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*Full Length Research Paper*

# Application of soil conditioners and man-made erosion control materials to reduce erosion risk on sloping lands

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**The objective of this study was to evaluate the effect of soil conditioners and man-made erosion control materials on stabilization of sloping hills using rainfall simulator and small flume facilities. Treatments were man-made erosion control materials (from polypropylene fabric) and soil conditioners (gypsum and PAM), these treatments were evaluated on a soil sample with a clay texture taken from a hill having 15 to 30% slopes. Soil surface were subjected to 3 simulated rainstorm including 25, 50 and 75 mm h$^{-1}$. Runoff and sediment loss rates were determined in different times for 60 min after initiation of runoff. Man-made erosion control materials were reduced sediment concentration and runoff intensity between ranges of 4 - 82% and 0 - 8% respectively compared with the bare soil. Also, amending soil surface with soil conditioners did not reduce runoff significantly compared with the control on steep slopes. Application of soil conditioners alone had low efficiency. Whereas application of high levels of conditioners reduced soil loss to non detectable levels as compared with the control treatment. Obtained results from measurements of aggregate stability index and mean weight diameter of soil particles, for various amount of soil conditioners also showed that using these materials with improving soil physical properties, decreasing surface sealing, and enhancing infiltration rate, will reduce soil loss.**

**Key words:** Soil conditioners, man-made erosion control materials, simulated rainfall, runoff and sediment yield.

## INTRODUCTION

With rapid growth of population and wide request for foodstuffs, doubtless in many areas of the world due to shortage of level lands or lands having little slopes, there is no option other than cultivation on sloping areas. Evidently cultivation on steep slopes without conservative managements leads to land degradation. Therefore, using conservative methods with economical advantages is so important for approaching to sustainable agriculture on agricultural sloping lands. But effectiveness and to be profitable of these methods are unclear yet. Recently, and especially on steeply sloped hillsides, contractors have chosen to establish vegetation by broadcasting seed and covering the seed with a man-made material. Commercially produced man-made erosion control materials that are often used include woven or bonded mats and blankets composed of biodegradable fibers such as excelsior (curled wood fiber), wood, jute, straw, coconut, or a combination of them, and geosynthetic materials such as polypropylene, polyethylene, nylon and polyvinyl chloride (PVC) which are known as the rolled erosion control systems (RECS) (Krenitsky et al., 1998; Sutherland and Ziegler, 2006). They are designed to reduce the energetics of rainfall and runoff, and at the same time foster an equitable microclimate for subsequent vegetation growth (Ziegler et al., 1997). Numerous studies have shown that dissipation of raindrop energy by any means, natural or artificial, leads to reduce erosion. In particular Ziegler and Sutherland (1998) claimed that some of the rolled erosion control systems (natural and synthetic) are able to reduce runoff and sediment significantly compared with the control. Agassi (1997) used 5 types of geomembranes to reduce runoff and erosion on 50% slope under laboratory and field conditions. The membranes dissipated the drops impact and reduced runoff

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(a) (b)

**Figure 1.** (a) five man-maid erosion control materials used in this study and installation of one of them with steel pins and (b) application of PAM and gypsum on the soil surface of the flume.

significantly compared with the control. There was no significant difference among the membranes regarding their effect on the runoff.

Another way of increasing the stability of soil structure is by the use of soil conditioners, which are substances that improve the physical properties of soils, and these include synthetic polymers and natural material like gypsum (Ben-Hur, 2006). Polyacrylamide (PAM) is one of the synthetic polymers with the ability to enhance soil stabilization. This polymer is able to reduce soil detachment, maintain the soil structure and increase infiltration rate early in the rain events. In 1990s has shown that PAM is an effective polymer in reducing erosion in furrow irrigation on fine silt/clay soils (Lado et al., 2004.). Whether used alone or in conjunction with other erosion control practices, PAM is both economical and effective in controlling erosion. Therefore it was found to be a cost-effective and safe technology (Roa-Espinosa et al., 2000). Another group of soil conditioners are the cementitious-based binders such as gypsum. Calcium ions are effective at improving soil structure and increasing water infiltration. In addition, calcium and sulfur are important micronutrients for plants. Gypsum ($CaSO_4.2H_2O$) is used commonly used as a soil amendment to provide calcium (an electrolyte source) and sulfur (Alcordo and Rechcigl, 1995). Brauer et al., (2005) demonstrated the usefulness low cost gypsum as soil amendments in reducing runoff and erosion. Tang et al., (2006) reported that because of economical advantages of gypsum, application of PAM along with gypsum can be recommended for increasing their efficiency in increasing aggregate stability and reducing runoff and sediment yield. Similarly Wallace-Cochrane et al. (2005) pointed out that due to cheap value and low cost of surface application of gypsum make this material a suitable option for erosion control by improving infiltration and reducing surface sealing.

Cultivation on sloping hills without doing suitable conservative activities causes irreparable damages to agriculture because of soil degradation and decreasing of crop productivity. The present study was therefore, carried out with objective to evaluate the effect of soil conditioners and man-made erosion control materials on stabilization of sloping hills using rainfall simulator and small flume facilities.

## MATERIALS AND METHODS

The site of sampling was in Sarcham village in Zanjan province of Iran which is located on downstream side of Zanjanrood. Sampling was conducted on 15 cm of the soil surface with clay texture taken from one of the sloping lands of this region. After transportation of soil sample to laboratory the experiments was conducted on air-dried soil that was passed through an 4.75 mm sieve. Soil texture, determined by the hydrometer method, was 49% clay, 32% silt and 19% sand. Organic mater was nondeductible, saturated paste pH 7.8, saturated paste electrical conductivity ($EC_e$) 17.18 dS $m^{-1}$, Na adsorption ratio (SAR) 9.85 and cation exchange capacity (CEC) 14.2 meq 100 g $soil^{-1}$. Water used for rainfall simulation experiments had electrical conductivity of 1.4 dS $m^{-1}$, pH 8 and sodium adsorption ratio of 2.2. Experimental treatments were consisted of: soil without cover and amendments (control), covering the soil surface with 5 types of man-made erosion control materials, spraying the soil surface with PAM, mixing gypsum with upper 5 mm of the soil surface and applying PAM + gypsum simultaneously.

The man-made erosion control materials, rolled erosion control systems (RECS), were composed of woven layers of non-biodegradable geosynthetic materials from polypropylene fabric. 5 of these materials with regular grid network of synthetic fibers of systematically arranged square apertures with diameters of 5.5, 3, 1.5, 1 and 0.5 cm were selected due to segregation of their effectiveness on runoff and sediment reduction. Also % of ground cover by each of them was calculated separately. The man-made erosion control materials that diameter of their apertures was 5.5, 3, 1.5, 1 and 0.5 cm, had the 13, 18, 36, 44 and 55% of ground cover, respectively. Before each run (24 h after complete saturation of soil) RECS was installed on soil surface with U shape steel pins to provide complete contact with the soil surface (Figure 1a). Dry granular anionic PAM copolymer with a molecular weight of about 5 Mg $mole^{-1}$ was used as well. Before application of PAM this polymer was dissolved in water and then was sprayed on the soil surface with 3 solution concentration of 25, 50 and 75 kg $ha^{-1}$. Also 10, 20 and 30 Mg $ha^{-1}$ dry powder of natural inorganic gypsum was mixed with upper 5 mm of the soil surface (Figure 1b). Also, combination of 25 kg $ha^{-1}$ PAM + 10 Mg $ha^{-1}$ gypsum, 50 kg $ha^{-1}$ PAM + 20 Mg $ha^{-1}$ gypsum and 75 kg $ha^{-1}$ PAM + 30 Mg $ha^{-1}$ gypsum was investigated in this study.

For each of experiments approximately 100 Kg of soil sample was packed in the 1 × 1 m tilting flume's tray (adjustable between 0 to 50% slopes) and leveled manually and investigated with an rainfall simulator with oscillating nozzle (Figure 2). The rainfall simulator was positioned 3 m above the soil surface. Uniformity of rainfall and determination of different rain intensities with necessary variation in angle of nozzle rotation has accomplished. This rainfall simulator was provided a mean drop size of 1.5 mm diameter with a kinetic energy of 15.1 J $mm^{-1}$ $m^{-2}$. In this study soil surface was leveled with the ledge of basin of the flume and saturated with a plastic pipe that was laid in the bottom of basin of flume. After complete exit of gravity water, the action of rainfall simulation in

(a) (b) (c)

**Figure 2.** The research institute of forests and rangelands of Iran (IRIFR) tilting flume and simulated rainfall facility consisting of: (a) steel frame with oscillating nozzle and tilting flume, (b) water container with water pump (up) and electronic control system (down) and (c) wet sieving apparatus (up) torvane (down).

different rain intensities (25, 50 and 75 mm $h^{-1}$) and different slope (15, 20, 25 and 30%) has done with the electronic control system for all treatments. Runoff water, percolation water, sediment yield, shear strength of soil surface and splash of soil particles was measured for each run. Runoff was collected for each run in different times for 60 min after initiation of runoff. Weight and volume of runoff sample were recorded. Sediment concentrations were determined gravimetrically using the evaporation method (Brakensiek et al., 1979) after drying the samples in the oven with temperature of 105°C after 24 h. Mean value (ultimate) runoff and sediment were measured finally.

Splash of soil particles was collected and measured for each run after drying the samples in the oven. Shear strength of soil surface before and after each run was measured with torvane apparatus. Water stable aggregate (WSA) and mean weight diameter of soil particles (MWD) before and after treatment with soil conditioners were determined using the wet sieving method (Figure 2c). Though for achievement to most accurate results some experiments were repeated, because of carrying a large amount of soil (about 100 kg) for each run, replication of experiments in prevalent models of statistical plots was not conceivable. Performance of experiments without replication is common in rainfall simulation studies. So any error in results may be possible.

## RESULTS

### Rainfall simulation in control treatments

Sediment yield, runoff water, percolation water, ahead splash of soil particles (bottom of the slope direction) and shear strength of soil surface (after the end of each run) for control treatments in different slopes (15, 20, 25 and 30%) and different rain intensities (25, 50 and 75 mm $h^{-1}$) in rainfall simulation experiments were collected and measured (Table 1).

As shown in Figure 3, with increasing in rainfall intensity, runoff increased to high values, whereas addition in slope inclination does not have great influence on runoff intensity. In other words, the main reason of runoff generation in this soil was the intensity of rainfall. Moreover, due to a large amount of clay particles at the soil surface on relatively steep slopes, by reason of raindrop impact, a structural seal at the soil surface was formed (Borselli et al., 1996). So infiltration rat in this soil due to this structural seal was confined and increasing in rain intensity enhanced runoff volume rapidly. Therefore addition in slope degree from 15 to 30% because of this surface sealing had not too much influence on runoff intensity. More explanation is, in low slopes partial change in slope had a perceptible influence on enhancement of runoff volume. For example increasing of slope degree from 0 to 3% had a grate influence on runoff intensity, whereas in steep slopes intense change in slope inclination had not this grate influence. Increase in sediment concentration with addition of slope and rain intensity is also presented in Figure 3. As shown in this Figure, rainfall intensity and slope degree had the grate influence on sediment concentration values. Increasing in sediment concentration with addition of slope and rain intensity is similar to splash of soil particles in the direction of front section of the flume (Figure 3). Thus can be concluded that, splash of soil particles and runoff had high effect on sediment concentration. Figure 3 also shows relation between shear strength of bare soil surface with rain intensity and slope after rainfall simulation experiments as well. As shown in this Figure, increase in slope inclination resulted in decline of shear strength. This phenomenon presumably is because of decreasing of surface area which receives rainfall with increasing of slope degree. Moreover, probably when slope inclination increases, raindrop impact on soil surface will reduce

**Table 1.** Various parameters measured in control treatments in different slopes and rain intensities in rainfall simulation experiments.

| Slope (%) | Rain intensity (mm $h^{-1}$) | Runoff (mm $h^{-1}$) | Infiltration rat (mm $h^{-1}$) | Runoff Coefficient | Sediment concentratio n (g $l^{-1}$) | Splash (g $h^{-1}$) | Shear strength (kg $cm^{-2}$) |
|---|---|---|---|---|---|---|---|
| 15.00 | 25.00 | 20.50 | 3.50 | 0.82 | 10.63 | 11.55 | 0.11 |
| 15.00 | 50.00 | 41.32 | 7.63 | 0.83 | 21.86 | 18.52 | 0.13 |
| 15.00 | 75.00 | 64.25 | 9.00 | 0.86 | 37.30 | 23.26 | 0.16 |
| 20.00 | 25.00 | 21.71 | 2.32 | 0.87 | 22.75 | 16.27 | 0.11 |
| 20.00 | 50.00 | 44.22 | 4.88 | 0.88 | 45.03 | 25.03 | 0.12 |
| 20.00 | 75.00 | 68.25 | 5.13 | 0.91 | 69.75 | 29.07 | 0.15 |
| 25.00 | 25.00 | 23.00 | 1.03 | 0.92 | 48.68 | 22.92 | 0.11 |
| 25.00 | 50.00 | 47.13 | 2.35 | 0.94 | 92.31 | 33.82 | 0.12 |
| 25.00 | 75.00 | 72.15 | 2.35 | 0.96 | 120.67 | 37.57 | 0.14 |
| 30.00 | 25.00 | 24.03 | 0.33 | 0.96 | 104.18 | 32.28 | 0.11 |
| 30.00 | 50.00 | 49.33 | 0.47 | 0.99 | 188.32 | 45.70 | 0.12 |
| 30.00 | 75.00 | 74.10 | 0.81 | 0.99 | 199.10 | 49.67 | 0.13 |

[a] shear strength measured before rainfall simulation experiments: (0.09 kg $cm^{-2}$)

which leads to formation of less surface sealing and less value of shear strength.

### Rainfall simulation in soils treated by soil conditioners and man-made erosion control materials

Sediment yield, runoff water, percolation water, ahead splash of soil particles, and shear strength of soil surface 24 h after treatment of soil surface with soil conditioners and man-made erosion control materials were collected and measured in different slopes (15, 20, 25 and 30%) and different rain intensities (25, 50 and 75 mm $h^{-1}$) during the rainfall simulation experiments were collected and measured.

### Sediment yield

Soil conditioners and rolled erosion control systems (RECS), man-made erosion control material, effect on reducing of sediment yield (mean sediment concentration) at 15 and 30% slopes and different rain intensities (25, 50 and 75 mm $h^{-1}$) are illustrated in Figure 4. Procedure of alterations in other slopes (20 and 25%) is similar to 15 and 30% slope. As shown in this Figure and accomplished calculations, between man-made erosion control materials, RECS with apertures of 1.5, 1 and 0.5 cm diameter were the most effective in sediment reduction compared with the control. Hence, can be concluded that RECS that diameter of their apertures was les than 1.5 cm or % of their ground cover was over 36% could be the most effective in sediment reduction. Also as shown in this figure and accomplished calculations, application of 25 kg $ha^{-1}$ PAM on steep slopes (30%) and under intense rain intensities (75 mm $h^{-1}$) had not any effect on sediment reduction compared with the control. But spraying the soil surface with this same amount of PAM could reduce sediment concentration approximately between 27 up to 40% at 15 to 20% slopes compared with the control. Also application of 75 kg $ha^{-1}$ PAM at 30% slope and under 75 mm $h^{-1}$ rain intensity was able to reduce sediment concentration about 58% compared with the control. Thus, with due attention to obtained results, it seems that application of 50 kg $ha^{-1}$ PAM has low efficiency in reducing sediment concentration at 30% slope and under intense rain intensities (50 and 75 mm $h^{-1}$). Whereas spraying the soil surface with this same amount of PAM is relatively high at 15, 20 and 25% slopes and under different rain intensities. Application of 30 Mg $ha^{-1}$ gypsum by formation of a thin protective layer on the soil surface and improvement of soil physical properties reduced soil loss to low levels at steep slopes and under intense rain intensities as well. So that application of 30 Mg $ha^{-1}$ gypsum at 30% slope and 75 mm $h^{-1}$ rain intensity was reduced sediment concentration approximately 85% compared with the control which is too considerable. Consequently reduction of soil loss to low levels is accessible by use of high contents of gypsum on steep slopes and under intense rains. This issue receives too much concern when use of gypsum at great volumes has not economical disadvantages. Also as shown in this Figure, application of 75 kg $ha^{-1}$ PAM along with 30 Mg $ha^{-1}$ gypsum reduced soil loss to non detectable levels as compared with control. So that application of these contents of soil conditioners together was reduced sediment concentration approximately 99% compared with the control on more slopes and rain intensities. Application of 50 kg $ha^{-1}$ PAM along with 20 Mg $ha^{-1}$ gypsum at 30% slope and under 75 mm $h^{-1}$ rain intensity was reduced sediment

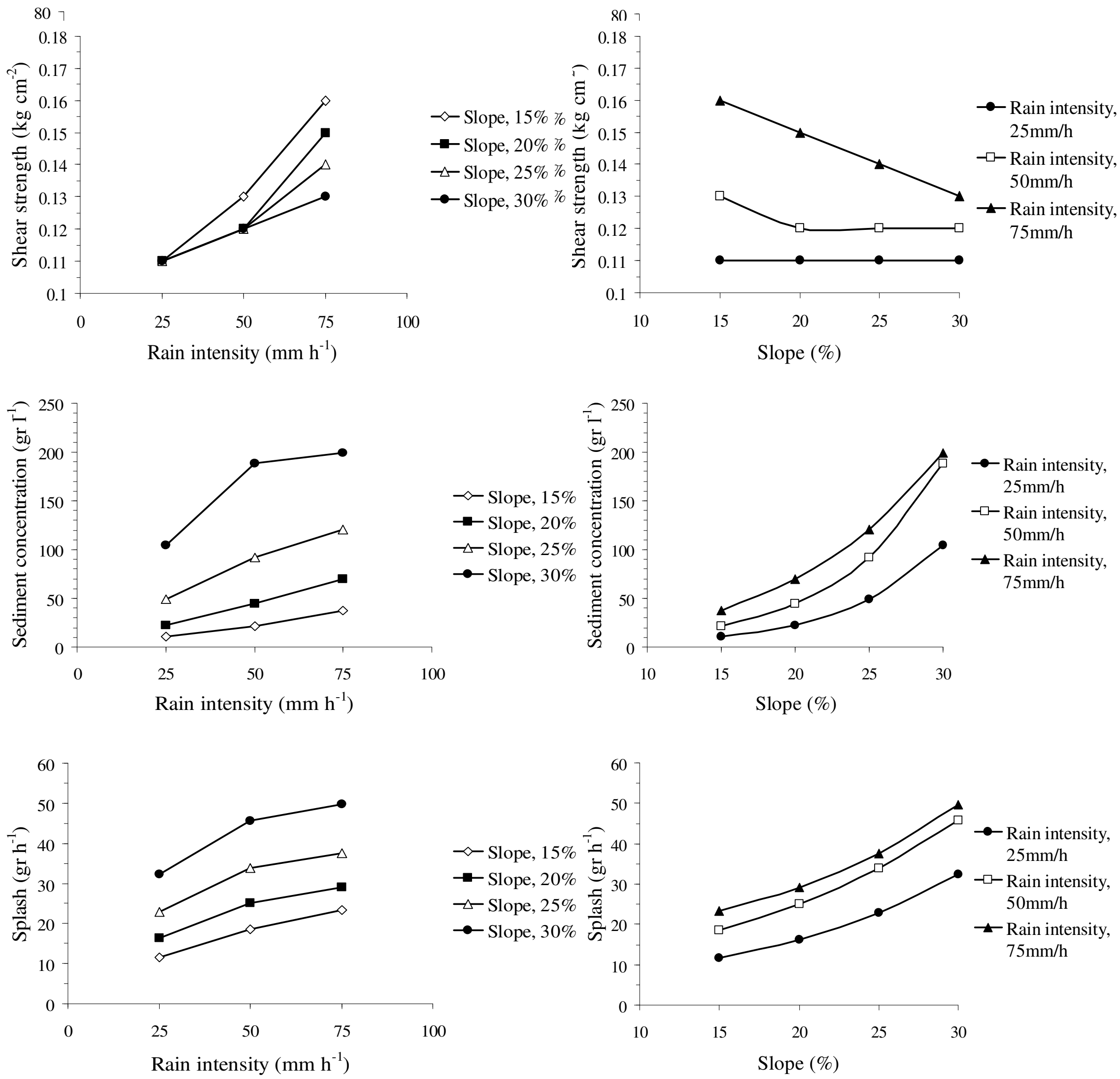


**Figure 3.** Slope inclination and rain intensity effects on runoff intensity, sediment concentration, splash of soil particles in the direction of front section of the flume and shear strength of soil surface in control treatments.

concentration approximately 73% compared with the control which is considerable.

The effect of different levels of soil amendments in reducing of sediment concentration in different times during 60 min after initiation of runoff on 30% slope and under 75 mm $h^{-1}$ rain intensity compared with the control is illustrated in Figure 5. As shown in this Figure, effectiveness of 25 kg $ha^{-1}$ PAM decreased at the initial moments of runoff generation rapidly. It means that alterations of sediment concentration with time for this treatment reached to a steady state so quickly. Whereas, effectiveness of 75 kg $ha^{-1}$ PAM decreased about 40 min after initiation of runoff in this slope and rain intensity (40 min lasted for reaching to steady state). Hence, spraying of soil surface with high amounts of PAM has considerable efficiency on soil loss.

Also as shown in this figure, effectiveness of 30 Mg $ha^{-1}$ gypsum on sediment reduction did not decreased even 1 hour after initiation of runoff. Alterations of sediment concentration with time for treatment of 50 kg $ha^{-1}$ PAM + 20 Mg $ha^{-1}$ gypsum reached to steady state approximately 60 minute after initiation of runoff as well. This figure also illustrates efficiency of 75 kg $ha^{-1}$ PAMalong with 30 Mg $ha^{-1}$ gypsum on soil loss reduction compared with the control on steep slopes and intense rains thoroughly. So that even 60 minute after initiation of runoff, sediment concentration is negligible for this treatment (~ 99 % lower than control treatment). So application of gypsum and PAM with one another by formation of a thin protective layer on the soil surface (role of gypsum) and floculation of clay particles and improvement of soil physical properties (role of gypsum + PAM) can reduce soil

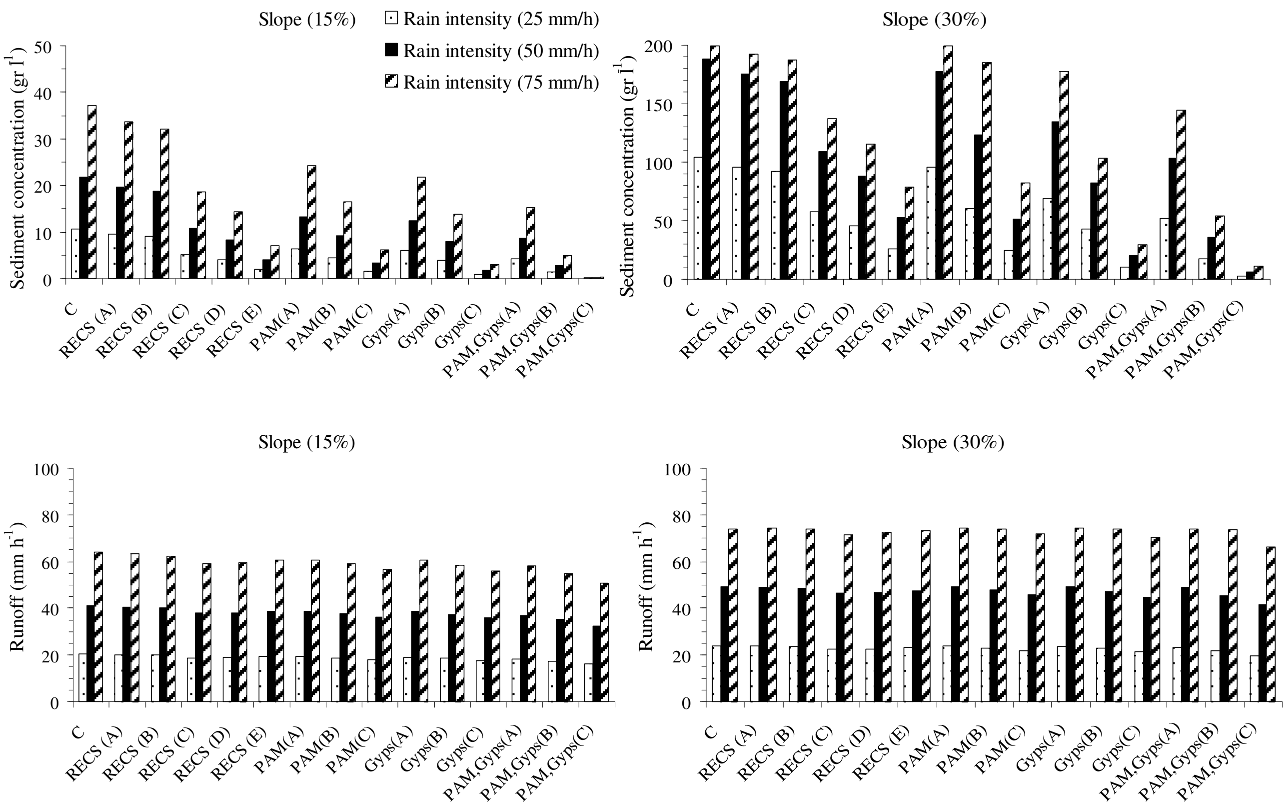


**Figure 4.** Soil conditioners and rolled erosion control systems (RECS) effect on reducing of sediment concentration and runoff intensity at 15 and 30 % slopes and different rain intensities compared with the control. In these diagrams and subsequent diagrams C is control treatment, RECS (A), (B), (C), (D) and (E) are RECS with apertures of 5.5, 3, 1.5, 1 and 0.5 cm diameter respectively, PAM (A), (B) and (C) are application of 25, 50 and 75 kg ha$^{-1}$ PAM respectively, Gyps (A), (B) and (C) are application of 10, 20 and 30 Mg ha$^{-1}$ gypsum respectively, PAM,Gyps (A), (B) and (C) are application of 25 kg ha$^{-1}$ PAM + 10 Mg ha$^{-1}$ gypsum, 50 kg ha$^{-1}$ PAM + 20 Mg ha$^{-1}$ gypsum and 75 kg ha$^{-1}$ PAM + 30 Mg ha$^{-1}$ gypsum.

loss to non detectable levels. Because of economical advantages of gypsum, so application of PAM along with gypsum can be recommended for increasing their efficiency.

## Runoff

Soil conditioners and rolled erosion control systems (RECS) effect on reducing of runoff (mean runoff intensity at 15 and 30% slopes and different rain intensities (25, 50 and 75 mm h$^{-1}$) is presented in Figure 4. Procedure of alterations in other slopes (20 and 25%) is similar to 15 and 30% slope. As shown in this Figure, installation of RECS and application of soil conditioners had not so influence on runoff reduction. The effect of different amounts of soil amendments in reducing of runoff intensity in different times during 60 min after initiation of runoff on 30% slope and under 75 mm h$^{-1}$ rain intensity compared with the control is shown in Figure 5. As shown in this Figure, effectiveness of various amounts of soil conditioners in runoff reduction decreases on steep slopes at the initial moments of runoff generation rapidly. So with due attention to this Figure, PAM and gypsum are not able to delay runoff production and will lose their effectiveness very fast.

## Splash of soil particles in the direction of front section of the flume

Our results showed that all of amounts of soil conditioners were not effective in decreasing of soil splash detachment. So that even application of 75 kg ha$^{-1}$ PAM + 30 Mg ha$^{-1}$ gypsum on 30% slope and under 75 mm h$^{-1}$ rain intensity decreased soil splash detachment by just 7% compared with the control. So soil conditioners rather with increasing of aggregate stability and prevention of aggregate detachment reduces the formation of surface sealing and has not so much role in decreasing of splash of soil particles. In addition, RECS with due attention to diameter size of their apertures reduced the impact of raindrop absorbing its energy. Consequently soil particle detachment, splash of these particles, accessibility and transportation of these particles by runoff, and soil loss was reduced. Thus, by decreasing of diameter size of their apertures (increase of their surface cover %) splash of soil particles was reduced.

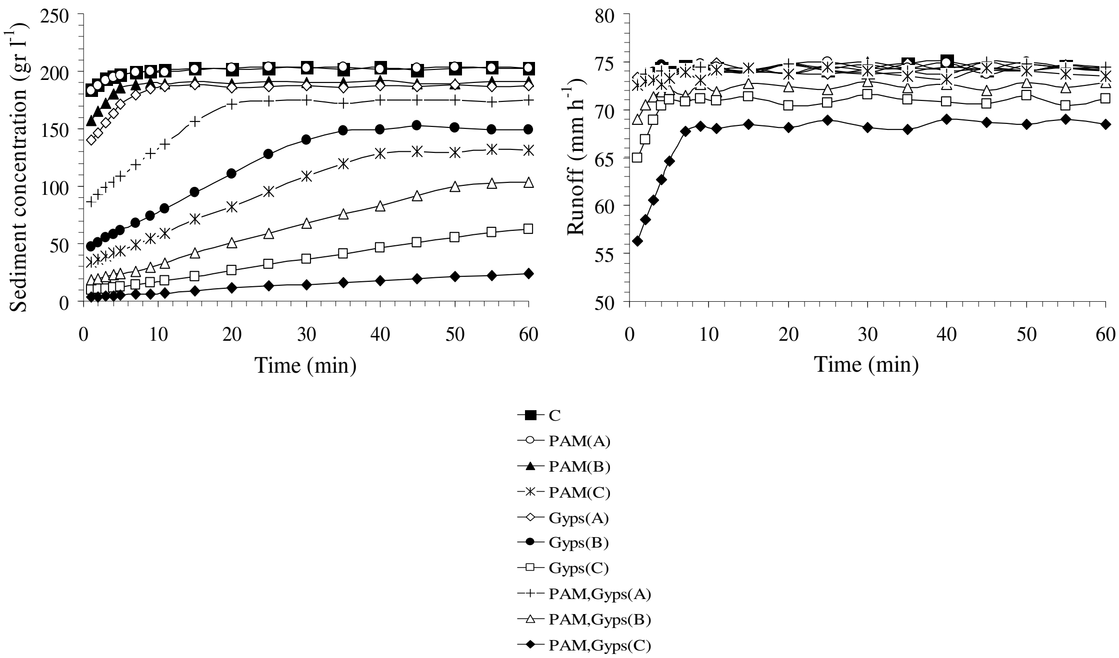


**Figure 5.** Soil conditioners effect on reducing of sediment concentration and runoff intensity at 30% slope and under 75 mm h$^{-1}$ rain intensity in different times during 60 minute after initiation of runoff compared with the control.

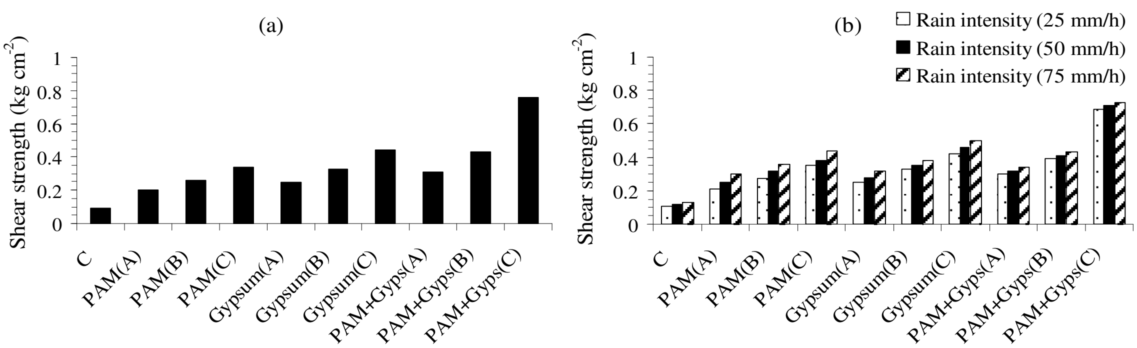


**Figure 6.** Soil amendments effect on shear strength of the soil surface: (a) before rainfall simulation experiments and (b) after rainfall simulation experiments at 30% slope and different rain intensities compared with the control.

## Shear strength of soil surface

As illustrated in Figure 6, measurement of shear strength of the soil surface before and after rainfall simulation experiments had shown that with addition of soil conditioners to soil surface due to improvement of soil physical properties and production of more stable aggregates its value increased.

## Aggregate stability

For better showing of effectiveness of soil conditioners on stability of soil structure, aggregate stability index in (WSA) criterion and mean weight diameter of soil particles (MWD) values for all treatments were determined using the wet sieving method (Table 2). Comparison of mean weight diameter and stability index of soil aggregates after treatment with soil binders shows with increasing of soil conditioners contents, larger and more stable aggregates will appear. Thus, with increasing of aggregate stability, less surface sealing can be expectable with application of soil amendments.

## DISCUSSION

### Rolled erosion control systems (RECS)

% of reduction variations of runoff in different slopes and

**Table 2.** Results obtained of aggregate stability measurement and stability index for various amount of PAM and gypsum.

| MWD (mm) | % WSA > 0.075 mm | % WSA > 0.125 mm | % WSA > 0.25 mm | % WSA > 0.5 mm | % WSA > 1 mm | % WSA > 2 mm | Treatments |
|---|---|---|---|---|---|---|---|
| 0.203 | 49.77 | 35.82 | 15.26 | 6.74 | 3.84 | 1.09 | Control |
| 0.231 | 55.26 | 40.47 | 17.85 | 8.14 | 4.71 | 1.37 | 25 kg $ha^{-1}$ PAM |
| 0.251 | 61.53 | 44.80 | 19.50 | 8.77 | 5.05 | 1.47 | 50 kg $ha^{-1}$ PAM |
| 0.268 | 67.02 | 48.74 | 21.19 | 9.52 | 5.49 | 1.59 | 75 kg $ha^{-1}$ PAM |
| 0.247 | 60.53 | 44.09 | 19.22 | 8.64 | 4.99 | 1.44 | 10 Mg $ha^{-1}$ gypsum |
| 0.266 | 65.90 | 47.89 | 20.75 | 9.33 | 5.37 | 1.56 | 20 Mg $ha^{-1}$ gypsum |
| 0.285 | 72.36 | 52.54 | 22.71 | 10.20 | 5.87 | 1.68 | 30 Mg $ha^{-1}$ gypsum |
| 0.258 | 64.43 | 46.86 | 20.34 | 9.17 | 5.27 | 1.53 | 25 kg $ha^{-1}$ PAM+10 Mg $ha^{-1}$ gypsum |
| 0.281 | 71.39 | 51.86 | 22.46 | 10.11 | 5.80 | 1.68 | 50 kg $ha^{-1}$ PAM+20 Mg $ha^{-1}$ gypsum |
| 0.379 | 90.14 | 65.46 | 28.46 | 12.79 | 7.36 | 2.12 | 75 kg $ha^{-1}$ PAM+30 Mg $ha^{-1}$ gypsum |

rain intensities for RECS with apertures of 5.5, 3, 1.5, 1 and 0.5 cm diameter was 0 - 2, 0 - 3, 3 - 8, 2 - 8 and 1 - 6% respectively compared with the control. So RECS with a pertures of 1.5 cm diameter was the most effective in runoff control compared with the other treatments. This may be mainly probably due to size and shape of apertures, method of installation of RECS on the soil surface, and size of the flume. It seems because of having finer apertures; water could not penetrate easily in to the soil treated with RECS with apertures of 1 and 0.5 cm diameter, compared with RECS with apertures of 1.5 cm diameter. So water rapidly reached to the end of the flume in soil treated with RECS with apertures of 1 and 0.5 cm diameter. Sutherland and Ziegler (2006) reported that RECS with regular grid network of fibers of systematically arranged square or rectangular apertures was less effective than those with irregular grid network of fibers in reducing erosion. So the shape, setting and status of apertures are important factors effecting on runoff conduction. For example plastic covers are impervious and have not any apertures for percolation of water in to the soil. So they can not reduce runoff and can cause erosion problems because of runoff conduction (Wan and El-Swaify, 1999). Hence RECS with apertures of less than 1.5 cm diameter (more than 36% of ground cover) can probably intensify runoff in receiving areas with steep slopes due to the excessive flow with increased velocities. We supposed that low efficiency of all RECS in reducing of runoff was due to small size of the flume as well. Ziegler and Sutherland (1998) stated a rolled erosion control product combines a number of some attributes will greatly reduce runoff and sediment transport. They showed favorable rolled erosion control products attributes for erosion control was consisting of (i) significant 3 dimensionality that reduces raindrop impact, interferes with splash transport of sediment, and increases hydraulic resistance to overland flow, (ii) fiber integration within the upper soil horizon, which increases shear strength of the soil thereby reducing overland flow velocities, (iii) significant surface coverage with small random openings that mitigate raindrop impact and splash transport; (iv) fibers with high water sorbance that reduce runoff volume, (v) fibers conforming to micro-topographic variations when wet (drapability), thereby reducing overland flow between the product and the soil surface and (vi) ability to pond water to depths greater than the medium raindrop diameter. In field or natural conditions usually RECS are installed on hillslopes with long lengths. So installation of RECS on small flumes, which is very different with natural conditions, can reduce their efficiency in erosion control explained above. RECS installed on this small flume were not able to delay the generation of runoff by maintaining structural surface integrity, and form micro dams and lengthen overland flow path presumably (Sutherland and Ziegler, 2006). So runoff did not reduced to low levels compared with the control after installation of RECS.

% of reduction variations of sediment concentration in different slopes and rain intensities for RECS with apertures of 5.5, 3, 1.5, 1 and 0.5 cm diameter was 4 -10, 6 - 14, 31 - 60, 42 - 62 and 60 - 82% respectively compared with the control. RECS with apertures of 5.5 and 3 cm diameter were not efficient in reducing sediment concentration due to having big apertures compared with other RECS similar to mentioned reasons about runoff. Similar results about the role of RECS in reducing sediment yield have reported before (Sutherland, 1998).

## PAM

% of reduction variations of runoff in different slopes and rain intensities for application of 25, 50 and 75 kg $ha^{-1}$ PAM was 0 - 6, 0 - 9 and 3 - 12% respectively compared with the control. With due attention to these Figures, application of low levels of PAM on steep slopes (30%) and under intense rain intensities (75 mm $h^{-1}$) has insignificant effect on runoff reduction compared with the control. Also application of low levels of PAM lost its effectiveness in reducing of runoff rapidly. This may be mainly due to soil saturation, surface sealing and soil consolidation. Our results support the findings of other studies. Blanco-Canqui et al. (2004) showed that 9 kg $ha^{-1}$ PAM applied on silty loam soils at 4.5 and 5% slopes under intense rains (69 and 93 mm $h^{-1}$) reduced runoff by 13% compared with the control. They reported that PAM is effective for reducing runoff only during the early stages of rainfall as well. So that, PAM effectiveness diminished rapidly with time. Similarly, Aase et al. (1998) found that 2 kg $ha^{-1}$ of PAM reduced runoff by 70%, however, runoff from PAM-treated and untreated soil after 30 min of irrigation at 80 mm $h^{-1}$ was the same. They suggested that runoff from the PAM treatment would quickly approach that of the control treatment under intense rains.

% of reduction variations of sediment concentration in different slopes and rain intensities for application rate of 25, 50 and 75 kg $ha^{-1}$ PAM was 0 - 40, 7 - 58, and 58 - 85% respectively compared with the control as well. The high efficiency of 75 kg $ha^{-1}$ of PAM in reducing of sediment concentration is presumably due to improving the soil structure stability. Also rainfall decreased PAM effecttiveness, leaving soil surface increasingly unprotected from the raindrop impact in the soils treated with low levels of PAM. We suggest that because of PAM penetration into the soil is limited; it quickly lost its effectiveness as the soil was eroded. Indeed Lu and Wu (2003) reported that PAM has very low penetration into the soil profile. The effectiveness of PAM for reducing erosion decreased from 94 to 82% between the first 30 min and the end of the 1 h dry run. Similarly, Blanco-Canqui et al. (2004) showed that effectiveness of 9 kg $ha^{-1}$ PAM decreased 30 min after initiation of rainfall (approximately 20 min after beginning of runoff) on a silty loam soil with 4.5% slope under 69 mm $h^{-1}$ rain intensity. They indicated that 9 kg $ha^{-1}$ of PAM is insufficient to control erosion to low levels for rainfall events longer than 30 min. Decrease in PAM effectiveness for application of 75 kg $ha^{-1}$ PAM after initiation of runoff in this study is approximately similar to findings by Peterson et al. (2002), who reported that soil loss from recently tilled soils treated with 60 kg $ha^{-1}$ PAM did not increase within 1 h of rainfall simulation at 75 mm $h^{-1}$. Similarly, Flanagan et al. (2002) reported that application of 80 kg $ha^{-1}$ PAM on disturbed 32% sloping soils was effective on reducing soil loss by 54% after 9 rainfall events and 40% from 19 events over a 6 month period. Because durability of erosion control by low application levels of PAM is short, we speculate split application of PAM after major rainfall events may be a successful treatment.

## Gypsum

% of reduction variations of runoff in different slopes and rain intensities for application of 10, 20 and 30 Mg $ha^{-1}$ gypsum was 0 - 7, 0 - 9, and 5 – 13% respectively compared with the control. Our results showed that application of low levels of gypsum on steep slopes and under intense rain intensities had insignificant effect on runoff reduction compared with the control. Also application of low levels of gypsum lost its effectiveness in reducing of runoff rapidly. This may be due to washing of gypsum by runoff, surface sealing and soil consolidation. Our results are similar to findings of other studies just in some aspects. For example Tishmack et al. (2001) showed that application of 5 Mg $ha^{-1}$ inorganic gypsum on a silty clay soil at 9.5% slope under 70 mm $h^{-1}$ simulated rainfall reduced runoff by 12% compared with the control. They reported that alterations of runoff with time for this treatment reached to steady state approximately 35 min after initiation of runoff (45 min after initiation of rainfall). Whereas in this study for treatment of 30 Mg $ha^{-1}$ gypsum just about 5 min time was needed to reached to steady state after initiation of runoff at 30% slope and under 70 mm $h^{-1}$rainfall. Our lower effectiveness may be explained by the higher slope in this study and different behavior of various soils treated by gypsum.

% of reduction variations of sediment concentration in different slopes and rain intensities for application rate of 10, 20 and 30 Mg $ha^{-1}$ gypsum was 11 - 44 , 48 -64, and 85 - 92% respectively compared with the control as well. The high efficiency of 30 Mg $ha^{-1}$ gypsum in reducing of sediment concentration is presumably due to improving the soil structure stability. Also rainfall decreased gypsum effectiveness in the soils treated with low levels of gypsum. Similarly, Tishmack et al. (2001) showed that application of 5 Mg $ha^{-1}$ inorganic gypsum on a silty clay 9.5% sloping soil under 70 mm $h^{-1}$ simulated rainfall reduced sediment loss by 28% compared with the control. They reported that alterations of sediment concentration with time for this treatment reached to steady state approximately 35 min after initiation of runoff (45 min after initiation of rainfall). With due attention to these findings it seems that durability of erosion control by gypsum is long and even at intense rains this material do not loss its efficiency in reducing of erosion. So we suggest that because of economical advantages of gypsum with high application levels of gypsum in one stage can reduce soil erosion to low levels. So can be concluded due to cheap value and low cost surface application of gypsum, this material is a suitable option for erosion control.

## PAM + Gypsum

% of reduction variations of runoff in different slopes and rain intensities for application of 25 kg $ha^{-1}$ PAM + 10 Mg $ha^{-1}$ gypsum, 50 kg $ha^{-1}$ PAM + 20 Mg $ha^{-1}$ gypsum and 75 kg $ha^{-1}$ PAM + 30 Mg $ha^{-1}$ gypsum was 0 - 11, 1 - 15 and 11 -22% respectively compared with the control. Our results showed that application of low levels of PAM + gypsum on steep slopes and under intense rain intensities had insignificant effect on runoff reduction compared with the control. Also application of low levels of PAM + gypsum lost its effectiveness in reducing of

**Table 3.** Cost of purchasing and installation of different types of soil conservation.

| Cost of installation ($/ha) | Cost of purchasing ($/ha) | Types of soil conservation |
|---|---|---|
| 1700 - 3700 | 187.50-375.00 | 25 kg $ha^{-1}$ PAM |
| | 375.00-750.00 | 50 kg $ha^{-1}$ PAM |
| | 562.50-1125.00 | 75 kg $ha^{-1}$ PAM |
| 2000 - 3000 | 100.00-200.00 | 10 Mg $ha^{-1}$ gypsum |
| | 200.00-400.00 | 20 Mg $ha^{-1}$ gypsum |
| | 300.00-600.00 | 30 Mg $ha^{-1}$ gypsum |
| 30000 - 70000 | 3000.00-5000.00 | RECS (geotextiles) |

[1] presented by Caltrans

runoff rapidly. Peterson et al. (2002) reported that 40 kg $ha^{-1}$ PAM + 5 Mg $ha^{-1}$ gypsum applied on silty clay loam packed in erosion boxes was highly significant in reducing runoff, but that runoff amount increased progressively beyond 30 min of rainfall. They suggested that runoff from the PAM + gypsum treatment would quickly approach that of the control treatment under intense rains. Yu et al. (2003) reported that higher amount of PAM application needs a higher amount of gypsum to achieve the best infiltration result. They showed that spreading dry PAM mixed with gypsum on the soil surface increased the final infiltration rate of the silty loam by up to 4 times compared with the control. Whereas using PAM or gypsum alone did not prevent seal formation, reduced the soil's hydraulic conductivity and its infiltration rate. With do attention to our results and findings of other studies we suggest that on sloping areas under intense rains high levels of PAM + gypsum should be applied to improvement of soil physical properties, preventing of seal formation, and therefore reducing of runoff.

% of reduction variations of sediment concentration in different slopes and rain intensities for application rate of 25 kg $ha^{-1}$ PAM + 10 Mg $ha^{-1}$ gypsum, 50 kg $ha^{-1}$ PAM + 20 Mg $ha^{-1}$ gypsum and 75 kg $ha^{-1}$ PAM + 30 Mg $ha^{-1}$ gypsum was 28 - 60, 73 - 78 and 94 - 99% respectively compared with the control as well. The high efficiency of 75 kg $ha^{-1}$ of PAM + 30 Mg $ha^{-1}$ gypsum in reducing of sediment loss to non detectable levels is explained by gypsum dissolution. When rain water comes in contact with the PAM plus gypsum mixture, gypsum dissolves and increases the electrolyte concentration in the soil solution. With increase in electrolyte concentration in the soil solution, the repulsion forces between the negative sites on the anionic polymer diminishes and the dissolved polymer exists as coiled and short chains whose effect on the polymer's solution viscosity diminishes, thus limiting the clay dispersion (Barvenik, 1994; Agassi and Ben-Hur, 1991). Also gypsum dissolution releases $Ca^{+2}$ cations into the soil solution. These cations increase the adsorption of the aggregates, so enhancing their stabilizing effect (Ben-Hur et al., 1989). Therefore, the short polymer chains are apparently ineffective in clogging pores, and effective in stabilizing the surface aggregates and preventing seal formation.

## Economical advantages

The purchase price of 1 kg PAM in market depending on its type, molecular weight, charge density and manufacturer is about 7.5 - 15 $. Gypsum is so cheap and can be provided from manufactures producing raw gypsum with low costs (less than 0.02 $ for each kg gypsum). Purchase price of 1 $m^2$ RECS in market depending on its type is about 0.3 - 0.5 $. So with due attention to the cost of PAM, gypsum, and RECS, their purchase price in market can be estimated for each ha. California department of transportation (Caltrans) has reported the cost of installation of different types of soil conditioners and RECS (Caltrans, 2002). The purchase price and cost of installation of PAM, gypsum and RECS is presented in Table 3. Figures presented in this Table indicate that use of gypsum for stabilizing of soil is lower than PAM. Also expenses usage of RECS is much more than PAM and gypsum.

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### REFERENCES

Aase JK, Bjorneberg DL, Sojka RE (1998). Sprinkler irrigation runoff and erosion control with polyacrylamide-laboratory tests. Soil Sci. Soc. Am. J. 62: 1681-1687.

Agassi M (1997). Stabilizing steep slopes with geomembranes. Soil Technol. 10(3): 225-234.

Agassi M, Ben-Hur M (1991). Effect of slope length, aspect and phosphogypsum on runoff and erosion from steep slopes. Aust. J. Soil. Res. 29: 197-207.

Alcordo IS, Rechcigl JE (1995). Phosphogypsum and other by-product gypsums. in: Soil Amendments and Environmental Quality. J.E. Rechcigl, Ed. CRC Press, Boca Raton, FL.

Barvenik FW (1994). Polyacrylamide characteristics related to soil application. Soil Sci. 158: 235-243.

Ben-Hur A, Faris MJ, Malik M, Letter J (1989). Polymers as soil conditioners under consecutive irrigations and rainfall. Soil Sci. Soc. Am. J. 53: 1173-1177.

Ben-Hur M (2006). Using synthetic polymers as soil conditioners to control runoff and soil loss in arid and semi-arid regions—a review.

Aust. J. Soil. Res. 44: 191–204.
Blanco-Canqui H, Gantzer CJ, Anderson SH, Thompson AL (2004). Soil berms as an alternative to steel plate borders for runoff plots. Soil Sci. Soc. Am. J. 68: 1689-1694.
Borselli L, Biancalani R, Giordani C, Carnicelli S, Ferrari GA (1996). Effect of gypsum on seedling emergence in a kaolinitic crusting soil. Soil Technol. 9(1-2): 71-81.
Brakensiek DL, Osborn HB, Rawls WJ (1979). Field manual for research in agricultural hydrology. USDA. Agric. Handb. 224. U.S. Gov. Print. Office, Washington, DC.
Brauer D, Aiken GE, Pote DH, Livingston SJ, Norton LD, Way TR, Edwards JH (2005). Amendment effects of soil test P. J. Environ. Quality. 34: 1682-1686.
Caltrans (2002). State of California Department of Tronsportation, Caltrans Statewide Erosion Control Review, CTSW-RT-01-067.
Flanagan DC, Chudhari K, Norton LD (2002). Polyacrylamide soil amendment effects on runoff and sediment yield on steep slopes. Part I. Natural rainfall conditions. Trans. ASAE 45: 1339-1351.
Krenitsky EC, Carroll MJ, Hill RL, Krouse JM (1998). Runoff and sediment losses from natural and man-made erosion control materials. Crop Sci. 38: 1042-1046.
Lado M, Paz A, Ben-Hur M (2004). Organic matter and aggregate size interactions in infiltration, seal formation and soil loss. Soil Sci. Soc. Am. J. 68: 935-942.
Lu JH, Wu L (2003). Polyacrylamide distribution in columns of organic matter-removed soils following surface application. J. Environ. Qual. 32: 674-680.
Peterson JR, Flanagan DC, Tishmack JK (2002). PAM application method and electrolyte source effects on plot-scale runoff and erosion. Trans. ASAE 45: 1859-1867.
Roa-Espinosa A, Bubenzer GD, Miyashita ES (2000). Sediment and runoff control on construction sites usuig four application methods of polyacrylamide mix. in: Proc. Tools for Urban Water Resources Management and Protection. Urban Water Resource Conf. Northeastern Illinois Planning Commission, Chicago, IL.
Sutherland RA (1998). Rolled erosion control systems for hillslope surface protection: a critical review, synthesis and analysis of available data. I. Background and formative years. Land Degrad. Develop. 9: 465-486.
Sutherland RA, Ziegler AD (2006). Hillslope runoff and erosion as affected by rolled erosion control systems: a field study. Hydrol. Process. 20: 2839-2855.
Tang Z, Lei T, Yu J, Shainberg I, Mamedov AI, Ben-Hur M, Levy GJ (2006). Runoff and interrill erosion in sodic soils treated with dry PAM and phosphogypsum. Soil Sci. Soc. Am. J. 70: 679-690.
Tishmack JK, Peterson JR, Flanagan DC (2001). Use of coal combustion by-products to reduce soil erosion. 2001 International ash utilization symposium, Center for applied energy research, University of Kentucky, Paper 63.
Wallace-Cochrane B, Eltz F, Reichert M, Norton LD (2005). Controlling soil erosion and runoff with polyacrylamide and phosphogypsum on subtropical soil. Trans. ASAE 48(1): 149-154.
Wan Y, El-Swaify SA (1999). Runoff and soil erosion as effected by plastic mulch in a Hawaiian pineapple field. Soil Till. Res. 52: 29-35.
Yu J, Lei T, Shainberg I, Mamedov AI, Levy GJ (2003). Infiltration and erosion in soils treated with dry PAM and gypsum. Soil Sci. Soc. Am. J. 67: 630-636.
Ziegler AD, Sutherland RA (1998). Reduction in interrill sediment transport by rolled erosion control systems. Soil Till. Res. 45: 265-278.
Ziegler AD, Sutherland RA, Tran LT (1997). Influence of rolled erosion control systems on temporal rainsplash response-a laboratory rainfall simulation experiment. Land Degrad. Develop. 8: 139-157.