Influence of super absorbent polymer on soil water retention, seed germination and plant survivals for rocky slopes eco-engineering

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\textbf{ABSTRACT}

To improve the utilization of water resources on rocky slopes eco-engineering, super absorbent polymer (SAP) with the function of water retention was applied. Super absorbent polymer in three levels, 0.15%, 0.30% and 0.45% were mixed with sandy loam soil. This study was aimed to evaluate the saturated water content, evaporation rate and water holding capability of SAP treated soils, determine seed germination rate and plant survivals in soil with SAP by absorbing and spraying experiments. The addition of SAP to the sandy loam soil resulted in a significant increase of the soil water retention compared to the controls. Also, the seed germination was significantly higher in SAP amended soil than in the soil without SAP, survival times of grass and woody were prolonged under water stress. 0.30% SAP treatment was the optimum selection for sandy loam soil improvement on steep rocky slopes. These studies indicated that SAP with good water retention properties, was very effective in enhancing water uptake and utilization of water for plants growth, and could be expected to have wide potential applications in rocky slopes eco-engineering.

1. Introduction

Extensive highway constructions have resulted in large numbers of steep rocky slopes, causing soil loss, and an unbalanced eco-environment (Zhou and Zhang, 2003; Koca and Kincal, 2004; Yang et al., 2011). To restore the ecological balance of the bare rocky slopes, eco-engineering is an important way to create the appropriate condition necessary for plant growth, enhance slopes stability by mechanical reinforcement of plant roots, and improve ecological environment through hydrologic effect of aboveground biomass (Zhou and Zhang, 2003; Yang et al., 2011; Chen et al., 2004). In addition to the steep slopes recovery, the presence of water in soil is essential for plant survival. Thus, it is important to determine the appropriate materials with which to improve the water-holding capacity of soil on rocky slopes. Taking into account the water imbibing characteristics of super absorbent polymer (SAP) materials, its application in rocky slope eco-engineering may be alleviate these problems (Zohuriaan-Mehr and Kabiri, 2008).

Super absorbent polymers are compounds that absorb water and swell into many times their original size and weight. Super absorbent polymers are used in soil to create a water reserve, near the rhizosphere zone (roots) and benefit agriculture (Zohuriaan-Mehr and Kabiri, 2008; Han et al., 2010). Current studies on SAP mainly focused on the development of its new material and new product and its own chemical properties as well as its field application (Yang et al., 2003; Han et al., 2005, 2010). Various applications of SAPs and active fields of applied research works on SAPs have been made. It was first applied in agricultural production of corn and soybean as well as seedling transplanting. Fanta et al. (1971) found that SAP contributed to water saving and yield enhancement. Later, SAP is also used in many areas such as pharmaceuticals, food packaging, paper production, the agricultural and horticultural industry, oil drilling, etc. (Wang et al., 1998, 2000a,b; Li et al., 2004; Han et al., 2010).

In the agriculture and horticultural industry, the application of SAP is in the form of seed additives, seed coatings, root dips, and so on (Zohuriaan-Mehr and Kabiri, 2008). Since SAP can ease the burden of water shortage, proper use is helpful in arid and semi-arid areas (Bakass et al., 2002; Zohuriaan-Mehr and Kabiri, 2008; Han et al., 2010). It has positive effect on water retention on various types of soils, can improve the physical properties of soil in view of increasing their water-holding capacity and nutrient retention of soil, delay the time to reach permanent wilting point, prolong plant survival under water stress (Hüttermann et al., 1999; Oscroft et al., 2000; Viero et al., 2002; Abedi-Koupai and Asadkazemi, 2006; Orikiriza et al., 2009).
Table 1
Soil physical and chemical properties.

<table>
<thead>
<tr>
<th>Texture</th>
<th>Particle size fraction (%)</th>
<th>CEC (cmol(c) kg⁻¹)</th>
<th>OM (g kg⁻¹)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>11.31</td>
<td>15.2</td>
<td>15.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Silt</td>
<td>18.53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>70.16</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CEC, cation exchange capacity; OM, organic matter.

In most researches, SAP was applied directly onto the soil surface. The use of SAP in disturbed soils on rocky slopes, however, may have different results. In this study, we aimed to investigate the influence of SAP on water retention, seed germination and plant survivals via hydro-seeding technology on a 60° rocky slope. We also plan to determine the optimal dose for sandy loam soil to improve water retention and life span of plants under water stress conditions. Understanding the influence of SAP on soils will be helpful to promote SAP application to rocky slopes eco-engineering where the availability of water is insufficient.

2. Materials and methods

2.1. Materials

Soil used in the experiments was sandy loam, which was collected from the top 15 cm of the field in Chengdu, China (103°53′ E, 30°59′ N). The area is a humid subtropical climate and basin topography, receives about 932.5 mm average rainfall, with a 15.6 °C mean annual temperature, a maximum annual temperature of 37.7 °C and a minimum of −5.1 °C during the last 30 years. Upon return to the lab, the soil was air-dried, and sieved to pass a 4.0 mm screen, to remove the identifiable root material during the process. Soil was stored at 25 °C until being used. Physical and chemical properties of the selected soil are shown in Table 1.

Super absorbent polymer sample was provided by SIDA Co., Beijing, China. It was white powders with a particle diameter of 50–250 μm, with the following concentrations added to the soil: 0 (the control), 0.15%, 0.3%, and 0.45%. The properties of SAP are shown in Table 2.

Seeds used in this study were Medicago sativa L., Festuca arundinacea Schreb., Melilotus suaveolens Ledeb., Leucaena glauca, Indigofera pseudotinctoria Matsum., Indigofera amblyantha Craib., Amorpha fruticosa Lind., Sophora viciifolia Hance, Lespedeza Formosa (Vog.) Koehne, Robinia pseudoacacia Linn.

2.2. Experimental design and measurements

In this study, three levels of SAP content were mixed with sandy loam soil, three replicates. Soil moisture characteristics and the growth of applicable plants were conducted in the absorbing and spraying experiments.

2.2.1. Absorbing experiment

The absorbing experiment was carried out in a glass-house (with nothing surrounding the glass top) in April, 2010. The samples were prepared as follows: 1020.0 g mixture including soil and SAP was placed in a 20-cm diam. by 4-cm ht. PVC cylinder. The cylinder was PVC slab with holes and a #1 Whatman filter paper on the bottom. Cylinders were set into trays for 48 h, and then transferred to the glass-house. The weight of the cylinders was recorded daily until no noticeable weight loss was observed. Saturated water content, evaporation rate and water holding capacity were calculated by the following equation:

\[ W = \frac{(W_1 - W_2 - 1020.0) \times 100}{1020.0} \]

\[ ER_n = \frac{(W_n - W_{n-1} - 1) \times 100}{W_1 - W_2 - 1020.0} \]

\[ WHC = (W_1 - W_2 - 1020.0) \times \left(1 - \sum \frac{ER_n}{100}\right) \]

where W% is the saturated water content, W_1 the total weight of saturated soil and cylinder (g), W_2 the weight of cylinder (g), ER_n the evaporation rate (%), W_n and W_{n-1} the total weight of soil and cylinder on the n and n-1 day (g), WHC the water holding capacity (g). \[\sum \frac{ER_n}{100}\] the sum of evaporation on the nth day (%).

2.2.2. Spraying experiment

A modified hydro-seeding technology (Zhang et al., 2013; Li et al., 2005, 2006) was conducted in the bioengineering stabilization laboratory of Sichuan University, China. The process illustrated as follows: Soil, pretreated seeds and SAP were mixed using a concrete mixer (JZC300, Henan Kowloon Machinery Co., Ltd., Zhengzhou, China). The mixture was transferred into a compressed-air spraying machine (12 m³, Ingersoll-Rand, Piscataway, NJ) by a rotor concrete conveyor (5 m³ h⁻¹, V-6-7, Hunan Changde Universal Compressor Co., Ltd., Changde, China). Under aerodynamic force, the mixture was blended with water at the outlet of the spraying machine and sprayed onto soil trays through a conveying pipeline (20 m long, 75 mm in diameter) (Yang et al., 2011; Chen et al., 2004). The spraying pressure was 0.12 MPa and the water discharge volume was 10 L min⁻¹.

The soil was covered with straw on the surface after spraying, and was put in natural condition after 24 h. The soil tray with 1.4 m long, 0.7 m wide and 0.1 m deep was set to a gradient of 60°. A V-shaped runoff collector was connected by flexible tubing, which transferred the runoff into a sampling barrel. (Yang et al., 2011) (Fig. 1). Runoff was recorded by electronic balance after rainfall, and soil water absorption was determined by subtracting the runoff

Table 2
The properties of super absorbent polymer.

<table>
<thead>
<tr>
<th>Water content (%)</th>
<th>Grain size (µm)</th>
<th>Water uptake capacity (g/g)</th>
<th>Grain composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>10.05 50–250</td>
<td>292</td>
<td>0.5–1 mm: 0.05%;</td>
</tr>
<tr>
<td>Tap water</td>
<td>220</td>
<td></td>
<td>0.25–0.5 mm: 0.06%;</td>
</tr>
<tr>
<td>NaCl 0.9%</td>
<td>45</td>
<td></td>
<td>0.15–0.25 mm: 29.40%;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;0.25 mm: 70.1%</td>
</tr>
</tbody>
</table>
from the rainfall, calculated by the following equation. Germination rate was determined by the ratio of highest germination and seeding amount.

\[ I = \frac{P \times S \times \cos \alpha - R}{S} \]

where \( I \) is the water absorption (mm), \( P \) is the precipitation (mm), \( S \) is the slope area (m²), \( \alpha \) is the gradient (°), and \( R \) is the runoff (kg).

After 50 days, the soil trays were transferred into the greenhouse with no watering, survival time of plants was calculated by subtracting the date of stop watering from the date of death of each individual plant. Death of plants was monitored by observing on a daily basis the color change of leaves and branches from green to brown and gray. When all the leaves and stems turned brown and started shedding off, and branches becoming brittle, the plant was declared dead (Agaba et al., 2010).

2.3. Statistical analysis

A one-way analysis of variance was carried out to determine the main effects of SAP content on water absorption rate, evaporation rate, seed germination rate and survival times. Significant difference (LSD) test at \( \alpha = 0.05 \) level. All statistical analysis was performed using SPSS 16.0 for Windows (SPSS Inc., Chicago, IL).

3. Results

3.1. Absorbing experiment

3.1.1. Saturated water absorption

All SAP treatments significantly increased saturated water content with increasing of the SAP content compared with the controls (Fig. 2). The maximum saturated water content was achieved when the SAP content was 0.45%, with a 42.69% increase compared with the controls. The 0.15% SAP treatment worked worst, but still had an increase of about 11.20%.

3.1.2. Evaporation rate

During the first 5 days, all SAP treatments reduced the evaporation rate compared with the controls. The efficiency of SAP treatments increased with increasing SAP content. The evaporation rate of soil without SAP had reached 26.84% on the 10th day, whereas that of soil with 0.45% SAP was 4.75%. After 5 days, no reduction in evaporation rate was observed in the SAP treated soils. In fact, opposite trend was found, soil with high SAP content lost more water than the controls, the evaporation rate of soil without SAP was 3.2% on the 6th day, whereas that of soil with 0.45% SAP had reached 27.95% (Fig. 3).

3.1.3. Water holding capacity

All SAP treatments significantly increased soil water holding capacity with increasing SAP content compared with the controls. On the 3rd day, the 0.45% SAP treatment performed best, increasing by 203.47% compared with the controls, even the 0.15% SAP treatment still increased by 108.91%. Soil without SAP was completely dry at the end of 6 days, while soil with 0.15% SAP was not dry until 10th day, soil with 0.3% and 0.45% SAP was dry after 11 days (Fig. 3).
3.2. Spraying experiment

3.2.1. Water absorption

Super absorbent polymer content and rainfall intensity were both significant factors influencing soil water holding capacity, and there was significant interaction between the two factors (Table 3). All SAP treatments increased water absorption rate by 39.3% to 139.4% compared with the controls. Water absorption rates increased with increasing SAP content under the rainfall intensity of 3.93, 4.77 and 5.43 mm h⁻¹ (Fig. 4).

3.2.2. Germination

Both grass and the woody germination rates were increased under SAP treatments compared with the controls. The plant germination rates increased with increasing SAP content. Amending sandy loam soil with 0.45% SAP significantly increased more than two fold in grass germination rate compared with the controls, and about 3.5-fold in the woody. While amendment at 0.15% SAP had a significant twofold in grass and woody compared with the controls (Fig. 5).

3.2.3. Survival time

The survival time of grass and woody in soil with SAP was extended. For 0.3% and 0.45% SAP treatments, the survival time of grass and woody were both doubled compared with the controls, surviving for 18 and 21 days, respectively. Woody in soil with 0.45% SAP had the maximum life span (21 days) compared to the control (11 days). However, there was no significant difference between 0.3% and 0.45% SAP treatments. Even more, the survival time of grass plant with 0.3% SAP treatment was longer than that of 0.45% SAP treatment (Table 4).

Table 3

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>Mean square</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP content (S)</td>
<td>3</td>
<td>1742.38</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Rainfall intensity (R)</td>
<td>8</td>
<td>566.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>S x R</td>
<td>24</td>
<td>17.24</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Error</td>
<td>72</td>
<td>0.803</td>
<td></td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Survival time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grass</td>
</tr>
<tr>
<td>CK</td>
<td>9 ± 1a</td>
</tr>
<tr>
<td>0.15%</td>
<td>13 ± 1b</td>
</tr>
<tr>
<td>0.30%</td>
<td>18 ± 2c</td>
</tr>
<tr>
<td>0.45%</td>
<td>17 ± 1c</td>
</tr>
</tbody>
</table>

0.15%, 0.30%, and 0.45% indicate SAP content in soil. CK, soil with no SAP.

4. Discussion

The results indicate that the addition of SAP to soil could obviously increase the water retention of the soil. This could be
attributed to the three-dimensional cross-linked structure of SAP. The high cross-linked SAP can absorb and hold up to 400 times their weight of water (Orkiriza et al., 2009; Hüttermann et al., 1999). It has strong adsorption and complexing capacities for its hydrophilic functional groups, such as hydroxyl, carboxyl, amide, and sulfonic groups. Water moisture enters into the internal network easily, and forms a water-blocking layer between soil particles when the molecular chain swelled under the three-dimensional cross-linked structure, which could inhibit moisture from moving either from soil surface to the atmosphere or to rock layer of slopes, but make it moving horizontally, or to the place that had little SAP (Flory, 1971; Hüttermann et al., 2009).

During the first 5 days in the absorbing experiment, the evaporation rate of soil with SAP reduced. It might be explained on the basis of hydraulic lift and hydraulic conductivity of soil. Hydraulic lift is the nocturnal resupply of water in the upper soil layers which have been depleted during daytime (Richards and Caldwell, 1987). The hydraulic conductivity of soil is influenced by the particle size distribution of soil (Arya et al., 1999) and is a function of soil texture (Hultine et al., 2006). Amendment with polymer could decrease the hydraulic conductivity of soils (Bhardwaj et al., 2007; Agaba et al., 2010). Furthermore, the soil with SAP treatment can absorb more water than soil without SAP and allows the absorbed water to be released slowly when the soil moisture decreases (Al-Darby, 1996; El-Rehim et al., 2004; Chen et al., 2004; Ni et al., 2010). Similar observations have been reported by Bakass et al. (2002) who suggested that the presence of the polymer in the soil made it possible to preserve water longer than a soil without the polymer did, avoid the evaporation phenomenon which was observed just at the beginning of the drying reaction of the soil.

Furthermore, soils amended with higher concentrations of SAP released more water than the controls during the stress period. It should be attributed to the chemical hydrophilic groups and network structure in SAP hydrogel molecule. The water molecules were charged by weak connections and could involve a good exchange of water between the polymer and the soil (Bakass et al., 2002). Bakass et al. (2002) reported that polymer could absorb a very significant quantity of water, but dried first before the soil under drying period. The results also concord with that of Hüttermann et al. (1999), who observed that soil with highest concentration of hydrogels lost more water during water stress period.

In addition, there was a dramatic advantage of SAP treatments on seed germination and plant survivals compared with other treatments. The results indicate that an amendment of SAP would greatly enhance the drought tolerance of the seedlings planted in sandy loam soil. This could be attributed to water storage and nutrient retention in the soil matrix. By amending the soil with SAP, an additional system was incorporated into the soil which had both high water retention and a high water potential. It was possible to save water by reducing the water losses through infiltration and evaporation, increasing the duration of the presence of water in the soil, which could improve the life span and quality of plants (Bakass et al., 2002; Abedi-Koupai and Asadkazemi, 2006; Agaba et al., 2010). Furthermore, soil with SAP could absorb more water than soil without SAP and allow the absorbed water to be released slowly when the soil moisture decreased, and fertilizer nutrients could also be released slowly with water decreases, nutrient retention in hydrogel amended substrate could be increased (Ni et al., 2010; Agaba et al., 2010). Thus, the utilization of water and fertilizer was improved efficiently, seed germination was increased, and survival times of plant were prolonged under water stress.

However, no significant difference was observed between 0.30% and 0.45% SAP treatments on the survival time of plants, moreover, the survival time of grass plant in soil with 0.3% SAP was longer than that of 0.45% SAP treatment. It might be explained on the basis of water utilization efficiency of plant. Although there was much more water in the soil with 0.45% SAP than soil with 0.3% SAP during the initial stage, a significant part of water stored by hydrogel was apparently not available for the plants (Hüttermann et al., 1999). As a result, 0.45% SAP treatment did not appear to have significant advantage in extending plants life span compared with the 0.30% SAP treatment during the water stress period.

5. Conclusion

In conclusion, the amendment of soils with SAP considerably enhanced water uptake and utilization of water for plants growth, the 0.45% SAP treatment worked best. The saturated moist content increased by 42.69% and 139.38% compared with the controls in flat soil and the 60° slope soil, respectively. The evaporation rate decreased by 88.85% compared with the controls. Germination rate increased more than 2 times in grass, and about 3.5 times in woody compared with the controls. However, no significant difference was observed between 0.45% and 0.30% SAP treatments in extending plants life span. All in all, with respect to the water retention efficiency of soil with SAP amendment and the project cost, 0.30% SAP treatment was the optimum selection for sandy loam soil improvement on steep rocky slopes. In addition, straw was covered on the surface of the soil in our study. So, soil erosion was not the focus of our study. The effect of SAP amendment on soil erosion would be studied in the next periods.

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