# Runoff and Interrill Erosion in Sodic Soils Treated with Dry PAM and Phosphogypsum

Z. Tang, T. Lei, J. Yu, I. Shainberg, A. I. Mamedov, M. Ben-Hur, and G. J. Levy*

## ABSTRACT

**Seal formation at the soil surface during rainstorms reduces rain infiltration and leads to runoff and erosion. An increase in soil sodicity increases soil susceptibility to crusting, runoff, and erosion. Surface application of dissolved polyacrylamide (PAM) mixed with gypsum was found to be very effective in decreasing seal formation, runoff, and erosion. The objective of this study was to investigate the effects of surface application of dry granular PAM (20 kg ha$^{-1}$) mixed with phosphogypsum (PG) (2 and 4 Mg ha$^{-1}$) and that of PG alone on the infiltration rate (IR), runoff, and wash erosion from four smectitic soil types (ranging in clay content between 10 and 62% and sodicity level between exchangeable sodium percentage [ESP] 2 and 20) exposed to simulated distilled water rainstorms. Increasing ESP from 5 to 20 in the loamy sand decreased final IR from 14 to 2 mm h$^{-1}$ and increased runoff and wash erosion in the control; similar trends but of different magnitude were noted in the other soil types. Spreading PAM mixed with PG or PG alone was effective in maintaining final IR $>$ 12 mm h$^{-1}$, low runoff, and wash erosion levels compared with their control. Use of PAM mixed with PG resulted in higher final IR and lower runoff levels than PG alone in all four soils studied. Conversely, with respect to soil erosion, PAM mixed with PG was more effective than PG alone in reducing wash erosion from the loamy sand and clay and had comparable effects on soil loss in the loam. It was concluded that for rain-fed agriculture, spreading of dry granular PAM mixed with PG was more effective than PG alone in reducing runoff and erosion in soils varying in texture and sodic conditions.**

Seal formation at the surface of cultivated soils exposed to the impact of raindrops (i.e., structural seal as opposed to depositional seal formed by translocation of fine particles and their subsequent deposition [Arshad and Mermut, 1988], as often occurs in furrow/basin irrigation [Kemper et al., 1985]), is a common phenomenon, particularly in arid and semiarid regions (Shainberg and Letey, 1984). Seal formation reduces soil IR (McIntyre, 1958), and increases runoff and erosion (Morin et al., 1981). Seal formation is due to two mechanisms: (i) physical disintegration of surface soil aggregates by rain wetting and drop's impact and, (ii) a physicochemical dispersion of soil clays, which migrate and clog the pores immediately beneath the surface (McIntyre, 1958; Agassi et al., 1981). Aggregate stability increases with an increase in clay content, and therefore higher wetting rates and impact energies are needed to disintegrate aggregates of clay soils (Shainberg et al., 2003). Physicochemical clay dispersion is enhanced with the increase in soil ESP and the decrease in soil solution electrolyte concentration (Shainberg and Letey, 1984).

Interrill soil erosion by rainwater is closely associated with seal formation. Erosion by water involves (i) detachment of soil material from soil mass by raindrop impact and/or runoff shear and (ii) transport of the resulting sediment by raindrop splash and/or flowing runoff. Raindrop detachment is greater than flow shear detachment because kinetic energy of raindrops is much higher than that of surface flow (Hudson, 1971). However, movement of detached soil down slope by rain splash is minimal, and most of the sediments are removed from the interrill area by runoff flow (Young and Wiersma, 1973); this type of erosion is termed "wash erosion." Furthermore, under dispersive conditions (e.g., sodic soils and distilled water rain), runoff flow may be sufficient for soil detachment (Warrington et al., 1989).

Sodic conditions reduce the value and productivity of soils (Sumner and Naidu, 1998). Accumulation of sodium in the soil solution and the exchange phase leads to deterioration of soil physical properties such as structural stability, infiltration rate, runoff, erosion, etc. (Shainberg and Letey, 1984). Many reviews have been published recently on the response of soils to sodicity and salinity (e.g., Sumner and Naidu, 1998; Levy, 1999). These reviews demonstrated that soil texture, clay mineralogy, and the potential of the soil to release electrolytes into the soil solution affect the response of soils to sodic conditions, and should be considered when sodic soils are investigated.

Amendments like gypsum (or PG) and PAM have been used to prevent seal formation, runoff, and erosion (Agassi and Ben-Hur, 1992; Bryan, 1992; Ben-Hur et al., 1992a; Cochrane et al., 2005; Flanagan et al. 1997a, 1997b; Fox and Bryan, 1992; Miller, 1987; Shainberg et al., 1990; Shainberg and Levy, 1994; Yu et al., 2003). Gypsum is effective because on dissolution gypsum releases electrolytes into the rainwater (the electrolyte effect) and because dissolved Ca ions displace Na ions from the exchange complex—the reclamation effect (Keren and Shainberg, 1981). Keren and Shainberg (1981) found that PG was more effective than mined gypsum in decreasing clay dispersion and seal formation because of its higher rate of dissolution and the higher concentration of electrolytes in the soil surface solution during rainstorms.

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**Abbreviations:** ESP, exchangeable sodium percentage; IR, infiltration rate; PAM, polyacrylamide; PG, phosphogypsum.

Use of synthetic organic polymers as soil additives started as early as the 1950s. A number of reviews have been published, discussing the role of organic polymers, and especially that of negatively charged high molecular weight PAM in improving soil structure and physical properties (Wallace and Wallace, 1990; Seybold, 1994; Levy and Ben-Hur, 1998). Laboratory and field studies with anionic PAM (e.g., Shainberg et al., 1990; Agassi and Ben-Hur, 1992; Levy et al., 1992, Aase et al., 1998; Bjorneberg and Aase, 2000; Green et al., 2000; Gardiner and Sun, 2002; Bjorneberg et al., 2003; Vacher et al., 2003) have clearly demonstrated that addition of small amounts of PAM (10–20 kg $ha^{-1}$) to the soil surface were effective in maintaining high permeability and decreasing runoff and soil erosion levels in soils exposed to impact of water drops, especially when the PAM was applied together with a source of electrolytes (e.g., Shainberg et al., 1990; Smith et al., 1990; Lentz and Sojka, 1996; Flanagan et al., 1997a, 1997b; Orts et al., 1999). Concerning sodic conditions, the impact of PAM on infiltration and soil erosion was tested with solutions of different electrolyte concentrations; the results obtained were inconsistent and were not related to the salt concentration in the solutions used. With respect to maintaining high permeability and low levels of runoff (i.e., seal development), it has been noted that already at ESP$\sim$9, PAM was ineffective or less effective compared with non-sodic conditions (Ben-Hur et al., 1992b; Levy et al., 1995; Lentz and Sojka, 1996). Conversely, PAM was very effective in reducing soil erosion even at ESP $>$ 25 (Ben-Hur et al., 1992b; Levy et al., 1995).

In nearly all studies on PAM applications for preventing rain-induced seal formation, PAM was initially dissolved in water and sprayed onto the soil surface, or added to the irrigation water. Neither practice is suitable for rain-fed agriculture because water for spraying the PAM solution is not available and because it is difficult to dissolve PAM in water. To apply 10 to 20 kg $ha^{-1}$ of PAM, the volume of PAM solution to be sprayed is 10 to 20 $m^3$ $ha^{-1}$ because solutions of $>$ 1000 g $m^{-3}$ are too viscous for practical use.

Studies on erosion control in furrow irrigation have shown that addition of dry granules of PAM to the gated irrigation pipe had comparably favorable effects on preventing erosion and increasing infiltration, to those of adding stock solution of PAM to the furrow inflows (Lentz and Sojka, 2000). The success of dry PAM granules in controlling erosion and/or infiltration in furrow irrigation encouraged scientists to consider a similar concept for applying PAM to stabilize the soil surface against rain, in which dry granular PAM mixed with a source of electrolytes is added to the soil before the rainy season. The reasons for adding PAM together with a source of electrolytes (e.g., PG) are two fold. As mentioned previously, PAM efficacy in preventing seal formation is enhanced in the presence of electrolytes (Shainberg et al., 1990). In addition, the amounts of PAM to be added are small ($\sim$20 kg $ha^{-1}$). Mixing the PAM with 2 to 4 Mg $ha^{-1}$ of a source of electrolytes can ensure a uniform spreading of the mixture on the soil surface.

Few studies have tested this new concept. Peterson et al. (2002) used a laboratory rainfall simulator to compare the effects of sprayed PAM plus gypsiferous material to addition of granular PAM together with gypsiferous material on runoff and erosion in a silty clay loam. Results showed that sprayed PAM was more effective than granular PAM in terms of total runoff, but no significant differences were noted between the two treatments with regard to total sediment yield (Peterson et al., 2002). Yu et al. (2003) studied in a laboratory rainfall simulator the effects of dry granular PAM mixed with mined gypsum on infiltration, runoff, and erosion from two nonsodic soils that were exposed to 72 mm of rain with intensity of 36 mm $h^{-1}$. Application of dry PAM mixed with gypsum resulted in significantly higher final infiltration rates compared with no amendment (control) or application of each amendment alone. Similarly, runoff and soil loss levels in the combined dry PAM plus gypsum were $\sim$30% of their corresponding levels in the control (Yu et al., 2003).

The preliminary data discussed above suggest that addition of dry PAM together with a source of electrolytes may contribute to combating seal formation, runoff, and erosion in soils exposed to rain. It is, however, recognized that the efficacy of the treatment may vary with soil properties. The current study was, therefore, designed to conduct a systematic investigation of the efficiency of spreading dry granular PAM mixed with PG on IR, runoff, and erosion under simulated rain conditions in smectitic soils varying in clay content and sodicity.

## MATERIALS AND METHODS

### Soils

Soil samples from cultivated fields, representing four main soil types in Israel were chosen for this study: a loamy sand (Typic Haploxeralf), a loam (Calcic Haploxeralf), a dark brown clay (Chromic Haploxerert) from the pleshet plains (clay-HH), and a dark brown clay (Typic Haploxerert) from the Northern Gallilee (clay-E). The soils were predominantly smectitic with kaolinite, illite, and calcite present in small amounts (Banin and Amiel, 1970). Samples with naturally occurring ESP levels in the cultivated layer (0–250 mm) from the four soil types were brought to the laboratory. The ESP levels studied were $<$ 2% (low), $\sim$5% (medium), $\sim$10% (high), and $\sim$20% (very high). Divergence in sodicity level within a soil type was due to differences in water quality used for irrigation (fresh water, treated effluent, and saline-sodic water) or to soil leveling that was done in the 1960s. The soils were characterized for particle- size distribution using the hydrometer method (Gee and Bauder, 1986), cation exchange capacity by sodium acetate (Rhoades, 1986), exchangeable sodium by ammonium acetate (Thomas, 1986), calcium carbonate content using the volumetric calcimeter method (Nelson, 1986) and organic matter content by wet combustion (Nelson and Sommers, 1986). Results are presented in Table 1.

### Rain Simulation Studies

The experiments were performed with a drip type rainfall simulator. The simulator consisted of a 750 by 600 by 80 mm closed chamber in which rainfall of a known constant drop size

**Table 1. Some physical and chemical properties of the soils studied (Means ± one standard deviation).**

| | | Texture | | | | | | ESP§ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Soil** | **Classification** | **Clay** | **Silt** | **Sand** | **CEC†** | **$CaCO_3$** | **OM‡** | **low** | **medium** | **high** | **very high** |
| | | % | | | $cmol_c\ kg^{-1}$ | $g\ kg^{-1}$ | | | | | |
| **Loamy sand** | **Typic Rhodoxeralf** | **8.8 ± 0.9**[d] | **4.8 ± 0.3** | **86.4 ± 0.9** | **8.3 ± 0.8** | **18.2 ± 5.8** | **4.3 ± 1.6** | **1.5** | **4.6** | **10.2** | **20.3** |
| **Loam** | **Calcic Haploxeralf** | **22.5 ± 1.1** | **26.4 ± 9.8** | **51.0 ± 9.0** | **18.9 ± 1.6** | **163.7 ± 24** | **10.6 ± 2.5** | **2.1** | **5.5** | **9.5** | **19.7** |
| **Clay-HH** | **Chromic Haploxerert** | **40.2 ± 2.7** | **18.5 ± 3.5** | **41.3 ± 5.9** | **33.4 ± 1.0** | **138.3 ± 60.5** | **9.6 ± 5.9** | **1.6** | **5.5** | **10.1** | **20.9** |
| **Clay-E** | **Typic Haploxerert** | **61.7 ± 1.4** | **19.7 ± 4.5** | **18.6 ± 5.4** | **57.4 ± 5.3** | **108.2 ± 51.0** | **12.7 ± 5.5** | **0.9** | **6.6** | **9.3** | **20.4** |

**† CEC = cation-exchange capacity.**
**‡ OM = organic matter.**
**§ ESP = exchangeable sodium percentage.**

was generated through a set of hypodermic needles (≈1000) arranged at a spacing of 20 by 20 mm and pointing downward. Average droplet diameter, determined by measuring the volume of a known number of drops falling into a measuring cylinder, was 2.97 ± 0.05 mm. A drop fall of 2.2 m was used to obtain drops with an impact velocity of 5.64 $m\ s^{-1}$ and a kinetic energy of 15.9 $J\ m^{-2}\ mm^{-1}$ (Epema and Riezebos, 1983). Rain intensity was maintained at 36 $mm\ h^{-1}$ using a peristaltic pump.

Air-dried soils, crushed to pass through a 4.0-mm sieve, were packed in trays 200 by 400 mm, 40 mm deep, over a 5-mm thick layer of coarse sand. Height of the tray walls above the soil surface at the top part and the two sides of the tray was 10 mm. The bulk density of the soils in the trays was maintained at the level similar to the natural bulk densities in the cultivated fields; 1.43, 1.39, 1.44, and 1.27 $Mg\ m^{-3}$ for the loamy sand, loam, clay-HH, and clay-E, respectively. The trays were saturated from below with tap water, were placed under the rain simulator at a slope of 15% and were exposed to 72 mm (2 h) of deionized water rain (simulating the chemistry of natural rain). We used 72 mm of rain to ensure that in most of the treatments a steady-state final IR will be attained. During each test, water infiltrating through the soils was collected, in 4-min intervals, in graduated cylinders placed underneath a special outlet at the bottom of the tray, and water volume was recorded as a function of time. Runoff water was collected in buckets continuously throughout the event, its volume was determined and three samples of the mixed runoff were dried and total amount of soil removed by runoff during the entire test was calculated. Splash from the soil trays was not measured. The sediments collected were mainly due to wash erosion and to a smaller degree to splash sediments that landed on the soil tray. Soil carried by splash has been found to be positively correlated with soil removed by runoff water (Young and Wiersma, 1973). Three replicates were performed concurrently (at the same rainfall storm) for each treatment.

## Treatments

Negatively charged PAM (CYTEC A110) with a high molecular weight ($12 \times 10^6$ Da) and 15% hydrolysis was used in this study. In the experiments where dry granular PAM was mixed with gypsum, PG (85% $CaSO_4$, and particle size < 2 mm) was used. After packing the soil samples in the trays and before exposing them to rain, the samples in the trays were treated with five treatments: (1) control (no addition of PAM or PG), (2 and 3) two rates of powdered PG equivalent to 2 and 4 $Mg\ ha^{-1}$ were uniformly spread on the soil surface using a 53-μm sieve, and (4 and 5) two mixtures of PAM and powdered PG (PAM at a rate of 20 $kg\ ha^{-1}$ mixed with PG at a rate of 2 or 4 $Mg\ ha^{-1}$, respectively) were spread on the soil surface using the same sieve.

## Data Analysis

Infiltration data obtained from the rainfall simulator were analyzed with the nonlinear equation proposed by Morin and Benyamini (1977):

$$I_t = (I_i - I_f)e^{-\gamma pt} + I_f \qquad [1]$$

where $I_t$ is the instantaneous infiltration rate ($mm\ h^{-1}$); $I_i$ is the initial infiltration rate ($mm\ h^{-1}$); $I_f$ is the final infiltration rate ($mm\ h^{-1}$); $\gamma$ is the soil coefficient related to surface aggregate stability ($mm^{-1}$); $t$ is the time (h) from the beginning of the test; and $p$ is the rain intensity ($mm\ h^{-1}$).

A nonlinear regression program used measured $I_t$, $I_f$, and $p$ values to calculate the other two parameters of the equation ($I_i$ and $\gamma$) that gave the best coefficient of determination ($R^2 >$ 0.9) between paired calculated and measured $I_t$ values.

Volume of runoff (Roff) for any given depth of rain ($n$) from each single rainstorm was calculated as follows:

$$\mathrm{Roff} = \sum_{j=i}^{\mathrm{n}} [d_j - (I_t)_j d_j/p] \qquad [2]$$

where $I_t$ is the calculated instantaneous infiltration rate (Eq. [1]) for interval number $j$, $p$ is the rain intensity, and $d_j$ is depth of rain applied during interval number $j$ (d was taken as 1 mm for all intervals). For cases where $(I_t)_j > p$, $(I_t)_j$ was taken as equal to $p$.

Under our experimental conditions water splash from the soil trays may reach up to 15% of the runoff (Agassi and Levy, 1991). The level of water splash depends on the treatment; the faster the seal forms, the greater the amount of water splash. Thus, use of measured runoff data would have caused a bias in the results in favor of the treatments where the seal formed quickly (e.g., control). Infiltration and runoff are inversely related and the sum of the two equals rain depth. Our infiltration measurement was not subjected to any bias known to us and therefore we considered it reasonable to compute runoff data from our infiltration measurements. Thus, total amount of runoff from the entire storm was calculated by using the parameters obtained from the fitting procedure of curves that described accurately the infiltration data. Cumulative runoff was calculated for each replicate of any given treatment; hence, the values of cumulative runoff presented are an average value derived from three replicates.

Final IR, cumulative runoff, and soil loss data were subjected to a multifactor analysis of variance (SAS Institute, 1995). In cases where interactions were noted among main treatments (soil type, ESP level and type and amount of amendment), differences among final IR, runoff or soil loss of individual treatments were determined using a single confidence interval value at level $P$ 0.05 (SAS Institute, 1995). In cases where ratios of final IR, runoff and soil loss were considered, standard deviation for the ratios was used rather than an ANOVA analysis because no normal distribution of these variables could have been assumed.

# RESULTS AND DISCUSSION

## Infiltration Rate and Runoff

### Effects of Exchangeable Sodium Percentage

Effects of cumulative simulated rain on the IR of the four soils, at two ESP levels (5 and 20) and the different treatments are presented in Fig. 1. It was evident that the treatments led to different IR curves and that soil type and ESP affected the impact of the treatments on the decrease in IR with the increase in cumulative simulated rain (Fig. 1). To enable a quantitative comparison among the effects of the different treatments on soil susceptibility to seal formation we examined the measured final IR and the calculated cumulative runoff for all the soils and all the treatments (Fig. 2 and 3). Our results for the nontreated (control) samples were in agreement with former studies (e.g., Agassi et al., 1981; Kazman et al., 1983; Shainberg and Letey, 1984), and re-emphasized that, in general, final IR of soils decreased and runoff increased with an increase in ESP of the soils. The magnitude of the effects of ESP on the final IR and runoff depended, however, on soil type (Fig. 1–3).

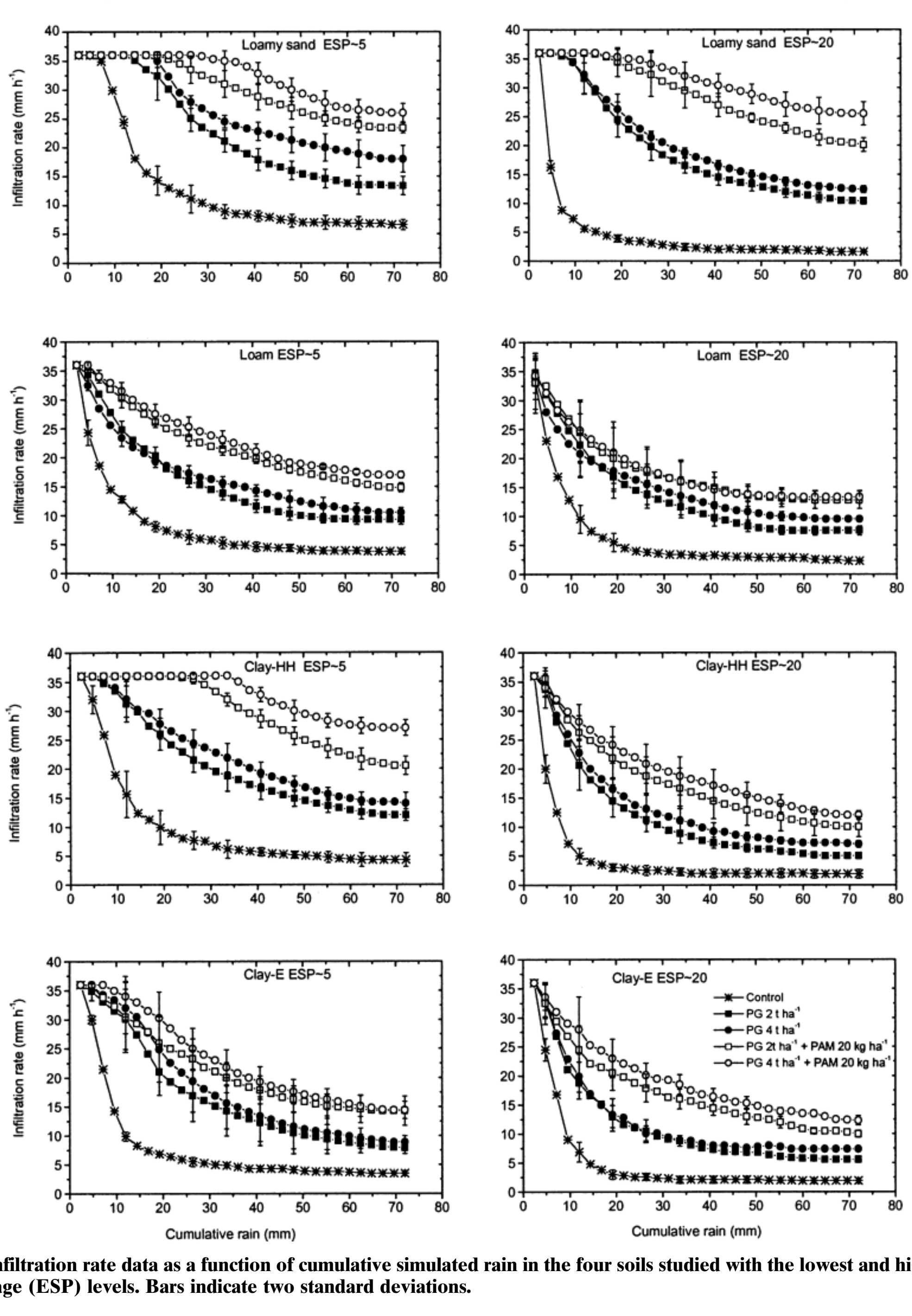

**Fig. 1. Measured infiltration rate data as a function of cumulative simulated rain in the four soils studied with the lowest and highest exchangeable sodium percentage (ESP) levels. Bars indicate two standard deviations.**

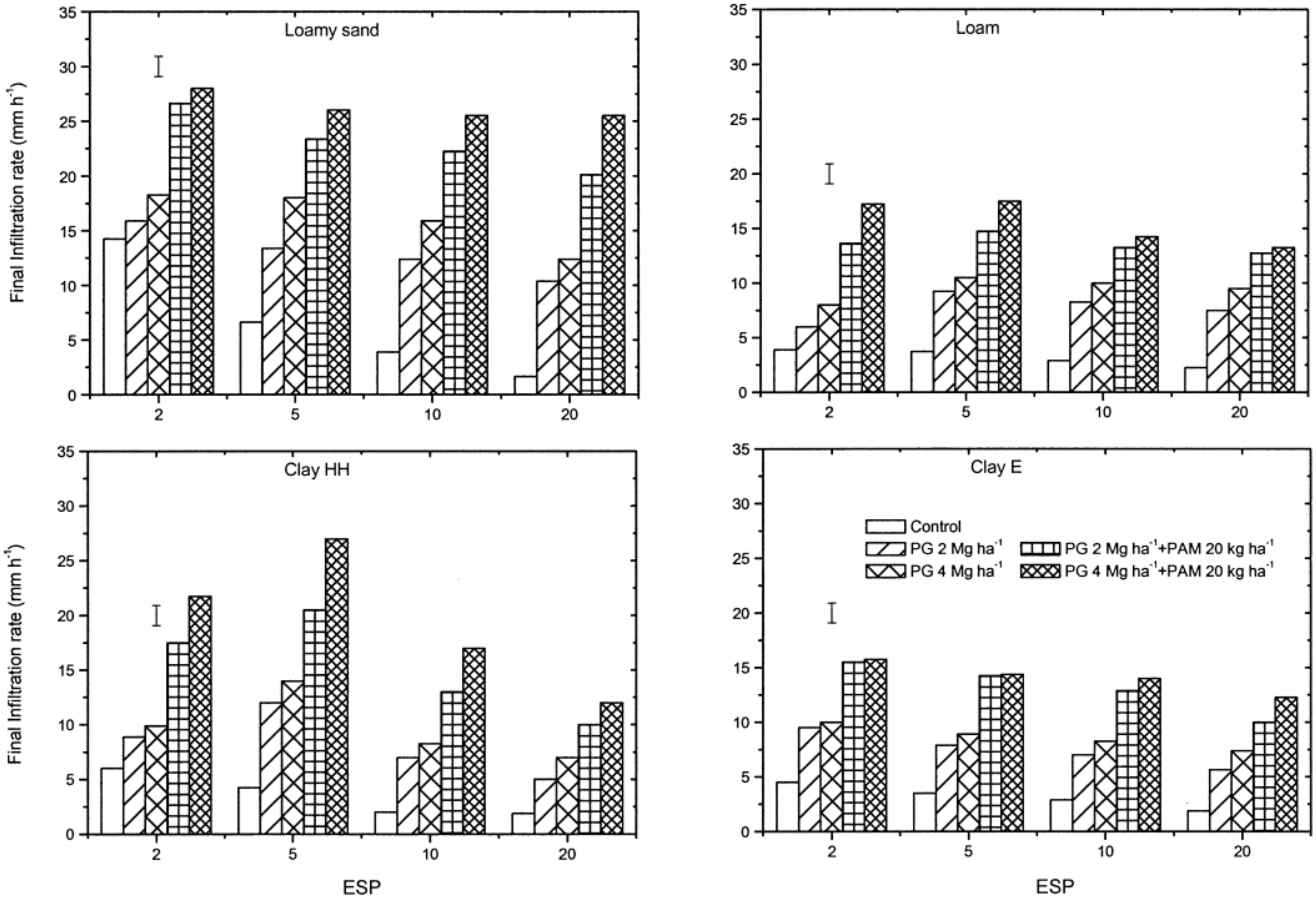

**Fig. 2. Measured final infiltration rate as a function of exchangeable sodium percentage (ESP) and the treatments studied in the four soils. Bars indicate a single confidence interval value at $p = 0.05$.**

The soil most affected by ESP was the loamy sand whose final IR at ESP 2 for the nontreated sample was the highest (14 mm $h^{-1}$), but dropped to 2 mm $h^{-1}$ at ESP 20 (Fig. 2). Similarly, the greatest increase in runoff with the increase in ESP from 2 to 20 was in the loamy sand (Fig. 3). The loamy sand was the soil most affected by ESP because of its low clay content and the absence of lime (Table 1). The latter, if present, may dissolve and reclaim the sodic soil, release electrolytes to the soil solution, and offset the adverse effect of sodicity on seal formation (Shainberg and Letey, 1984; Agassi et al., 2003). The low stability of the aggregates associated with low clay content coupled with the presence of large-size pores which enabled clay movement and the formation of the "washed in" layer (McIntyre, 1958), contributed to the high sensitivity of the sandy loam to sodicity. The soil least affected by ESP was the loam with 22% clay and 35% silt. This soil has already been reported as having low hydraulic conductivity (Shainberg et al., 2001) mainly because of its high silt/clay ratio and its low structural stability. Consequently, the final IR of the loam at ESP 2 was already low (3.8 mm $h^{-1}$), and increasing the ESP of this soil to 20 resulted only in a small decrease in the final IR to 2.5 mm $h^{-1}$ (Fig. 2). The relative small influence of ESP on this soil was probably due to its high lime content and the low hydraulic conductivity (Table 1). The low flow rate enables enough dissolution of lime, which provided Ca-electrolytes to the soil surface solution, which lessened clay dispersion and movement, and the reduction in final IR.

The soils that were intermediately affected by ESP were the clays (Fig. 2 and 3). The high clay content in the two soils (Table 1) enhanced the stability of the aggregates against disintegration, clay dispersion, and seal formation at high ESP levels.

The combined impact of ESP, lime, and clay content on seal formation, final IR, and runoff in our study suggested that in soils that are structureless and poorly aggregated (e.g., loamy sand and loam) chemical dispersion and presence of lime play a dominant role in soil susceptibility to seal formation. Conversely, in well-structured and aggregated soils, such as the two clay soils, stability of the aggregates determined to a large extent the sealing process with ESP playing only a moderate role.

## Effects of Phospogypsum and Polyacrylamide Mixed with Phosphogypsum

In general, spreading PG or PAM mixed with PG on the soil surface increased the final IR and decreased cumulative runoff compared with the untreated samples

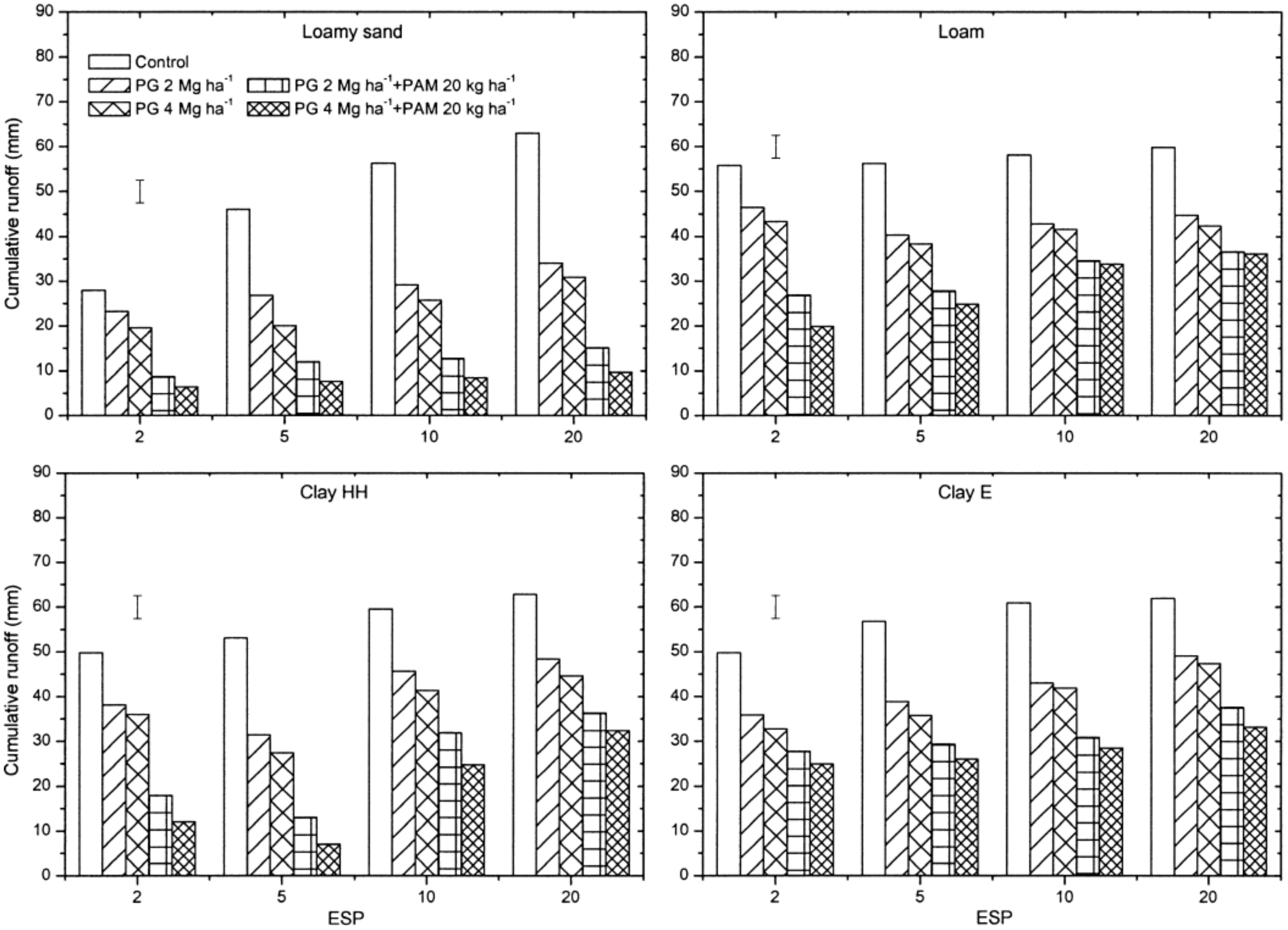

**Fig. 3. Calculated cumulative runoff as a function of exchangeable sodium percentage (ESP) and the treatments studied in the four soils. Bars indicate a single confidence interval value at $p = 0.05$.**

(Fig. 2 and 3). The multi-factor analysis of variance for the final IR and runoff data showed a significant triple interaction among the main treatments (soil type, ESP, and type and amount of amendment) (Table 2). Thus, a single confidence interval was added to Fig. 2 and 3. The existence of the aforementioned triple interaction suggested that the combined effects of the three tested variables on the final IR and runoff were complex. Therefore, to have a clearer picture of the impact of the amendments on seal formation for the different soil types and ESP levels we calculated the relative final IR (i.e., the ratio of final IR at a given ESP and amendment treatment to the final IR obtained for the control at the same ESP level). Relative IR data were > 1; the higher the relative IR the more effective the treatment in maintaining a permeable seal. But for one case (clay-HH with ESP 20), the relative final IR increased with the increase in ESP for all the treatments (Fig. 4), indicating that the efficiency of the amendments in maintaining high final IR increased with the increase in soil sodicity in the four soil types studied.

When PG is added to the soil surface it dissolves during the simulated rainstorm and releases electrolytes to the soil solution and thus prevents clay dispersion

**Table 2. Significance of effect of soil and treatment on final infiltration rate (FIR), runoff and soil loss.**

| Response | Source | DF† | Sum of squares | *F* ratio | Prob > *F* |
|---|---|---|---|---|---|
| **FIR** | **Soil** | **3** | **2230.92** | **572.01** | *** |
| | **ESP** | **3** | **730.45** | **187.29** | *** |
| | **Soil × ESP‡** | **9** | **367.88** | **31.44** | *** |
| | **Treatments** | **4** | **6538.03** | **1257.27** | *** |
| | **Soil × treatments** | **12** | **375.36** | **24.06** | *** |
| | **ESP × treatments** | **12** | **95.36** | **6.11** | *** |
| | **Soil × ESP × treatments** | **36** | **231.72** | **4.95** | *** |
| **Runoff** | **Soil** | **3** | **10144.76** | **344.98** | *** |
| | **ESP** | **3** | **5214.79** | **177.33** | *** |
| | **Soil × ESP** | **9** | **1131.06** | **12.82** | *** |
| | **Treatments** | **4** | **33854.16** | **863.43** | *** |
| | **Soil × treatments** | **12** | **850.69** | **7.23** | *** |
| | **ESP × treatments** | **12** | **464.34** | **3.95** | *** |
| | **Soil × ESP × treatments** | **36** | **1630.38** | **4.62** | *** |
| **Soil Loss** | **Soil** | **3** | **201624.67** | **312.02** | *** |
| | **ESP** | **3** | **151300.25** | **234.14** | *** |
| | **Soil × ESP** | **9** | **36841.29** | **19.00** | *** |
| | **Treatments** | **4** | **231660.82** | **268.88** | *** |
| | **Soil × Treatments** | **12** | **21131.32** | **8.18** | *** |
| | **ESP × Treatments** | **12** | **8031.50** | **3.11** | *** |
| | **Soil × ESP × Treatments** | **36** | **11893.52** | **1.53** | * |

† **DF, degrees of freedom.**
‡ **Exchangeable sodium percentage.**
* **Significant at 0.05 probability level.**
*** **Significant 0.001 probability level.**

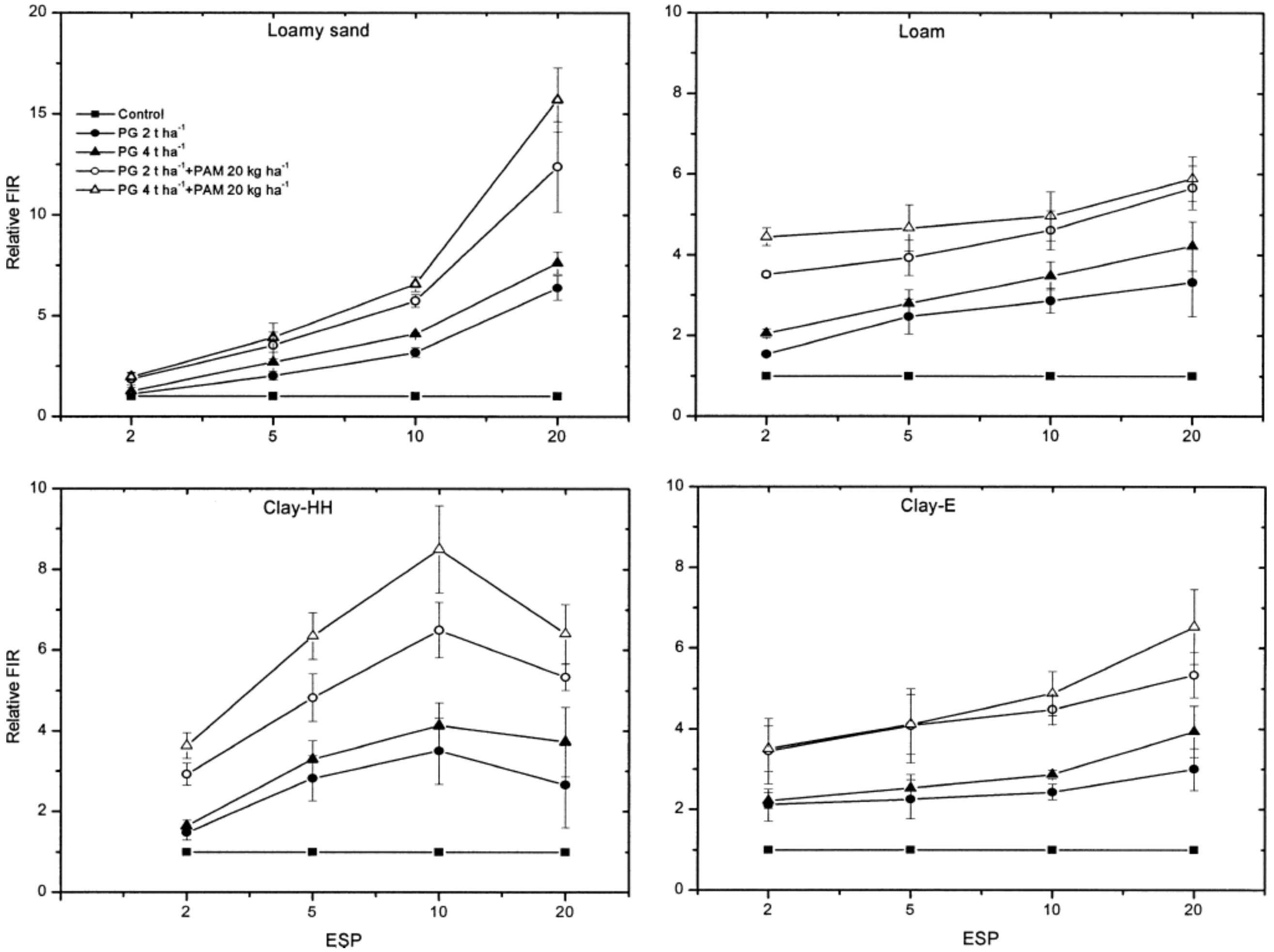

**Fig. 4. Relative final infiltration rate (FIR) as a function of exchangeable sodium percentage (ESP) and the treatments studied in the four soils. Bars indicate two standard deviations.**

(Keren and Shainberg, 1981). Increasing soil sodicity increases the intensity of clay dispersion and its importance in the processes of seal formation (Agassi et al., 1981). Also, the increase in soil sodicity increases PG dissolution rate because exchangeable sodium acts as a sink for dissolved Ca (Keren and Shainberg, 1981). Consequently, PG, which prevented the clay at the soil surface from dispersing during the simulated rainstorm, became more effective in maintaining a seal with high permeability with the increase in ESP (Fig. 2 and 4). Under our experimental conditions spreading PG at a rate of 4 Mg ha$^{-1}$ had a limited benefit over spreading 2 Mg ha$^{-1}$ of PG (Fig. 4). However, under field conditions, where spreading the PG has been noted to be less uniform than in the laboratory (Agassi et al., 1985), the larger amount of PG used could have a significant advantage over the lower amount in maintaining seals with higher final IR.

Spreading the mixture of dry PAM with PG resulted, in all cases, in higher relative final IR values, over the entire ESP range studied, compared with those obtained for spreading just PG (Fig. 2 and 4). This observation was in agreement with former studies (e.g., Shainberg et al., 1990; Smith et al., 1990) in which PAM was added to a PG-amended soil by spraying concentrated PAM solutions. Furthermore, our data confirmed the observations of Yu et al. (2003), who studied the effects of mixtures of dry PAM with PG on seal formation and IR in a loam and a sandy clay. Our study extended the applicability of Yu et al.'s (2003) findings to additional soil types and to sodic conditions. The high efficiency of dry PAM and PG mixture in maintaining final IR, being six times or more that of the control for ESP 20, was attributed to the facts that (i) dissolution of granular PAM was high enough to maintain enough PAM in solution to be active in cementing the clay particles into stable flocculi and aggregates (Shainberg et al., 1990) and (ii) PG dissolution caused the dissolved polymer chains to be coiled and relatively short, thus being effective in stabilizing the surface aggregates but ineffective in clogging the surface pores (Yu et al., 2003). No clear trend could be noted regarding the effect of the amount of PG, in the PAM plus PG mixtures, on the relative final IR (Fig. 4). It is postulated that the optimal amount of PG that must supplement the dry granular PAM should be tailored individually based on soil type, sodicity level, and possibly, rain intensity—a parameter that has not been tested in this study.

The greater efficiency of the combined PAM and PG treatment in decreasing soil susceptibility to seal formation, compared with the PG treatment, was also evident from the runoff data (Fig. 3). Treatments with mixtures of PAM plus PG were most effective in the loamy sand (runoff reduction to 17 and 25% of the control, in the high and low ESP, respectively) and least effective in the loam (values which are 36 to 60% those of the control in the low and high ESP, respectively) with intermediate runoff reduction in the clay soils (Fig. 3). We calculated the relative runoff (i.e., the ratio of cumulative runoff at a given ESP and amendment treatment to the cumulative runoff obtained for the control at the same ESP level). Relative runoff data ranged between unity and zero; values close to zero indicated that the treatment in question was very effective in decreasing runoff compared with its level in the control (Fig. 5).

Unlike the relative final IR data, where for all the soils the impact of the two amendments increased with the increase in sodicity (Fig. 4), no clear trend could be observed in the relative runoff data with respect to the impact of sodicity on the performance of the two amendments (Fig. 5). In the loamy sand, most of the decrease in relative runoff in both amendments occurred at the low ESP range with no further decrease in relative runoff with further increase in sodicity, implying that the effect of the amendments in decreasing runoff increased with increase in sodicity at the low range of sodicity. Conversely, in the loam, no clear trend was observed in the dependence of relative runoff on ESP for the two amendments (Fig. 5); relative runoff for PG tended to decrease (i.e., the impact of PG on runoff increased) with the increase in sodicity while the opposite was noted for the PAM + PG treatment. In the clay-E, the relative runoff seemed to be unaffected by sodicity in both types of amendments (Fig. 5).

This observed inconsistency in the response of final IR and runoff to the application of soil amendments, may have stemmed from the different aspects of the seal that the two parameters represent. Final IR represents the IR of the soil at the end of the simulated rainstorm where both seal formation and seal reclamation by the amendments were complete. Conversely, cumulative runoff reflects the IR values during the entire simulated rainstorm under conditions where both seal formation and seal reclamation have not yet been completed. Thus, relative runoff represents the rate of reclamation by the amendments and the rate at which the seal had been formed. Our data suggested that amendments affected more the final IR of sodic soils (and the degree of their seal development), than the rate at which the seal was formed (cumulative runoff) and reclamation by the amendments took place.

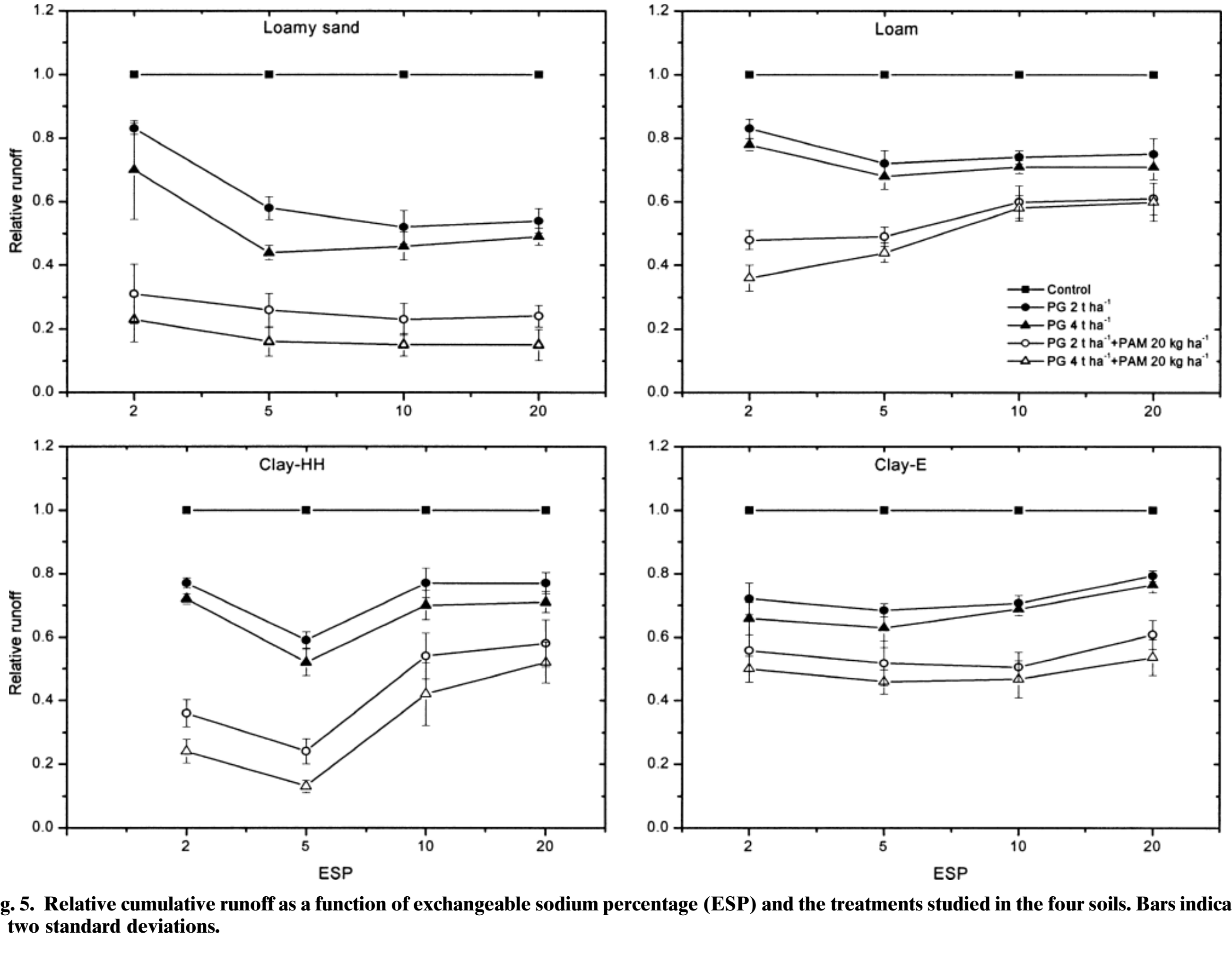

**Fig. 5. Relative cumulative runoff as a function of exchangeable sodium percentage (ESP) and the treatments studied in the four soils. Bars indicate two standard deviations.**

Based on the effects of the treatments on final IR and cumulative runoff we may conclude the following:

1. Use of PG, which has been reported to dissolve at a fast rate and prevent clay dispersion (Shainberg et al., 1989), is effective in maintaining high final IR and low levels of runoff under dispersive conditions (e.g., ESP $> 5$) and/or in soils with low to medium clay content (e.g., loamy sand and loam) where the seal formed was noted to be controlled by clay dispersion rather than physical processes such as aggregate disintegration and soil compaction (Mamedov and Levy, 2001).
2. The beneficial effect of PAM mixed with PG, was superior to PG alone, when seal permeability and runoff were considered. It is suggested that in this treatment, the presence of dissolved polymer molecules apparently assisted, as previously noted by Lentz (1995), in the cementation of flocculated clays into bigger particles.

## Wash Erosion

Soil loss by the 72-mm simulated rainstorms for the four soils and the four ESP levels, treated with PG and PAM are presented in Fig. 6. The multi-factor analysis of variance for the soil loss data showed a significant triple interaction among the main treatments (Table 2). Thus, a single confidence interval was added to Fig. 6.

Similar to previous observations (e.g., Levy et al., 1994), soil loss in the control treatment, within a given soil type, increased with the increase in ESP and, among soils, soil loss within a given ESP level increased with the increase in clay content (Fig. 6). Similar to their effect on runoff, spreading PG or PAM mixed with PG on the soil surface decreased soil loss compared with the untreated samples (Fig. 6).

The combined effects of the amendments tested, ESP and clay content on soil erosion should be analyzed in view of the processes that take place at the soil surface during seal development. Seal formation may have two opposing effects on soil erosion: (i) seal development may increase the shear strength of the soil surface (Bradford et al., 1987) and thus reduce soil detachment and erosion (Moore and Singer, 1990), and (ii) seal formation increases runoff volume and hence the transport capacity of the entrained material (Moore and Singer, 1990). Both mechanisms are used to explain the experimental results.

Use of PG was effective in reducing wash erosion compared with the control due to (i) runoff reduction (Fig. 3) and (ii) flocculation of the entrained particles

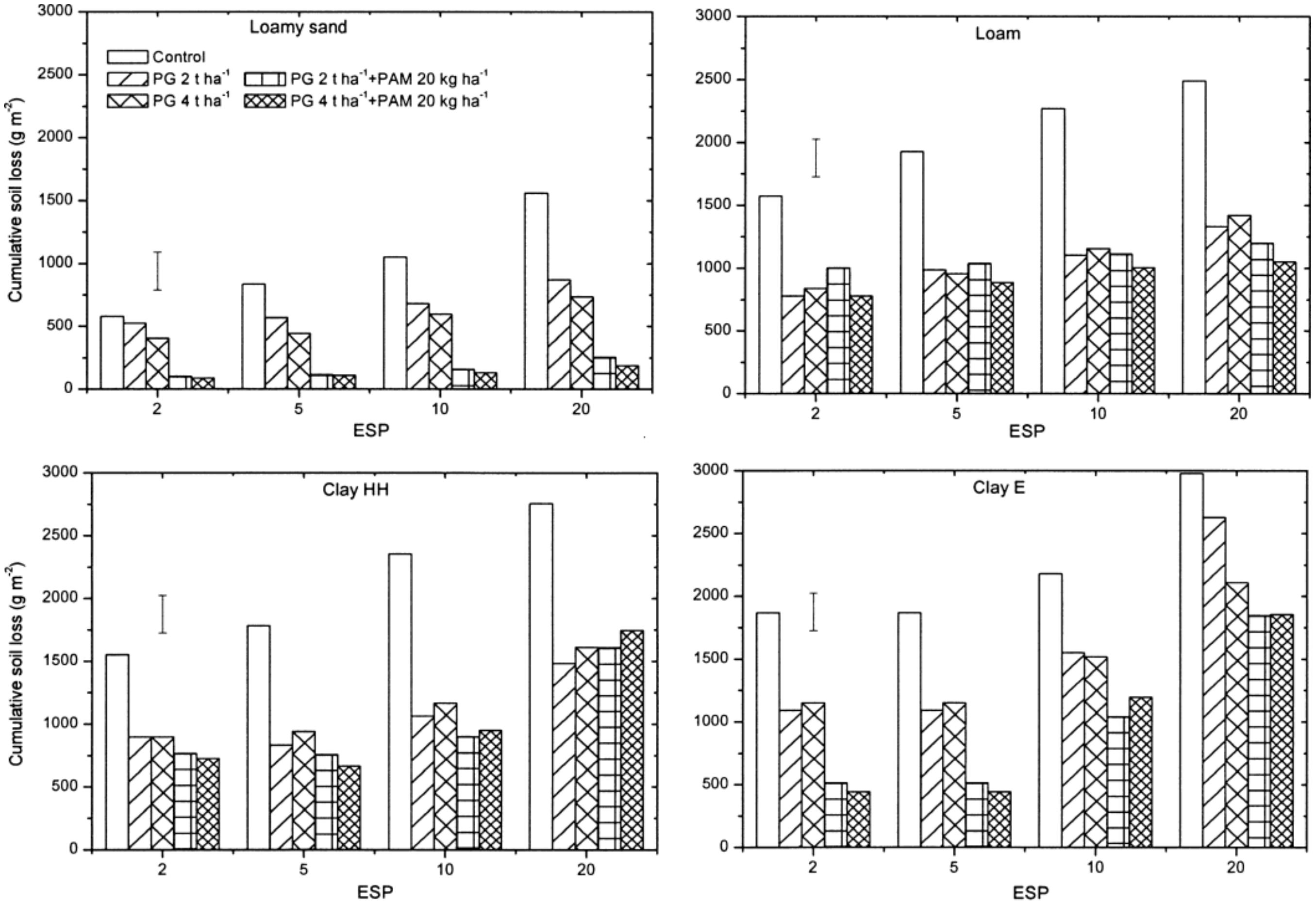

Fig. 6. Measured soil loss as a function of exchangeable sodium percentage (ESP) and the treatments studied in the four soils. Bars indicate a single confidence interval value at $p = 0.05$.

that enhanced their deposition and hindered their removal by the runoff water (Levy et al., 1994; Yu et al., 2003). Application of PAM mixed with PG decreased soil loss by the same mechanisms specified for PG and also by binding particles at the soil surface by the polymer chains (Smith et al., 1990). Cementing the soil particles stabilized them against detachment and increased their deposition rate.

Relative soil loss (the ratio of soil loss at a given ESP and given amendments to the soil loss obtained for the control at the same ESP level) was calculated for clearer assessment of the impact of the amendments on soil loss for the different soil types and ESP levels. Relative soil loss data ranged between unity and zero (Fig. 7). Relative soil loss values close to zero indicated that the treatment in question was effective in decreasing soil erosion compared with the amount of erosion obtained in the control. Based on the relative soil loss data, the soils studied were divided into two groups. The first group included the loamy sand and the clay-E where relative soil loss values in the PAM + PG treatments were substantially smaller than those in the PG treatment, suggesting that the PG treatment was less effective than the PAM + PG treatment in reducing soil erosion (Fig. 7). In the loamy sand, relative soil loss in the PAM + PG treatment was very low ($< 0.2$) and was not affected by sodicity. It should be born in mind, however, that as expected, soil loss increased with increase in ESP in the control treatments (Fig. 6) and only the relative soil loss was not affected by sodicity (Fig. 7). Applying PAM + PG, decreased soil loss so drastically probably because the presence of dissolved PAM molecules contributed to the cementing of entrained flocculi and increased their deposition and prevented their removal by runoff water. In the PG treatments, soil loss (Fig. 6) and relative soil loss (Fig. 7) in the loamy sand were quite high at the lowest sodicity (ESP 1.5), because runoff was high (Fig. 3). With the increase in ESP, clay dispersion became more severe and thus the efficiency of spreading PG in preventing the dispersion of the clay, and subsequently decreasing soil loss compared with the control, increased (Fig. 7).

In the clay-E, both types of amendments were effective in reducing soil losses at ESP $< 6.6$ (Fig. 6 and 7) and the relative soil loss increased with the increase in sodicity thereafter, indicating that the efficiency of the two treatments in controlling soil erosion decreased as the ESP level increased. By contrast, runoff (Fig. 3) and relative runoff (Fig. 5) in the clay-E was hardly affected by changes in ESP in both types of amendments, indicating that runoff in both amendments increased only slightly with the increase in ESP and increased at a

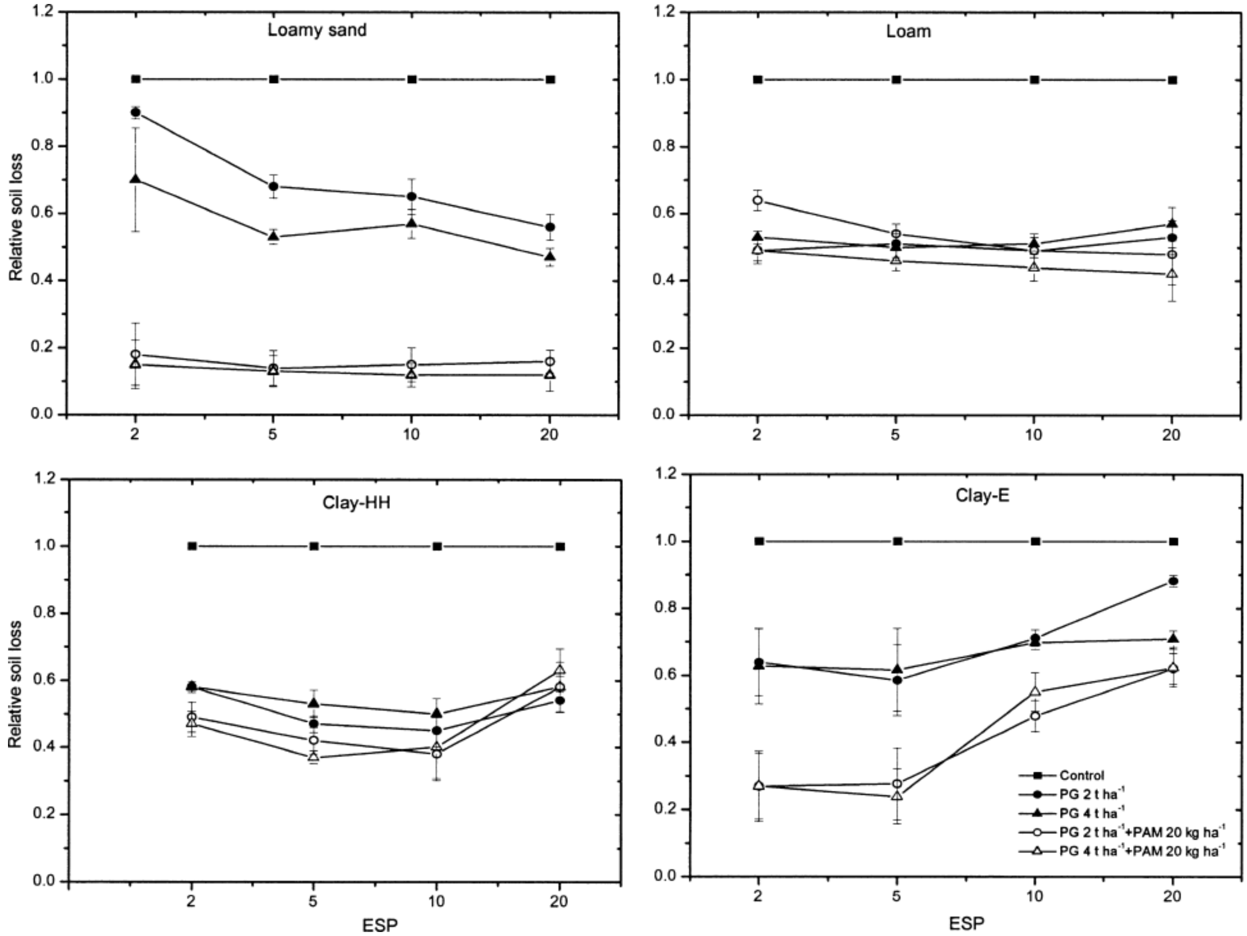

**Fig. 7. Relative soil loss as a function of exchangeable sodium percentage (ESP) and the treatments studied in the four soils. Bars indicate two standard deviations.**

similar rate to that in the control. The observed disparity with respect to the impact of the amendments on runoff and on soil loss as a function of ESP in the clay-E could be ascribed to the aforementioned opposing effects of seal formation on soil loss. Increasing soil sodicity increases aggregate disintegration and clay dispersion, and thus makes the soil surface more susceptible to detachment, all resulting in an increase in soil loss with the increase in sodicity (Fig. 6). However, soil sealing was almost complete at ESP 6.6 with no further sealing of the soil surface with further increase in sodicity and clay dispersion. Thus, runoff was not affected by the increased sodicity and soil loss increased mainly due to the increase in soil detachment.

The second group included the loam and the clay-HH where the effects of the two types of amendments on soil loss were, in general, comparable (Fig. 6 and 7). In both soils, the changes in soil loss (Fig. 6) and relative soil loss (Fig. 7) with changes in ESP were relatively minor compared with those noted in the soils from the first group. Conversely, in these two soils, both runoff and relative runoff were affected by the amendment type and PAM plus PG was more effective than PG in controlling runoff (Fig. 3 and 5). The greater efficacy of PAM plus PG compared with PG on maintaining a seal of higher permeability was ascribed to the favorable impact of PAM on stabilizing the surface aggregates that supplemented clay flocculation by the PG, thus leading to higher IR and lower runoff levels. Conversely, addition of PAM to the loam and clay-HH did not have a beneficial effect on reducing soil loss beyond that of PG, (Fig. 6 and 7). Soil erosion consists of particles' detachment from the soil surface and their transport and deposition. Our observations indicated that detachment of surface particles by runoff water was not affected by the presence of dry granular PAM at the surface of the loam and clay-HH, probably because clay content in the two soils was not sufficiently high ($< 40\%$) and therefore the effect of the PAM on stabilizing microaggregates and decreasing wash erosion was limited. The similar impact of both type of amendments on soil loss in the loam and clay-HH suggested that clay flocculation/dispersion was the predominant mechanism that determined the susceptibility of both soils to wash erosion; in our case enhancing flocculation resulted in reduced wash erosion.

## CONCLUSIONS

We investigated in the laboratory the effects of surface application of dry granular PAM (20 kg ha$^{-1}$) mixed with PG (2 and 4 Mg ha$^{-1}$) and that of PG alone on the IR, runoff, and the wash component of interrill erosion from four smectitic soils and different ESP levels. Increasing the ESP of the soils decreased IR and increased runoff and erosion in the control; the magnitude of these changes depended on soil type, being the greatest in the loamy sand and the least in the calcareous loam. Spreading PAM mixed with PG or just PG was effective in maintaining high final IR and low runoff and wash erosion levels compared with the control. Use of PAM mixed with PG resulted in higher final IR and lower runoff levels than just PG in all four soils studied. Conversely, with respect to wash erosion, PAM mixed with PG and PG alone had comparable effects on soil loss in the loam and clay-HH probably because clay flocculation/dispersion was the predominant mechanism determining the susceptibility of soil particles to detachment. In the loamy sand and the clay-E, use of PAM mixed with PG resulted in lower erosion levels than spreading only PG, indicating that stabilizing surface aggregates by PAM contributed to reducing aggregate susceptibility to detachment in these soils. The existence of significant interactions among our treatments (i.e., soil type, ESP and amendments) with respect to their effects on IR, runoff, and soil loss suggested that spreading of dry granular PAM mixed with PG could potentially be considered as a management tool for reducing soil susceptibility to seal formation in rainfed agriculture mainly under conditions where the dominant mechanism in sealing and erosion is physical destabilization of the surface aggregates.

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