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Use of Coal Combustion By-Products to Reduce Soil Erosion

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Abstract

High-calcium coal combustion by-products such as flue gas desulfurization (FGD) sludge and fluidized bed combustion (FBC) ash are suitable soil amendments for reducing soil erosion. Previous studies have shown that they improved water infiltration, decreased runoff, and reduced soil erosion. A laboratory study was conducted to examine two types of CCBPs, a reclaimed, class C fly ash marketed under the name "Nutra-Ash" and an industrial biosolid stabilized with alkaline Fluidized Bed Combustion (FBC) ash called "SoilerLime". Natural gypsum and turkey compost were also studied as soil amendments.

Runoff volume and sediment loss were measured for amended soil and compared to untreated soil. The SoilerLime, Nutra-Ash, and gypsum treatments all reduced total runoff and sediment loss, but they varied widely in their effectiveness at reducing final runoff rate and sediment yield. The SoilerLime was the most soluble amendment and initially released the highest concentrations of calcium and sulfur. However, its solubility decreased with time, as did its effectiveness at reducing final runoff rate and sediment yield, which were comparable to that of gypsum.

The effectiveness of the Nutra-Ash peaked at about 50 minutes, and then runoff rate and sediment yield increased to that of the control. This was probably due to the lower solubility of minerals in the weathered ash. Gypsum maintained a relatively constant release of calcium and sulfur. It remained effective longer and reduced both final runoff rate and sediment yield rate.

Calcium-containing coal combustion by-products can be effective amendments for reducing soil erosion, but their effects are very dependent on the solubility of their calcium containing minerals.

Keywords: Class C fly ash, FBC ash stabilized biosolids, FGD gypsum, electrolytes, organic matter, soil erosion, and soil amendments.

Introduction

Soil erosion caused by the agriculture, construction, and forestry industries is a leading source of water pollution in the U.S. The presence of suspended sediment in storm water runoff is one of the most common pollutants affecting rivers, lakes, and streams (US EPA, 1996). The interaction of rainwater with bare soil results in runoff and soil loss, processes that are dependant on the physical structure and chemical nature of a given soil.

Calcium ions are effective at improving soil structure and increasing water infiltration. In addition, calcium and sulfur are important micronutrients for plants. Gypsum ($CaSO_4 \cdot 2H_2O$) is used commonly used as a soil amendment to provide calcium (an electrolyte source) and sulfur. In addition to natural gypsum, there are several types of industrial by-products that contain gypsum that could be used as soil amendments (Alcordo and Rechcigl, 1995). Coal combustion by-products from sulfur scrubbing technologies, such as FGD and FBC, contain large concentrations of soluble calcium and sulfur (McCarthy and Solem-Tishmack, 1996).

U.S. power plants generate more than 25 million tons of flue gas desulfurization (FGD) sludge, approximately 40 million tons of high calcium fly ash and bottom, and an estimated 2 million tons of fluidized bed combustion (FBC) ash (ACAA, 1998 ash; Tishmack and Olek, 1999). Approximately 18% of the FGD materials and 40% of the high calcium fly ash and bottom ash were utilized, and most of this was in the construction industry (ACAA, 1999). The use of these by-products as soil amendments could provide a significant potential market for CCBP.

A well aggregated soil is less erodible because it is porous and has a greater infiltration rate and lower runoff than a poorly aggregated soil. Soil erosion is caused by the three principal mechanisms: 1) the impact of raindrops, 2) flowing water, and 3) chemical dispersion of clay particles. During a rainstorm the energy of rain drop impact physically breaks apart soil aggregates. Erosion by flowing water occurs when the critical shear stress of the soil is exceeded by the shear stress of the water (Laflen et al., 1991). Soil aggregates can also be broken down by dispersion of clay minerals due to the absence of electrolytes (calcium and magnesium) in the soil solution. When soil aggregates break down the dispersed soil particles become entrained in flowing water (runoff) thus entering streams, rivers, and lakes as suspended solids. They also migrate downward into soil pores, effectively clogging them and reducing infiltration of water and increasing runoff.

There are several approaches to reducing the breakdown of soil structure. The surface of bare soil can be covered with organic mulch (straw or compost) to protect the surface from raindrop impact. Soil amendments can be added to increase soil electrolyte concentrations, which increases clay flocculation and reduces soil dispersion.

Previous studies of FGD gypsum and FBC ash applied to soil showed that they increased electrolyte concentration, improved water infiltration, decreased runoff, and reduced soil erosion (Reichert and Norton, 1996; Flanagan, Norton, and Shainberg, 1997a,b). The current erosion study evaluated two other types of CCBP.

Materials and Methods

A laboratory study was conducted to examine a reclaimed Class C fly ash and an FBC stabilized industrial biosolids. The Class C fly ash was produced at a power plant in Indiana that burns a low sulfur bituminous coal from the Wyoming Powder River Basin. The fly ash had been in an ash landfill on site for several years. The ash landfill was subsequently reclaimed by excavating the hardened ash and crushing and screening it into various sized fractions. Several products were made from the reclaimed ash including various sized aggregate (gravel and sand) and an agricultural liming material marketed in Indiana under the name "Nutra-Ash".

The stabilized industrial biosolids was manufactured at Purdue University from FBC ash produced by the Purdue power plant and an organic by-product from Eli Lilly & Co. Mixing wet biosolids with dry, dusty FBC ash forms a material that is easier to handle than the individual materials alone. The material is regulated under a permit issued by the Indiana Department of Environmental Management and distributed to local farmers as a liming material. It is also used by the Indiana Department of Natural Resources for mine land reclamation.

Because the stabilized biosolids contained organic matter, turkey compost was also included in the study to determine the effects of organic matter. A turkey farmer in Indiana provided the turkey compost, which consisted primarily of aged turkey litter and sawdust bedding. Natural gypsum mined from Indiana was also included in the study for comparison.

Samples of the mineral amendments were submitted to a commercial laboratory (A&L Laboratory, Inc.) for fertilizer/lime analyses and the results are given in Table 1.

The SoilerLime contained approximately 1% more calcium than the gypsum and 6.5% more than the Nutra-Ash (on a dry basis). SoilerLime contains approximately 12% organic, higher moisture content (27.2 %), and a lower bulk density (58.4 lb/cu ft) than the other mineral amendments. Due to its lower bulk density and higher moisture content, a larger volume of SoilerLime was needed in order to get the same amount of calcium as gypsum. Particle size analyses showed that SoilerLime was slightly finer than gypsum and the Nutra-Ash was slightly coarser. Smaller sized particle have higher surface area and generally have higher chemical reactivity, dissolving faster than larger sized particles.

Table 1. Fertilizer/Lime Analysis of the Mineral Amendments.

Parameter	SoilerLime		Nutra Ash		Gypsum	
	As Rec.	Dry basis	As Rec.	Dry basis	As Rec.	Dry basis
% Calcium (Ca)	17.3	23.8	16.0	17.2	22.4	22.4
% Magnesium (mg)	0.19	0.26	2.72	2.92	1.44	1.44
% Calcium Carbonate Equivalent (CCE)	26.73	36.82	48.05	51.55	11.73	11.7
% Moisture (105 deg. C)	27.2		6.8			
% Passing U.S. #8 Sieve		95.0		87.1		97.6
% Passing U.S. #20 Sieve		76.8		46.6		68.2
% Passing U.S. #60 Sieve		29.6		27.5		24.6
Bulk Density (lb/ft^3)	58.4		79.9		77.8	

The solubility of each sample was tested by A&L Laboratories, Inc. using a sequential extraction procedure. Fifteen grams of each sample was placed into separate 500 mL plastic bottles to which 300 mL (20:1 ratio) of room temperature ultra-pure water was added. The mixtures were agitated on a mechanical shaker for 10 minutes and then filtered with suction through a Whatman #1 filter paper in a buchner funnel. All the liquid was removed from the plastic bottles, and the solutions were tested by ICP-MS using water matrix standards. The filtered solids were returned to their bottles with an additional 300 mL of water, and the procedure repeated. Three 10-minute extractions were thus performed on each of the mineral amendments, and the results are presented in Table 2.

Nutra-Ash formed the lowest concentration of calcium in solution, and SoilerLime formed the highest in its first extraction, but calcium concentrations decreased in the second and third extractions. By comparison, gypsum maintained approximately the same concentration of calcium in all three extractions. Previous studies of FBC ash have shown it contains large amounts of very soluble calcium- and sulfur-containing minerals in the form of calcium sulfate and calcium hydroxide (McCarthy and Solem-Tishmack, 1996; Tishmack and Deshamps, 1999). SoilerLime extractions contained significantly higher concentrations of sulfur than either gypsum or Nutra-Ash, as a result of the presence calcium sulfide in the FBC ash.

Table 2. Metal Concentrations (ppm) by ICP-MS in solutions (20:1).

	SoilerLime			Nutra-Ash			Gypsum		
Parameter	10min	20min	30min	10min	20min	30min	10min	20min	30min
Calcium (Ca)	14,200	7,850	7,220	660	700	660	12,500	12,300	12,300
Magnesium (Mg)	<1	<1	<1	<1	<1	<1	18	61	62
Sodium (Na)	100	17	7	920	340	200	11	7	<1
Potassium (K)	940	102	24	34	17	10	28	18	11
Sulfur (S)	74,000	37,000	20,000	530	350	370	9070	8870	8740
Boron (B)	0.6	0.9	0.7	20	14	10	1.4	1.0	0.6
Copper (Cu)	4.8	1.3	1.1	0.1	0.1	<0.1	2.2	1.9	1.8
Iron (Fe)	6.6	10.1	6.2	2.1	3.6	8.0	2.0	2.4	1.7
Manganese (Mn)	0.1	0.2	0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1
Zinc (Zn)	0.3	0.2	0.3	<0.1	<0.1	<0.1	0.2	0.2	0.1

A rapid decrease in the concentration of a given ion is often referred to as a "first flush", where easily dissolvable minerals are quickly depleted when the ash first contacts water. The SoilerLime appears to contain calcium and sulfur that is rapidly dissolved, but gypsum does not. Because Nutra-Ash had been exposed to moisture for several years while in the landfill, it contained less soluble minerals than fresh material. Grinding of the weathered ash may have exposed new surface area that had slightly higher solubility than the otherwise cemented matrix.

The application rate of gypsum, 5,000 kg/ha (2.23 tons/ac surface applied) was based on a previous study conducted by Chaudhari and Flanagan (1998). The application rates for SoilerLime, Nutra-Ash, and turkey compost were based on their nutrient contents such that they did not exceed annual nutrient requirements for the soil. The Nutra-Ash was surface applied at a rate of 19,500 kg/ha (8.7 tons/ac), based on soil requirements for phosphorous. The SoilerLime application rate of 26,675 kg/ha (11.9 tons/ac, surface applied) was based on nitrogen. The application rate of turkey compost, 17,100 kg/ha (7.6 tons/ac, incorporated) was based on phosphorous. Unfortunately, this resulted in varying rates of calcium application, and it may have been more suitable to choose calcium concentration as the criterion rather than nutrient requirements.

The soil used in the study was obtained locally from the river flood plain. It was classified as silty clay (18% sand, 40% silt, 42% clay) and contained 3.4% organic matter, 325 ppm Mg, 3800 ppm Ca, and had a cation exchange capacity of 22.0 meq $100g^{-1}$. The soil was gently crushed and sieved to pass an 8 mm opening then allowed to air dry. Sand was placed in the lower 5 cm of each erosion pan measuring 32 cm wide × 45 cm long × 20 cm deep. The remaining 15 cm of each pan was packed with soil to achieve a bulk density of approximately 1.35 g/cm^3.

Three to four pans were run at one time with treatments assigned randomly. Three replications were done of each treatment, and the results were reported as an average of three measurements. Soil amendments were broadcast onto the surface of the soil according to the application rates listed above. The amendments were not incorporated into the soil. The slope of the pans was set at 9.5%. Simulated rainfall was applied using deionized water at an intensity of 70 mm/hr (2.76 inches/hour) for 2 hours. Runoff samples were collected in 1 L bottles every 5 minutes and runoff rate was determined by measuring the mass of runoff. Sediment concentration was determined gravimetrically.

Results and Discussion

Total runoff and total sediment yield for each treatment are shown in Figure 1. A reduction in runoff is an indication of improved infiltration and a decrease in sediment yield is an indication of improved resistance to soil erosion. The SoilerLime was the most effective treatment; reducing total runoff by 48% and sediment loss by 30%. Gypsum treatment reduced runoff by 12% and sediment loss by 28%. The Nutra-Ash reduced runoff volume by 9% and sediment loss by 15%. The turkey compost decreased sediment loss by 11% but increased runoff volume by 2%.

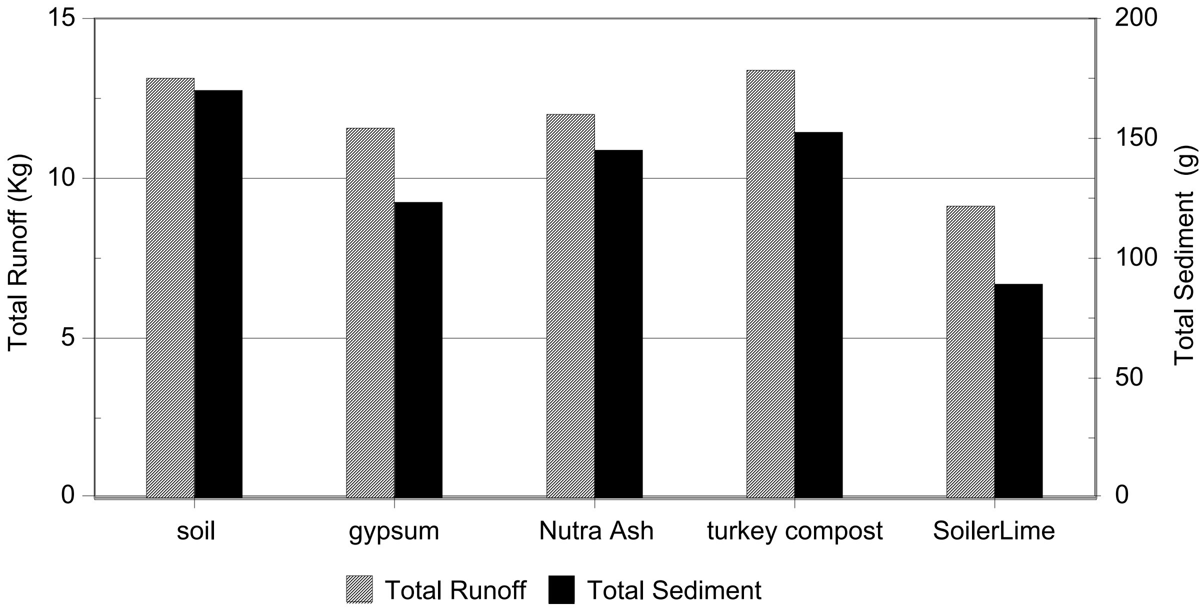

Figure 1. Total runoff and total sediment yield for each treatment.

Runoff Rate

The runoff rate versus time for each treatment is plotted in Figure 2. All of the treatments had lower initial runoff rates compared to the control. However, their rates increased with time presumably because of the breakdown of soil aggregates, which results in surface sealing and reduced infiltration. The runoff rates for gypsum, Nutra-Ash, and turkey compost all reached steady state within 60 minutes. Although total runoff rate for Nutra-Ash was lower than the control, its final runoff rate was slightly higher. The turkey compost treatment had a reduction in runoff rate initially, but its final runoff rate was significantly greater (18%) than that of the control. This may have been because the application rate was too low to provide adequate surface coverage.

The runoff from the SoilerLime treatment continued to increase slowly and did not reach steady state during the experiment. The amount of calcium released from SoilerLime was initially only slightly greater than that of gypsum; therefore, the reduction in runoff rate was not solely due to electrolytes. It seems likely that organic matter in the stabilized biosolids affected the runoff rate. An organic mulch or compost broadcast on the soil surface will absorb rainfall impact energy and reduce surface sealing, and this contributes to higher infiltration rates and less runoff.

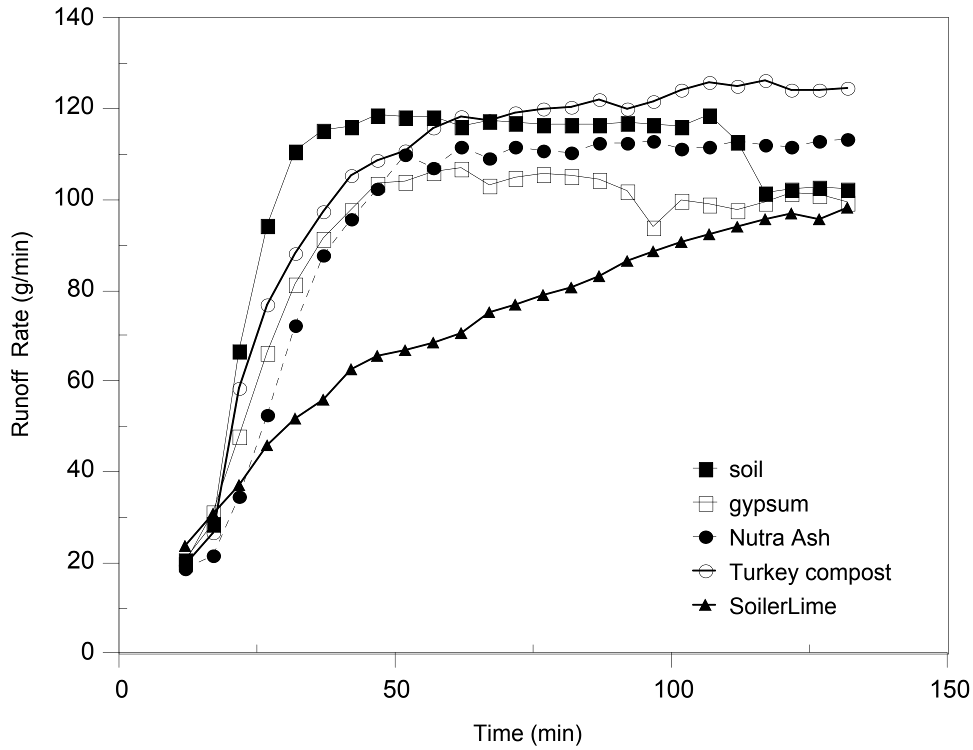

Figure 2. Runoff rate versus time for each treatment.

Sediment rate

Sediment yield rates for all the treatments are shown in Figure 3. The maximum rate of sediment loss occurred within approximately 45 minutes, approximately the time when the runoff reached steady state. Interestingly, both gypsum and control treatments reached a maximum and then decreased with time, while the other treatments reached a steady state (*i.e.* their sediment loss rate did not decrease with time). This resulted in a higher final sediment yield rate for both the turkey compost and Nutra-Ash treatments although they lost less total sediment (Figure 1). Only SoilerLime and gypsum had lower final sediment yield rates.

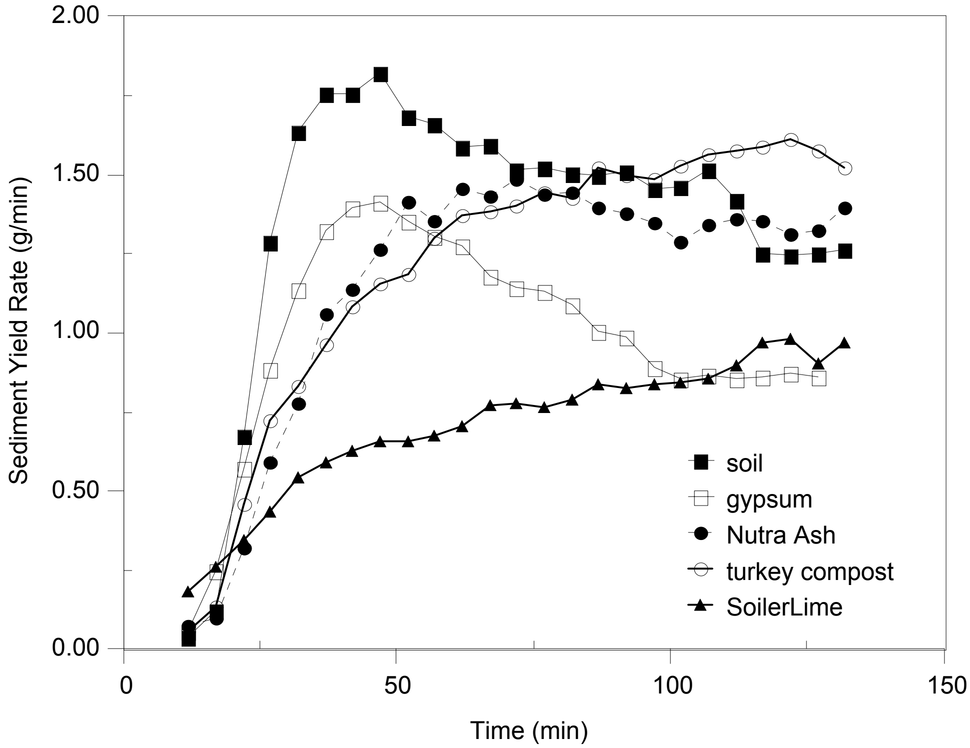

Figure 3. Sediment yield rate versus time.

The sediment yield rate from SoilerLime continued to increase slowly throughout the experiment and reached a final rate comparable to the gypsum treatment. This indicated that the relative effectiveness of SoilerLime was greater than gypsum at the beginning of a run, but gypsum was more effective at the end. This may be due to several factors. The SoilerLime released a slightly higher initial concentration of calcium (Table 2), but it decreased rapidly, whereas gypsum continued to release the same amount of calcium. Also, SoilerLime contained organic matter but gypsum did not. As with the turkey compost, this may have initially helped to protect the soil from raindrop impact by reducing soil breakdown and decreasing surface sealing. But the benefits of organic matter appear to be more effective in the early stages of a rainstorm rather than later.

Conclusions

Soil erosion is a leading source of water pollution in the U.S. High-calcium coal combustion by-products such as flue gas desulfurization (FGD) sludge and fluidized bed combustion (FBC) ash are suitable soil amendments for reducing soil erosion. Although SoilerLime treatment had the lowest runoff and sediment loss of all treatments, its effectiveness decreased with time. Nutra-Ash, having been exposed to water for several years, had fewer soluble calcium-containing minerals and released less calcium than gypsum or SoilerLime, making it was less effective. It is possible that fresh, unhydrated Class C fly ash would have been more effective, particularly fly ash with greater than 25% CaO. Gypsum was a better source of electrolyte than Nutra-Ash, and it was more effective at later times than the SoilerLime. FGD by-products may be nearly as effective as natural gypsum.

The addition of the turkey compost to bare soil reduced total sediment yield but not final sediment yield rate, and it increased total and final runoff rate. It was likely that the application rate was insufficient to provide adequate surface cover for the duration of the experiment. Organic matter broadcast as a surface mulch protects the soil particles from dispersion due to raindrop impact and thus reduces soil erosion. Compost with lower nutrient concentrations would not be limited by land application regulations, and could be applied at heavier rates.

The greater effectiveness of the SoilerLime at reducing both runoff and sediment loss may be due to a combination of both soluble calcium and organic matter. Mixing dry CCBP (having high surface area) with wet organic by-products such as biosolids or animal manures improves the stability and handling properties of both materials. Dry CCBP and organic by-products could result in an excellent amendment for reducing soil erosion (in addition to their fertilizer value), and create a significant new market for these materials.

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