CATENA SUPPLEMENT 24 p. 77–92 Cremlingen 1993

Utilization of Gypsiferous Amendments to Reduce Surface Sealing in Some Humid Soils of the Eastern USA

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Summary

Dispersion of soils by rainwater and subsequent surface sealing is a well known phenomenon in smectitic soils of semi-arid regions. In this study, three soils representing major land-use resource areas from the humid eastern USA with mineralogy dominated by mica/kaolinite and low sodium contents were studied to determine their infiltration behavior with time during rainfall and interrill erosion, and if a beneficial effect could be obtained with gypsiferous amendments. The effectiveness of different sources of gypsiferous materials on infiltration and erosion was also studied. The critical flocculation concentration of the natural clays (naturally Ca-saturated) was measured in the laboratory and was found to be between 1 and 3 $mmol_+ L^{-1}$. Surface runoff, soil loss, infiltration and soil strength were measured using small erosion pans in the laboratory under rainfall simulation of 37 mm hr^{-1} for 2 hours at slopes of 5 and 30%. The soils were susceptible to sealing and phosphogypsum treatments improved rain infiltration and reduced interrill erosion. Two sulfitic materials from coal desulfurization were less effective than phosphogypsum in reducing runoff and erosion. One by-product consisting of almost pure gypsum was even more effective. More surface sealing occurred on the 5% slope than the 30% slope, but erosion was greater at the steeper slope. The beneficial effect of gypsiferous materials on reducing erosion was less pronounced at the 30% slope. It was concluded that the increased electrolyte content of the eroding water from gypsiferous materials was responsible for the decrease in erosion and surface sealing in these humid region Ca dominated soils.

ISSN 0722-0723
ISBN 3-923381-33-6

38162 Cremlingen-Destedt, Germany
3-923381-33-6/93/5011851/US$ 2.00 + 0.25

1 Introduction

The ability of a soil to take water in is important for plant growth and for the prevention of erosion. In some soils, structural instability leads to surface sealing which reduces infiltration and therefore results in considerable amounts of runoff. Chemical dispersion as a result of the physical beating of raindrops and the low electrolyte content of rainwater also enhances sealing and promotes erosion. In semi-arid region soils subject to dispersion and surface sealing, gypsum has been used effectively to reduce runoff by increasing the electrolyte content of the water (Agassi et al. 1982, Chartres et al. 1985). The effectiveness of gypsum was also shown for a kaolinite soil in Georgia by Miller (1987).

In the USA, the phosphate fertilizer industry produces a considerable amount of phosphogypsum as a by-product. This material also has been shown to be effective in reducing runoff and erosion (Miller 1987). Unfortunately, this material has been banned by the US Environmental Protection Agency because of emissions of radon gas. However, even greater quantities of relatively clean gypsiferous materials are being produces as a result of the US Clean Air Act as amended in 1990. With the recent amendment, even older coal-fired power plants are mandated to reduce their SO_2 emissions. The technology used results in hundreds of thousands of tons of gypsiferous materials being produced each year from a single plant. Most of these materials are being produced in the eastern USA where much high sulfur coal is used.

Considering the two factors mentioned above, the objectives of this study were:

1. to evaluate the susceptibility of some soils from the eastern USA that are naturally highly Ca-saturated and having differing mineralogies to surface sealing when exposed to simulated rain;

2. to determine whether gypsiferous material additions can reduce surface sealing and erosion in these soils; and

3. to compare the effectiveness of materials produced from the desulfurization of stack gases from coal fired power plants with that of phosphogypsum.

2 Materials and methods

The soils chosen for study were three of those studied in the USDA Water Erosion Prediction Project (WEPP) (Lane & Nearing 1989). The soils included Cecil from Georgia, (clayey, kaolinitic, thermic Typic Hapludult), Miami from Indiana (fine-loamy, mixed, mesic Typic Hapludalf), and Opequon from Maryland (clayey, mixed, mesic Lithic Hapludalf). The soils were sampled at field moisture conditions, air-dried and ground to pass a 4-mm sieve. The sieved soil was packed into small erosion pans and equilibrated over a sand base with controlled moisture tension (Bradford & Ferris 1987). For each soil, two pans each at 5 and 30 percent slope were subjected to rainfall at a target rate of 37 mm hr^{-1} for two hours using the Purdue Programmable Rain Simulator (Neibling et al. 1981). Runoff, sediment concentration, electrical conductivity and infiltration were measured in 2 and 5-minute intervals respectively. Following rainfall, the pans were leveled and equilibrated to 5 cm water tension after which soil strength was measured using the Swedish Fall Cone apparatus (Bradford & Grossman 1982). For each erosion pan 15 measurements were taken.

Runoff and infiltration samples were weighed on a digital electronic balance connected directly to a PC. Sediment concentration samples were weighed, flocculated with alum, the supernantant decanted, and then dried overnight at 105°C and reweighed. Sediment concentration was determined as the weight of sediment divided by weight of the runoff including sediment.

Natural water dispersible clays from the three soils were collected by shaking untreated soil in deionized water on an oscillating shaker overnight and decanting after the appropriate settling time. The clay fraction was placed in a series of $CaCl_2$ solutions ranging from 1 to 5 $mmol_+ \ L^{-1}$ to determine the critical flocculation concentration (CFC) (Miller et al. 1990).

Four types of gypsiferous materials were collected for study. The first was phosphogypsum from Lakeland, Florida — a by-product of the phosphate fertilizer industry. Two gypsiferous materials from flue gas desulfurization (FGD) processes were taken directly from evaporators at the Hoosier Energy Power Plant at Merom, Indiana, and at the Public Service Indiana Power Plant at Gibson, Indiana. Additional gypsiferous material was collected from a fluidized bed combustor at the Purdue University Power Plant in West Lafayette, Indiana. These four materials were surface-applied at a rate of 5 t ha^{-1} (Miller 1987) to the Miami soil and the same rainfall procedures performed. Phosphogypsum was added to the Cecil and Opequon soils. Controls without any gypsum were run in duplicate on all three soils, and at two slope steepnesses. A slope of 5 percent was chosen to be representative of agricultural land and 30 percent for a slope more typical of construction sites.

Clay mineralogy of the dispersed clay was determined using various treatments on Mg-saturated, oriented slides using a Phillips X-ray diffractometer with Co K_α radiation. Unoriented powder mounts of the gypsiferous materials were also scanned with the same equipment.

The infiltration rate was modeled using the modified Hortonian equation of Morin & Benyamini (1977) as:

$$I_t = (I_i - I_f)\, e^{-\gamma p t} + I_f \qquad (1)$$

where

I_t = infiltration rate in mm hr^{-1} at time t
t = time into the run
p = rainfall intensity in mm hr^{-1}
I_i = initial infiltration rate in mm hr^{-1}
I_f = final infiltration rate in mm hr^{-1}
γ = dimensionless decay coefficient

The greater the decay coefficient the faster the infiltration rate decreases. The value for I_f used to model each curve was taken as the average value found for the 5 percent slope of each soil using the PROC NLIN procedure of PC-SAS (SAS Institute 1988).

3 Results and discussion

3.1 Soil properties

Diffractograms of the soil clays are presented in fig. 1. They show that the Miami clays contained a near equal mixture of smectite (1.77 nm), vermiculite (1.40 nm), clay mica (1.00 nm) and kaolinite (0.72 nm). The Cecil soil was predominantly kaolinite with a trace amount of illite and vermiculite. The Opequon soil had a predominance of clay mica and contains some kaolinite and vermiculite.

Water dispersibility of the three soils varied (tab. 1). The Opequon soil was the most dispersive with a critical flocculation concentration (CFC) of 3 $mmol_+$ L^{-1}. The Miami soil was intermediate with a CFC of 2 and the Cecil soil the least dispersive with a CFC of 1 $mmol_+$ L^{-1}. The percentage of water dispersible clay to primary clay was in the order of Opequon > Cecil > Miami (tab. 1). Considering the mineralogy of the soil clay, our results indicate that clay mica is more dispersive than smectite which is more dispersive than kaoli-

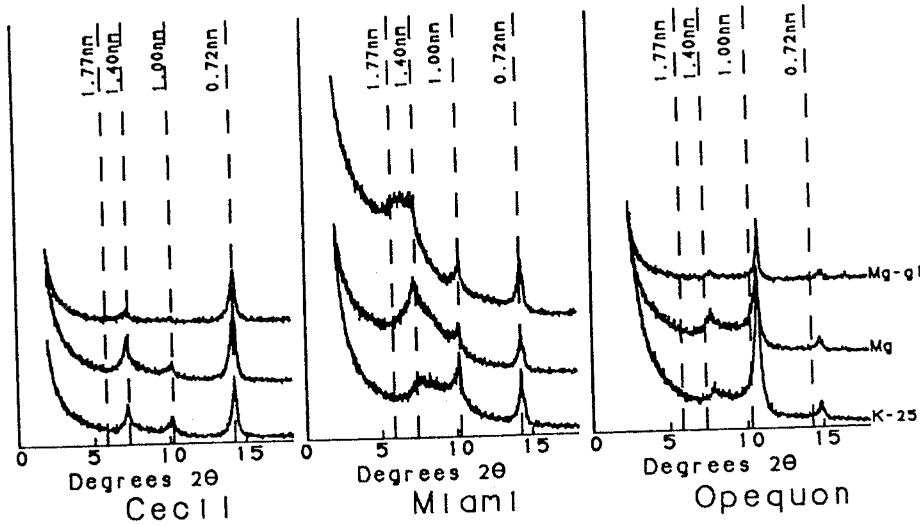


Fig. 1: *X-ray diffraction with various treatments of the <2μm fraction from the soils studied.*

Soil	Sand %	Primary Silt %	Clay %	W.D. Clay %	CFC mmol+ L^{-1}	Dominant* Clay	Strength kPa
Cecil	64.6	21.6	14.7	72.7	1	Kaol	11.5
Miami	4.2	72.7	23.1	32.5	2	Exp	15.7
Opequon	37.7	31.2	31.1	78.4	3	Mica	10.7

* Kaol-kaolinite, Exp-Expandables (Smectite, vermiculite, etc.)

Tab. 1: *Some physical and chemical properties of the soils studied (Elliot et al. 1989 and this study).*

nite clay. A similar order was reported in the literature for the reference clays (e.g. Oster et al. 1980). However, the actual values of CFC for Ca-saturated reference clays are lower than those measured for these soil clays. Adsorption of anionic polymers such as anionic organic polysaccharides at the edges of the soil clays may explain their high dispersion (Miller et al. 1990).

Soil texture varied primarily in the sand and silt contents (tab. 1). The Cecil soil contained the greatest amount of skeletal sand grains and the least clay. The main skeletal component of the Miami soil was coarse silt with only a minor amount of sand. The clay content of Miami was intermediate while the Opequon soil had the greatest clay content and near equal amounts of sand and clay. The shear strength of the soils is related to their clay plus silt content. The Miami soil with the highest percent silt and clay fractions has the highest strength. This texture enables the formation of particle to particle contacts and bonds which is reflected in high strength. As the clay content decreases (Cecil), there are less opportunities for particle contacts and less cohesiveness occurs. As the clay content increased (Opequon), more stable aggregates were formed with less cohesive forces between the aggregates (Line & Meyer 1989); therefore, less strength.

3.2 Infiltration

In the control plots, all three soils exhibited a reduction in infiltration rate (IR) with amount of rain applied, indicating that they had developed surface seals even at the low intensity of the rain applied (~37 mm hr^{-1}). The reduction in IR, as sealing progressed, approached a steady state in all three soils after application of 40 mm of rainfall (fig. 2). The final IR was low (<5 mm hr^{-1}) for all three soils with Miami > Cecil > Opequon (tab. 2). The Cecil and Opequon soils had an infiltration rate declining at a similar rate. The decay coefficient (γ) being similar for Cecil and Opequon and greater than that of the Miami soil (tab. 2). This is an indication that these two soils have a less stable structure than the Miami soil, since the infiltration rate drops off faster. The order of the soils in terms of the final IR and the rate of seal formation (γ) were in the same order as the ratio of water dispersible clay to primary clay (tab. 1). The greater the percentage of water dispersible clay, the lesser the final IR and the greater the rate of seal formation observed (tab. 2). The electrolyte concentration in the rain water was very low (deionized water) and was below the CFC of all three soil clays. Thus, the CFC of the clay had no relation to the final IR or the percentage of water dispersible clay observed.

The addition of phosphogypsum (PG) to the soil surface increased the final IR (figs. 3 and 4) and decreased the coefficient γ considerably for all three soils (tab. 2). The effect on the final IR was greatest for the Opequon soil (over 3 times), and nearly equal for the Cecil and Miami soils (2 times). Apparently, the effect of PG was to flocculate the water dispersible clay (Kazman et al. 1983). The effect of PG was more pronounced the more dispersive the clay. Thus, the effect of PG is more pronounced as the sodicity of soil clay increased (Kazman et al. 1983). Similarly, the effect of PG was more pronounced in the Opequon since it contained the most water dispersible clay and had the highest CFC. This would support the concept that dispersion of clay in this range of particle sizes is an important process in surface sealing (Agassi et al. 1981).

The effect of final IR of adding power plant by-products to the Miami soil was equal to or better than phosphogypsum except for the Gibson Power Plant material which had a final IR nearly equal to that of the control (fig. 4). Both the Merom and Purdue materials produced greater final infiltration rates than phosphogypsum. The Purdue material was almost pure gypsum due to the nature of the process used to produce it. Hence it dissolved more rapidly than PG and it's effect was greater. The coarser the particles, the less soluble the material due to surface area constraints. The Merom material was $CaSO_3{\cdot}xH_2O$ with a solubility similar to that of PG. The Gibson material was $CaSO_3{\cdot}1/2H_2O$ with a low

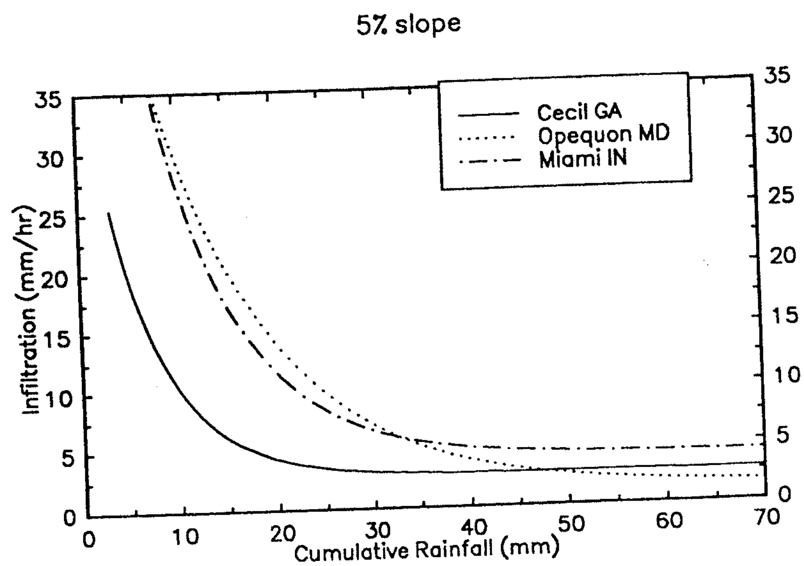


Fig. 2: *Infiltration rates (IR) with cumulative rainfall for the three soils at 5 percent slope.*

Soil	Treat-ment*	Strength kPa	I_i mm hr^{-1}	I_f mm hr^{-1}	γ	Total Infil-tration mm	Total Soil Loss kg	Total Run-off mm
Cecil	none	11.5	40.6	2.7	0.162	10.1	0.38	49.4
	PG	11.1	40.6	5.2	0.100	17.2	0.08	49.7
Miami	none	15.7	79.0	4.3	0.116	19.9	0.18	50.5
	PG	21.4	79.0	8.4	0.138	23.1	0.15	48.9
	Gib	21.6	79.0	4.9	0.181	12.9	0.28	45.1
	Mer	24.3	79.0	10.0	0.141	26.4	0.13	49.9
	Pur	17.7	79.0	11.2	0.109	31.0	0.12	52.9
Opequon	none	10.7	65.2	2.1	0.081	18.9	0.24	53.2
	PG	6.5	65.2	7.5	0.140	21.6	0.08	50.5

* PG-phosphogypsum, Gib-Gibson, Mer-Merom and Pur-Purdue

Tab. 2: *Strength, infiltration coefficients and soil loss at 5% slope for the three soils studied.*

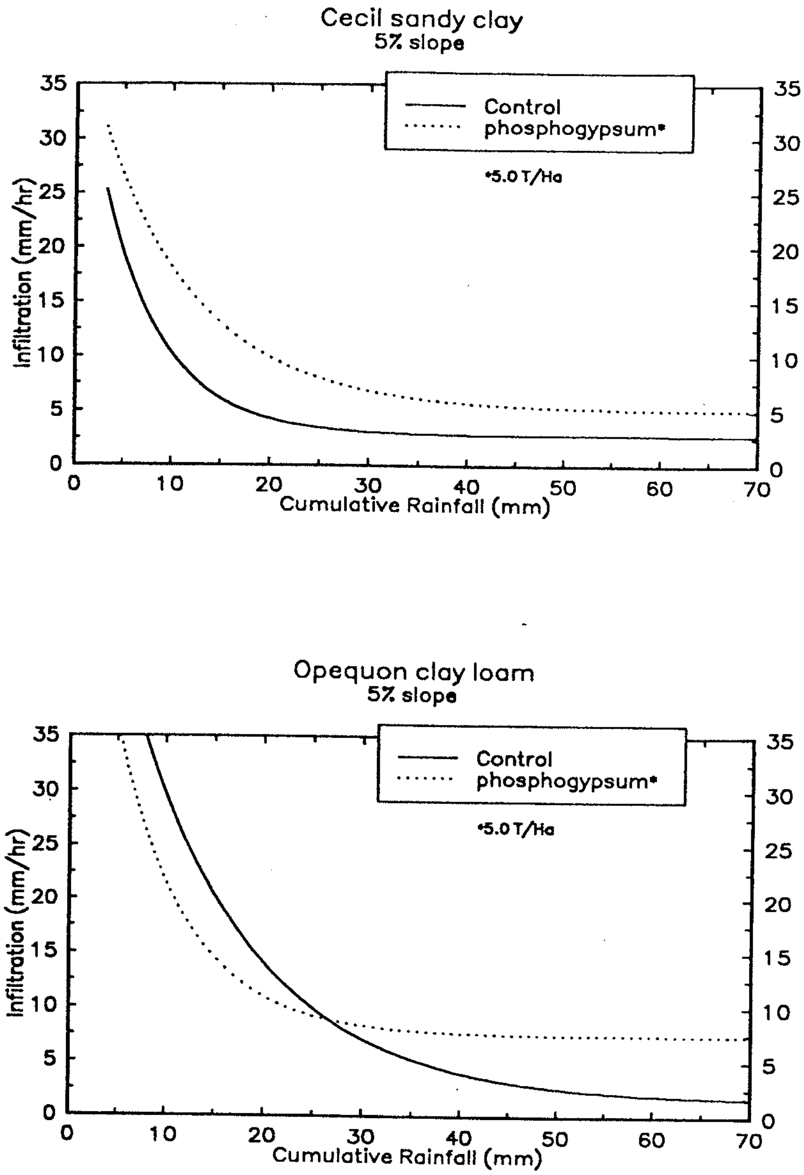


Fig. 3: *Effect of phosphogypsum on infiltration rate with cumulative rainfall for the Cecil and Opequon soils at 5 percent slope.*

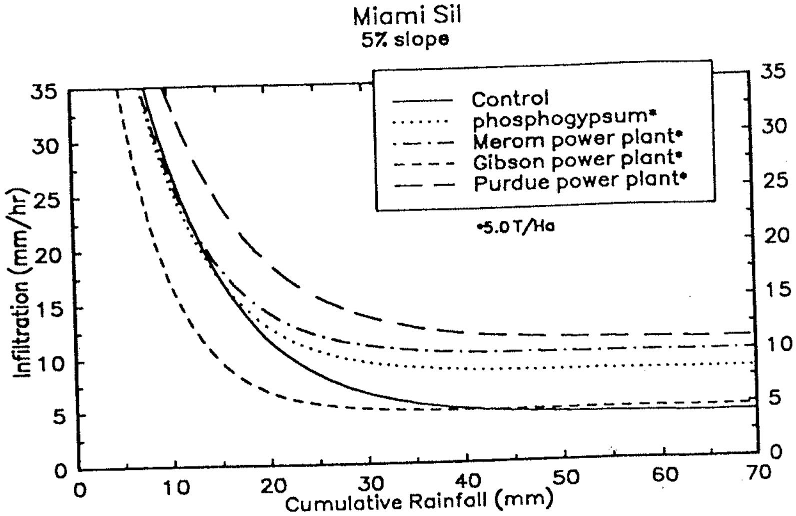
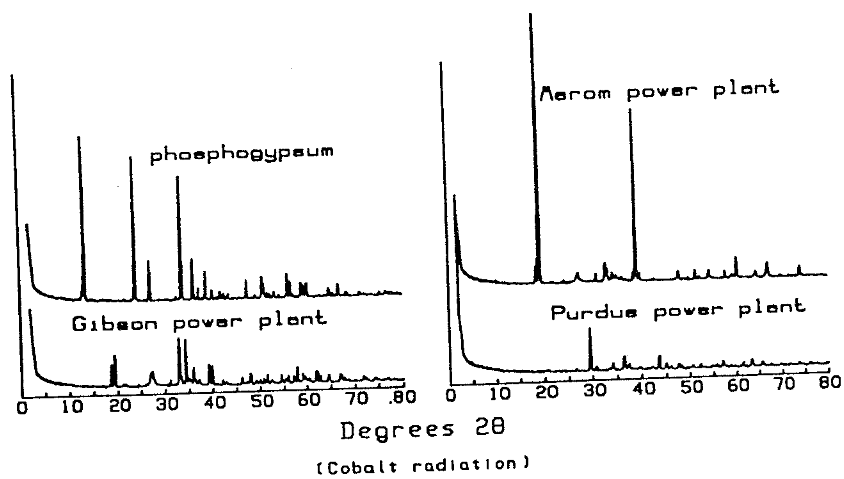


Fig. 4: *Effect of phosphogypsum and gypsiferous power plant by-products on infiltration rate with cumulative rainfall for the Miami soil at 5 percent slope.*



solubility and very fine silt particle size (fig. 5). Apparently, the slow release of electrolyte from the Gibson material did not allow it to prevent sealing.

3.3 Soil erosion and runoff

In the control pans for all three soils, the soil loss rate tended to first increase as sealing progressed, then reached an equilibrium rate (fig. 6). The initial increase in soil loss rate is due to the increase in runoff production. At cumulative rain of 40 mm, runoff and soil detachment rates tend to steady state values (figs. 2 and 6). The detachment rates for the Cecil soil is the highest, that for Miami the lowest and that for Opequon intermediate. The reader should note that IR and runoff, respectively are about the same for the Cecil and Opequon soils. Thus, the differences in detachment rates may reflect the differences in shear strength between the soils. Since the shear strength of the Opequon soil is greater than that of the Cecil soil (tab. 1), interrill shear erosion is much lower. Accordingly, the greatest total soil loss was found for the Cecil soil followed by Opequon and Miami soils (tab. 2).

Phosphogypsum reduced the total soil loss for each soil (tab. 2). The total soil loss during two hours of rainfall was only 83 percent of the control for the Miami, but for Opequon and Cecil it was 33 and 25 percent of the control, respectively. If not for the high soil loss rate up to the midway point of rainfall with Miami, the reduction would have been much greater (fig. 6). This could be due to experimental error in the early stages of rainfall because after 40 minutes of rainfall the soil loss rate is considerably less for the rest of the rainfall duration (fig. 6). In the PG treatment, runoff for the Miami soil was 84 percent of the control, whereas the soil loss ratio was 0.83. The concentration of sediment in the runoff was similar for both the control and PG treatments for the Miami soil. Conversely, for the other two soils, the runoff ratios in the PG treatment were 0.83–0.84 (values similar to that of the Miami soil) but the soil loss ratios were 0.33 and 0.25 for the Opequon and Cecil soils, respectively. It is evident that the concentrations of sediment in the runoff from these two soils were much lower than in the control. The presence of electrolytes in runoff enhances flocculation and sedimentation of soil clays and interrill erosion is low.

The effect of the gypsiferous by-products on the detachment rate was similar to that observed for infiltration. The Gibson material had greater detachment rates than the control throughout the experiment and greater total soil loss (fig. 7). This appears to be a result of two factors. First, the particle size of the Gibson material was approximately 20μm. This makes it an effective material to physically plug pores, and subsequently produce more runoff (tab. 2). Second, the solubility and ability to release electrolytes from this material was low compared with the other gypsiferous materials; resulting in more dispersion of clay and surface sealing.

Both the Merom and Purdue by-products were more effective than phosphogypsum in reducing soil loss on the Miami soil with the Purdue product slightly better than the Merom. Except at the very initial stages of the rainfall, both materials resulted in less cumulative soil loss than the control. Total soil loss was reduced by about one half that of the Gibson for both materials (fig. 8).

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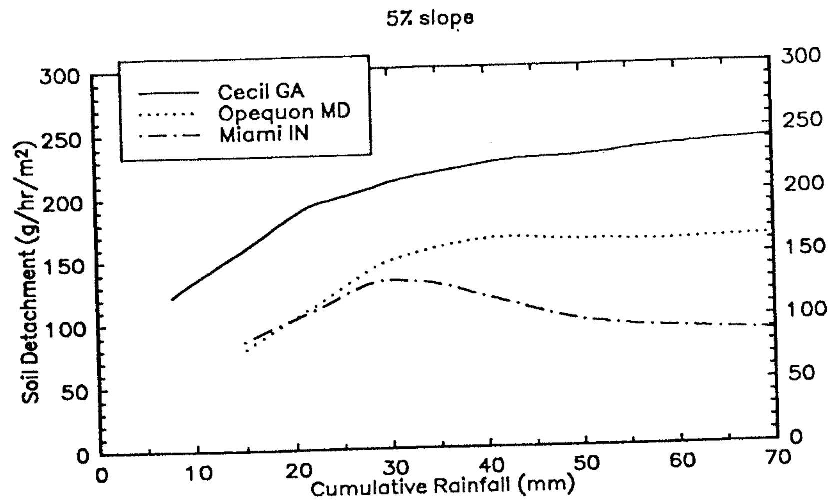

Fig. 6: *Detachment rate as a function of cumulative rainfall for the three soils.*

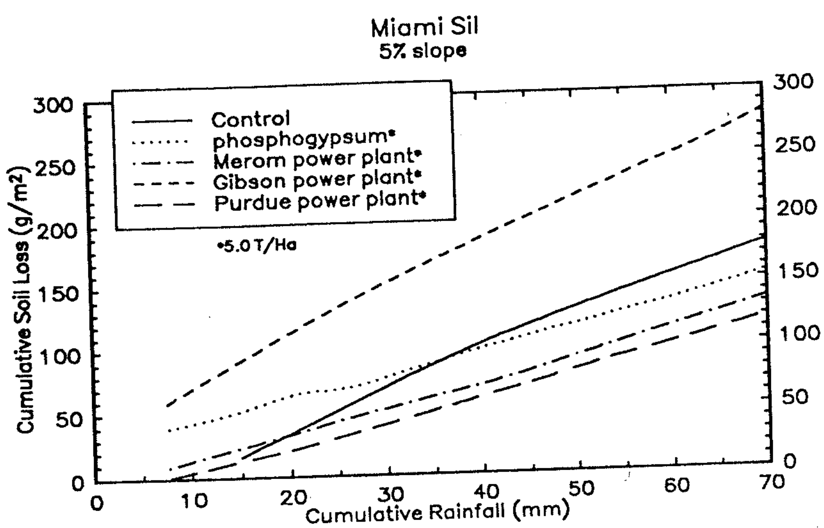

Fig. 7: *Cumulative soil loss for the Miami soil at 5 percent slope.*

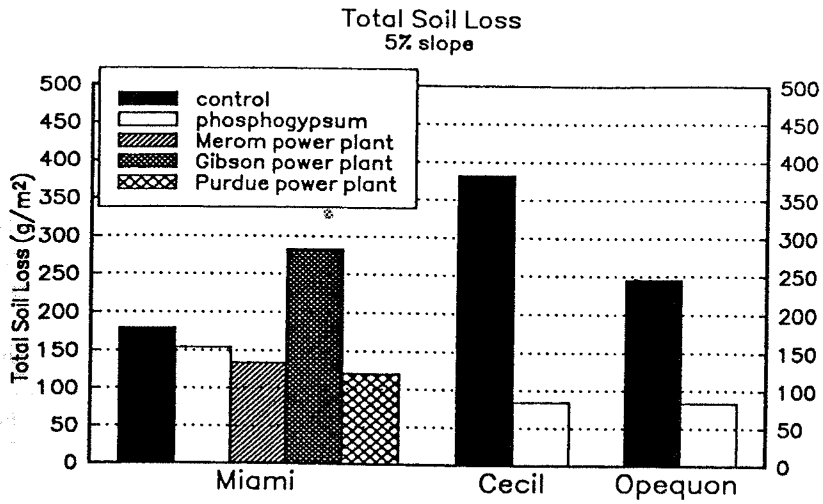

Fig. 8: *Total soil loss during 2 hours of rainfall for the controls and by-products added at 5 percent slope.*

3.4 Effect of amendments on soil strength

Interpretation of the effect of the gypsiferous materials on soil strength as measured with the Swedish fall cone apparatus (tab. 2) is not simple. PG treatments reduced the shear strength in two soils and increased shear strength in one soil (Miami). When the soils are rained upon with deionized water (DW) raindrop impact initially formed small craters or pits at the soil surface. As rain proceeded, a smooth surface develops. As the seal developed, the strength of the soil surface increased and pitting by raindrops was prevented. When PG was applied, pitting continued throughout the entire rainstorms in all three soils. Similar observations were reported for other soils by Warrington et al. (1989). Based on the smoothness of the soil surface for the non PG soils, it was concluded that PG weakens the strength of the seal and raindrops were able to form pits and craters. However, the results with the Swedish fall cone device agree with this conclusion only in two of the three cases. One problem with the fall cone is that rather than measuring strength at the very surface, it measures an "average" strength to the depth of penetration. This may not relate to the actual strength of the seal.

In the Cecil and Opequon soils, PG application indeed weakened the measured strength of the soil seal. In the Miami soil, gypsum treatment increased the measured strength of the seal. In the two soils where PG weakened the strength of the seal, PG was very effective in reducing erosion (tab. 2), contrary to the expectation that a seal with high strength reduces erosion. With the PG treatment soil splash and detachment increased compared with the control and soil losses were lower as a result of sediment flocculation by the Ca electrolytes and subsequent deposition.

The effect of PG on seal strength was in two opposing directions. The increase in Ca-electrolyte concentration reduces the swelling and repulsion between soil particles, thus increasing the strength of the bonds between particles and soil cohesiveness. Conversely, with the increase in flocculation and aggregate stability the number of contacts between aggregates decreases and soil cohesiveness decreases. Whereas, the first mechanism prevailed in the Miami seal and PG increased the shear strength of the seal, the second mechanism prevailed in the Cecil and Opequon seals and strength was reduced.

3.5 Slope effects

The effect of slope on soil loss was considerable for all three soils studied. For the controls, the total soil loss was greater in each case at the greater slope (tables 2 and 3), but the magnitude varied among the soils. The greatest increase was for the Miami soil with the slope factor (S_{30}/S_5) of 3.61, followed by Opequon (3.04) and Cecil (1.94).

The effect of slope on shear strength was also pronounced. The strength of the seal at 30% slope was always less than at 5% slope. Erosion of the seal at the 30% slope reduced its strength and also increased the final IR (tables 2 and 3). The strength of the seals at 30% slope in the PG treatment was very similar to the strength in the control. Apparently, the PG was washed off and its effect was minimal.

Phosphogypsum and by-product materials were not as effective in reducing soil loss at the 30 percent slope (figs. 9, 10 and 11) as at the 5 percent. With the exception of the Opequon soil (fig. 10), the soil loss reduction from the control was minimal. The soil loss reduction for the Opequon soil was slightly more than half at the 30 percent as compared to one quarter for the 5 percent slopes. Apparently, because surface sealing occurs to a lesser extent, phosphogypsum was less effective on the 30 percent slope.

As with the 5 percent slope, the Gibson by-product resulted in less infiltration and greater soil loss than the control at 30 percent slope on the Miami soil (tab. 3, fig. 11). The other by-products, particularly the Purdue by-product, produced a reduction in soil loss over the control. Since the general reduction from the control was minimal, the advisability of applying these by-products at slopes of 30 percent is questionable.

4 Conclusions

Surface sealing and reduction in infiltration rate occurred for all three soil/mineralogical systems. Addition of phosphogypsum increased final IR and decreased soil loss to a greater extent at the 5 percent than at the 30 percent slope. Flocculation of the clays appeared to be the mechanism responsible for the greater reduction in soil loss rather than the improvement in infiltration. Phosphogypsum was not as effective in reducing soil loss at 30 percent slope.

Additions of gypsiferous by-products to the Miami soil gave results comparable to phosphogypsum. Depending on the material, some were more and others less effective. Materials with greater solubility were effective in reducing erosion and improving infiltration. One material which was not very soluble and had a

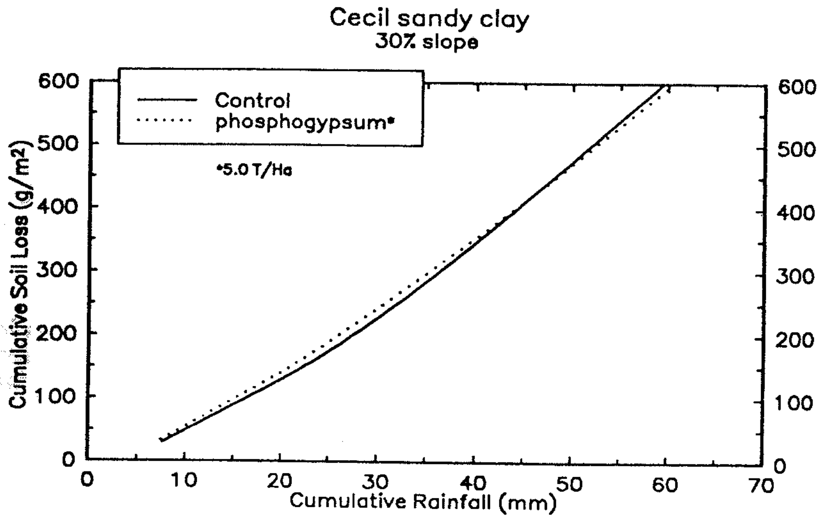

Fig. 9: *Cumulative soil loss for the Cecil soil at 30 percent slope.*

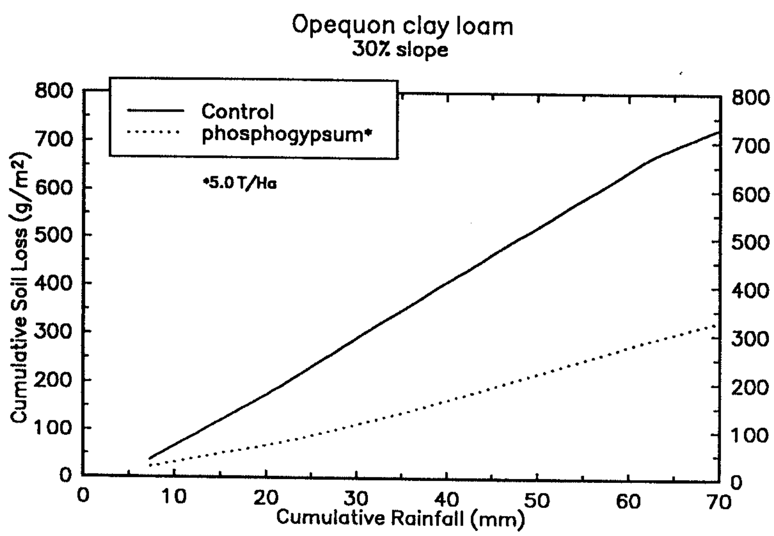

Fig. 10: *Cumulative soil loss for the Opequon soil at 30 percent slope.*

Soil	Treat-ment*	Strength kPa	I_i mm hr^{-1}	I_f mm hr^{-1}	γ	Total Infil-tration mm	Total Soil Loss kg	Total Run-off mm
Cecil	none	9.4	40.6	3.8	0.197	9.1	0.74	43.2
	PG	9.2	40.6	6.9	0.117	17.7	0.72	35.7
Miami	none	11.3	79.0	7.3	0.182	17.7	0.65	34.0
	PG	12.0	79.0	9.0	0.232	18.6	0.55	34.0
	Gib	16.3	79.0	5.2	0.228	11.7	1.00	40.5
	Mer	18.7	79.0	9.8	0.228	19.5	0.62	34.7
	Pur	17.6	79.0	10.5	0.225	21.4	0.52	33.7
Opequon	none	7.5	65.2	4.6	0.257	10.7	0.73	43.0
	PG	6.3	65.2	6.9	0.189	16.5	0.33	36.8

* PG-phosphogypsum, Gib-Gibson, Mer-Merom and Pur-Purdue

Tab. 3: *Strength, infiltration coefficients and soil loss at 30% slope for the three soils studied.*

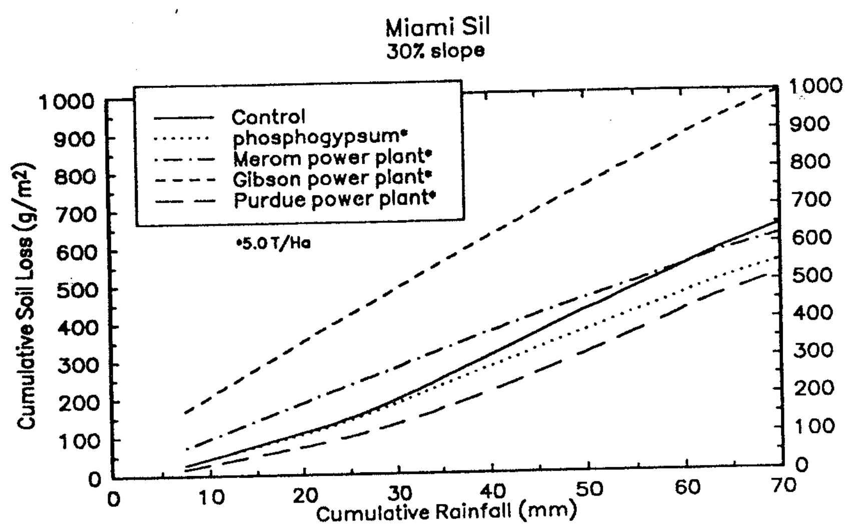

Fig. 11: *Cumulative soil loss for the Miami soil at 30 percent slope.*

very fine particle size actually increased soil loss. The by-product from a fluidized bed combustor was the most effective material tested. This technology produces nearly pure gypsum with fine sand-sized particles. This material provided more electrolyte concentration in the eroding water and thus was most effective in reducing erosion. Addition of these materials to 30 percent slopes gave minimal reduction in soil loss over the control. However, application of some of these gypsiferous by-products from the coal-fired power industry to gently sloping land (e.g. 5 percent slopes) appears to be a viable method for environmentally safe disposal of the material for erosion control.

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