reduced irrigation levels. Plant stress indicators, plant growth measurements, and environmental factors were not significant.

1. Introduction

Colorado State University has received many inquiries regarding soil amendments that may be helpful in storing water in soils against shortages. With the uncertainty of continued drought in our region, manufacturers are aggressively marketing a super-absorbent cross-linked polymer as a soil water conservation amendment. Cross-linked polyacrylamide is commonly referred to as PAM, however the non-cross-linked PAM form is effectively used for soil erosion control, sediment reduction in surface waters, and earthen canal bed stabilization. Therefore, the cross-linked, water absorbent, crystalline form will be referred to as CLP rather than PAM.

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2. Background

Polyacrylamide polymer is a byproduct of the plastics industry that necessitates disposal. Cross-linked polyacrylamide has been marketed on and off over the last 20 years as a soil amendment to increase water retention and reduce irrigation frequency. In an effort to find a beneficial use for this byproduct, the plastics industry has been marketing CLP for its high water absorbency that is 200 to 400 times its weight in water for the pure material. It has numerous industrial uses including disposable diapers, packaging materials, and direct-bury cable coatings. Among its many commercial uses as an absorbent, CLP has also been marketed for application to soil and potting mixes as a water storage enhancement amendment with a manufacturer-claimed soil life of two to six years. With the likelihood of continued drought, CLP has been promoted as a soil water conservation amendment.

Despite CLP's obvious potential benefits, results of greenhouse and field research on the effectiveness of CLP to alleviate water stress have been mixed and unpredictable. While some researchers report improved plant growth and reduced irrigation frequency that have polymers added to the soil mix (El-Hady et al., 1981; Wang and Boogher, 1987), others found no significant benefit from the addition of polymers (Ingram and Yeager, 1987; Tu et. al., 1985). Other studies have found a potential detrimental effect on the survival and yield of plants treated with CLP already in water-abundant soils (Austin and Bondari, 1992; Boatright et al., 1997). The greatest benefit to water holding through the addition of polymers has been in coarse-textured soils (Hemyari and Nofziger, 1981), though it is unclear if the additional water was usable to plants (Tripepi et al., 1991). Letey et al. (1993) concluded that polymer amendment was not an effective conservation approach because although the polymer extended the period between irrigations, more water was required when irrigating. In a comprehensive field study involving turf grass, Dahlin (1992) incorporated CLP at rates ranging from 244 to 3904 kg ha^{-1}. This author concluded that the CLP amendment had no significant effect on drought tolerance, clipping yield, or root distribution. Pearson (2000) banded CLP at two rates in corn grown under reduced irrigation and reported no significant difference in grain yield from treated and non-treated plots.

Taylor and Halfacre (1986) and Hensley (2001) found that natural soil salinity and fertilizer salts might have severely limited the water holding properties of CLP and render it useless. Saline soils would inherently cause alterations in osmotic pressure, causing the CLP to be less able to absorb water. Bowman et al. (1990) concluded that osmotic response was not sufficient to explain losses in water holding capacity.

Despite conflicting findings in regards to the water storage benefits of CLP, CSU scientists continue to hear anecdotal accounts from growers and public interest groups of extension specialists and water conservation districts advising use of CLP as a soil amendment to improve drought tolerance in plants. Research is needed to clarify the water storage benefits of CLP. It may be that successes using CLP in container systems do not translate to field planting because of the radically different soil water potentials in these contrasting systems. Given the intense interest in water conservation, the objectives of this research are to test the effectiveness of CLP to reduce water stress during periods of drought and to determine environmental conditions leading to the failure of CLP as a water storage material.

3. Objectives

While previous studies have primarily focused on soil-water relation measurements for increasing water storage, this study was designed to quantify the energetics of water retention and release from CLP to address its usefulness as a water storage enhancement amendment. The first objective was to evaluate the effectiveness of CLP as a soil amendment to sustain plant growth and reduce water stress during periods of drought by testing the water holding properties of CLP in the presence of dilute salt solutions or distilled water via laboratory experiments. The second objective was to apply CLP at different rates in a field soil setting to evaluate the effectiveness of sustaining growth under reduced irrigation.

4. Methods

4.1 Laboratory Experiments

4.1.1. Moisture Energetics of Cross-linked Polyacrylamide

A laboratory experiment addressed the first objective pertaining to the retention and release of water from CLP as it passed through various levels of water content, over the water content range from saturation to wilting point, and back again.

The pressure plate method was used to measure the moisture retention of CLP from 0 cm (saturation) to 10000 cm (wilting point) tension. This evaluation tests whether the highly water absorbent CLP releases water at energy levels typical of the soil-root environment.

4.1.2. Cross-linked Polyacrylamide's Responses to Salinity

Moisture retention was also evaluated after wetting CLP with 0, 0.5, 2, and 4 dS m^{-1} NaCl (aq) or $CaCl_2$ (aq). An amount of 0.5 g CLP was placed into 10-cm tall aluminum cylinders that were sealed with plastic screening and filter paper on the bottom. A small amount of soil was sprinkled into the gap between the filter paper and the screen to improve contact with the pressure plate. Next, samples were saturated in either NaCl or $CaCl_2$ solutions with 4 replicates of each. After reaching each desired tension (0, 100 cm, 300 cm, and 10000 cm) water was drained from samples by lowering the water table to the bottom of the samples, after which the samples were weighed.

4.2 Field Application of Cross-linked Polyacrylamide

A field experiment using crop yield under reduced irrigation was employed to elucidate the effectiveness of CLP as a soil amendment to reduce plant stress and sustain yields under reduced irrigation. The field evaluation was performed at the Agricultural Research, Development, and Education Center near Fort Collins, Colorado. Two bean cultivars, Othello and Bill Z. were irrigated at 100% and 50% of estimated crop requirements. These irrigation levels were used to evaluate the impact of CLP at the manufacturer recommended rate (22.4 kg ha^{-1}), a super rate (20x the recommended rate – 448 kg ha^{-1}), and without CLP addition. Within these irrigation treatments, dry CLP was banded (5 to 15 cm depth increment) along the center of the row at seeding. Figure 1 illustrates the plot design including bean cultivar, irrigation and CLP application rates.

North

North Field

Rows 1 - 4	1-BZ-MIN	1-OT-MIN	1-BZ-MAX	1-OT-ZERO	1-OT-MAX	1-BZ-ZERO
	4 ROWS OF BUFFER					
Rows 9 - 12	0.5-OT-MAX	0.5-OT-MIN	0.5-OT-ZERO	0.5-BZ-MIN	0.5-BZ-ZERO	0.5-BZ-MAX

South Field

Rows 1 - 4	0.5-OT-MIN	0.5-OT-MAX	0.5-BZ-MAX	0.5-BZ-ZERO	0.5-OT-ZERO	0.5-BZ-MIN
	4 ROWS OF BUFFER					
Rows 9 - 12	1-OT-ZERO	1-OT-MIN	1-BZ-MAX	1-BZ-ZERO	1-BZ-MIN	1-OT-MAX

Figure 1. Map of Field Plot at ARDEC. The first section indicates irrigation rate, the second indicates cultivar, and the third indicates CLP rate. Irrigation rates: 0.5 – half irrigation, 1 – full irrigation; Cultivar: BZ – Bill Z., OT – Othello; CLP rates: ZERO– No CLP, MIN– 22.4 kg ha^{-1}, MAX– 448 kg ha^{-1}.

During the growing season, several plant and soil variables were monitored to assess plant stress and growth per treatment. These variables included: soil water potentials (taken biweekly at 30 cm and 60 cm soil depths), stomatal conductance, biomass measurements, light absorbance by plants (measured as photosynthetically active radiation (PAR) using a PAR Ceptometer), TDR soil water content (in the 0-15 cm soil depth increment) and above-ground environmental variables (air temperature, solar radiation, rainfall and wind) measured via an on-site weather station.

5. Results and Discussion

5.1 Moisture Retention Experiment

Plant water uptake is an active process requiring the expenditure of energy on the part of the plant and surrounding environment. Water removal from soils only occurs under specific conditions. After the saturation of soil pores with water, soil-water content rapidly changes as water drains under gravitational forces. The water that drains under forces is considered unusable by plants. After gravity drainage ceases, the soil-water content is at "field capacity." Field capacity water content requires plant roots to overcome the attraction of water's polarity toward the negatively charged soil surfaces in order to absorb water. As soils become progressively drier, the remaining water becomes less plentiful and is more tightly held to the soil surfaces. Eventually, water is held so tightly by these attractions, that it is no longer available for plant uptake (referred to as "wilting point"). The water absorption of pure CLP greatly exceeds that of a typical soil. At saturation, the water content of CLP was about 130 g water per g of product (Figure 2).

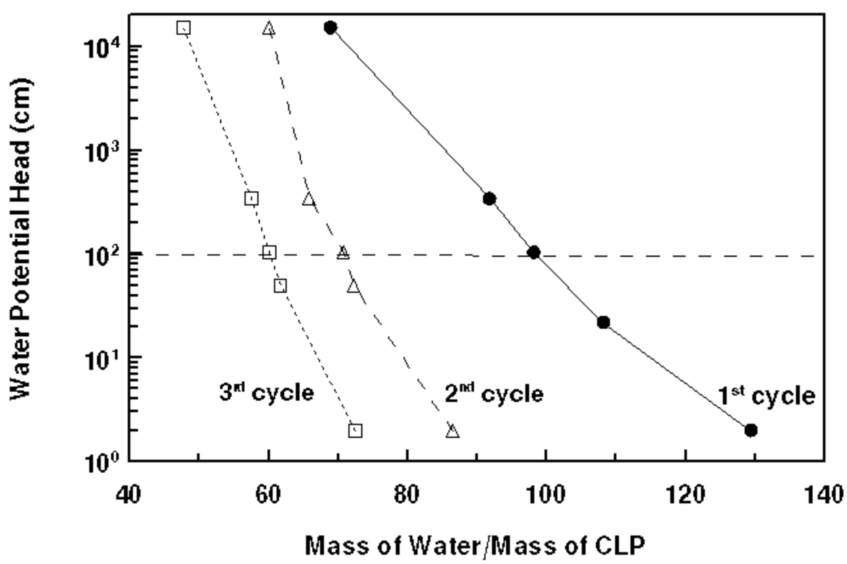

Figure 2. Retention of water by CLP from saturation to the permanent wilting point.

A portion of this capacity was rapidly drained by gravitational forces and upon reaching field capacity (100 cm of tension), the water content of the material decreases by approximately 25%. The water not retained by soil (the water held between saturation and field capacity) was considered unavailable to plants because of the rapidity of its removal by gravity drainage. Figure 2 shows the moisture retention upon pure CLP's initial wetting and second and third re-wettings.

The useful (plant available) water storage for CLP was about 30 g water per g CLP, or only about 25% of bulk water storage capacity after saturation. Having been drained to 10000 cm tension after its initial wetting, the CLP could not be re-wetted to its original saturated water content. Following the initial drainage to 10000 cm tension, the soil/CLP mixtures were re-saturated and drained two additional times through the same sequence of water contents. The results were similar to the first drainage cycle, except near saturation where the water contents were lower for the consecutive re-wettings. Consolidation of the soil might have contributed to water content variations, however a trend in water content reduction between the initial and final drainage cycles from saturation to the wilting point was observed.

The addition of CLP to soil increases soil water contents, particularly near saturation (Figure 3).

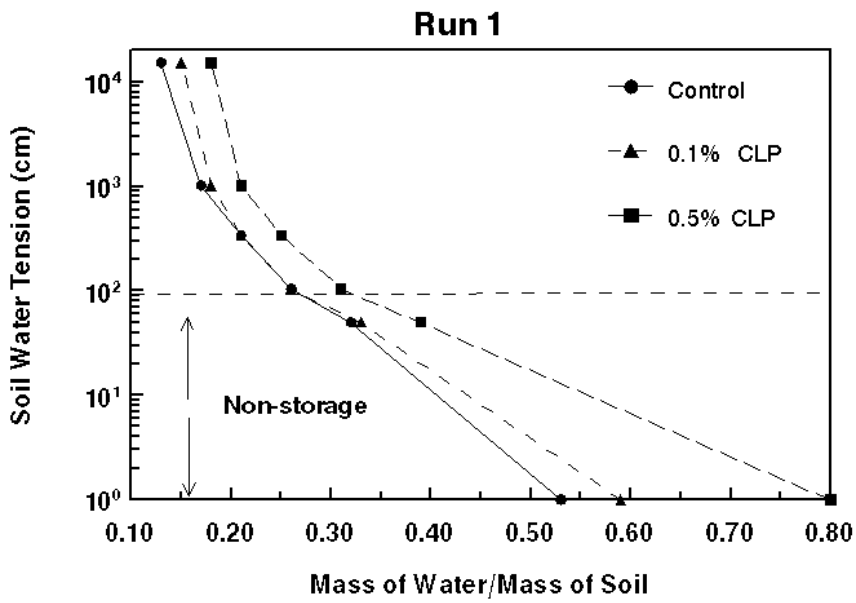

Figure 3. Water retention in a sandy clay loam soil with and without CLP amendment. The amendments at 0.1% and 0.5% are 80 and 500 times the recommended rates, respectively.

However, the effect of CLP on plant-available water storage (at 80 and 500 times the recommended loading rates) was minimal. For example, the plant available water (between field capacity and wilting point) increased from 0.13 to 0.14 (g water g^{-1} soil) with the addition of CLP at 0.5% (by weight).

5.2 Salinity Experiment

Cross-linked polyacrylamide was evaluated after its mixture with solutions containing 0, 0.5, 2 and 4 dS m^{-1} NaCl (aq) or $CaCl_2$ (aq). Figure 4 elucidates CLP's responsiveness to salt.

Figure 4 illustrates how exposure to salts (especially divalent cations) collapsed the CLP into a gelatinous goo-like substance and drastically reduces its water holding capacity. Even the dilute solution of 0.005 M $CaCl_2$ (0.5 dS m^{-1} $CaCl_2$) (a very low salt concentration compared to typical soil water) to the saturated CLP demonstrated the sensitivity of CLP to the presence of salts. Plant available water reduced from 58.8 g g^{-1} CLP in distilled water to 18.2 g g^{-1} CLP in 2 dS m^{-1} $CaCl_2$ to 9.1 g g^{-1} CLP in 4 dS m^{-1} $CaCl_2$. Water available to plants from CLP's water retention capacity was reduced to 43% of the distilled water's capacity for 4 dS m^{-1} NaCl.

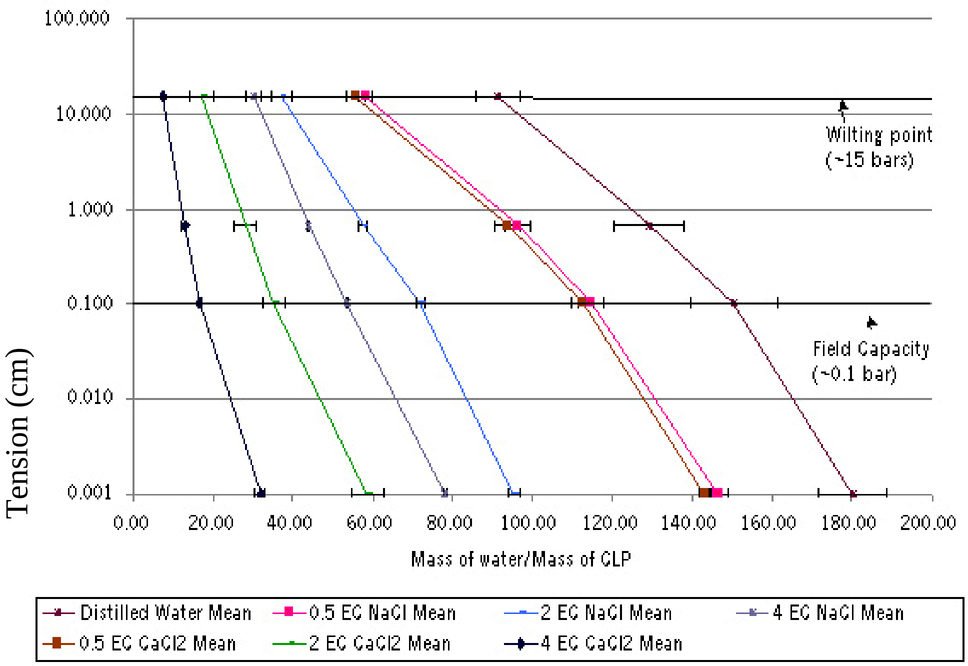

Figure 4. Water retention by CLP exposed to salt concentrations.

5.3 Field Experiment

Germination rates for all trials were about the same (Figure 4). At germination, irrigation rates for the half and full irrigation trials were not different yet. The only statistically significant differences were between the 1-OT-MAX, 1-OT-MIN, and 1-OT-ZERO trials. In these trials, the plots without CLP addition had greater germination than the maximum CLP application rate (p-value 0.063, α=0.05). The minimum CLP rate germination was greater than the maximum CLP application rate (p-value 0.093, α=0.05).

The pinto bean field study results indicated that the 100% irrigation treatment at the manufacturer's recommended CLP rate and 20x that rate had no significant (α=0.05) effect on yield. The 50% irrigation treatment significantly (α=0.05) reduced the bean yields in comparison to the 100% irrigation treatment for all CLP treatments. No significant (α=0.05) difference was found between CLP treatments for soil water potential, stomatal conductance, light absorbance by plants, TDR soil water content or above ground environmental variables. The only significant (α=0.05) difference was between irrigation levels.

6. Conclusions

The water absorption of pure CLP greatly exceeds that of typical soil, however only about 25% would be available for plants during its initial wetting. The results for three wetting-drying cycles verify that, while a portion of the water absorbed by CLP is plant available, the drying cycles reduce the absorbency of CLP for subsequent re-wettings. Following a single drying cycle, and its structural sensitivity to dilute salt solutions, the changes in CLP's water absorption capacity may be serious impediments to its usefulness in field applications. The addition of CLP at 20x the recommended rate for water storage in field applications reduced yields by 17% when irrigated at 100% (relative to the control). The addition of CLP did not sustain yields with reduced irrigation levels and the plant stress indicators, plant growth measurements, and above-ground environmental factors were not significant (α=0.05). Differences in field plots observed indicated that plants in the CLP treatments that were 20x the manufacturer's recommended application rate may have been encountering more stress.

7. References

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