Erodibility of a Sodic Soil Amended With FGD Gypsum

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ABSTRACT

High sodium concentrations in coastal plain soils of the lower Mississippi River valley are a serious management problem due to salt toxicity and their dispersive nature. Remediation of sodic soils with mined gypsum in the southeastern region is not often considered due to its relatively high cost. The FGD gypsum product of coal-fired power plants, may be a cost effective alternative for managing these soils. We determined the effectiveness of FGD gypsum at reducing the erodibility and dispersive nature of sodic soils in the region. Fine earth soil samples (< 2mm) collected from the A-horizon of a sodic soil were characterized for a range of basic physical and chemical properties. Additional sub-samples (< 8 mm) were amended with FGD gypsum at rates equivalent to 0, 3.36, 6.72, and 13.44 Mg ha^{-1}, packed to a depth of 7.6 cm in plexiglass cylinders, and subjected to simulated rainfall (64 mm h^{-1}) for 1 h. As the FGD gypsum rates increased, we detected increases ($P < 0.05$) for all aggregation/dispersion parameters (% aggregation, aggregation index, % transmission). Improvements in soil structural stability was attributed to Ca displacement of Na and produced a 71 % increase in total infiltration, a 36 % decrease in total runoff, and a 77 % decrease in soil loss at the 13.44 Mg ha^{-1} rate relative to the 0 treatment. Sediment size distributions between 53 and 500 µm increased an average of 38 %, and the fractions < 5 µm decreased by 21 %. The results indicate that FGD gypsum can be used effectively to remediate sodic soils, and that improvements can be expected in the form of increased infiltration, and lower runoff and soil loss rates. The gypsum-induced increases in the larger sediment size distributions indicate that the quality of surface waters increase as the proportion of finer sediment in the runoff is diminished.

INTRODUCTION

Soil erodibility is essentially a measure of soil aggregate tendencies to disperse when exposed to erosive forces such as raindrop impact or flowing water. Numerous soil chemical and physical properties influence the extent to which aggregates disperse. These include the amount and type of clay, organic matter and sesquioxide contents, and the content of dispersive cations such as sodium. The former properties generally contribute to aggregate stabilization; however, when Na concentrations are great enough to produce sodic soils, erodibility may be maximized. Although an exact definition of sodic soils is problematic[1], the criteria used by the USDA-NRCS includes a sodium adsorption ratio (SAR) of >13, and an electrical conductivity (EC) of <4 mmhos/cm.


Figure 1 Sodium affected stream bank eroding into an adjacent cotton field.

Sodic soils occupy an estimated 210 million ha worldwide[2], and are most concentrated in Australia and the former USSR[3]. The United States has an estimated 2.6 million ha principally in the northern Great Plains with smaller acreages in the midwest and the southeast[4]. In the southeast, soils with high sodium concentrations are a serious management problem primarily in portions of Arkansas, Louisiana, Mississippi, and Tennessee. The acreage of these soils is uncertain since many soil surveys were completed prior to 1965 when Soil Taxonomy first recognized natric horizons in these states. Currently, natric soils are mapped as separate series, but natric soils also occur as inclusions in soils mapped previous to 1965.

Specific problems associated with these soils include Na concentrations so high that areas ranging from less than an acre to entire fields are un-vegetated or contain only stunted plants. In terms of erodibility, these soils have the highest k factors (0.80) in the region, which results in poor soil physical properties such as decreased structural stability and infiltration along with increased runoff, and erosion[5]. Their dispersive characteristics also contribute to streambank instability problems (Fig. 2) that are responsible for Na concentrations that exceed 7,000 mg kg^{-1} (unpublished data) in some reservoirs, and also for excessively high failure rates of drop-pipe structures installed to stabilize streambanks to reduce loss of adjacent farmland.

Relative to remediation of the dispersive characteristics of sodic soils, gypsum from both natural and byproduct sources is the most commonly used amendment[3]. Gypsum produces electrolytes and Ca ions upon dissolution which displace Na ions on the exchange complex[6]. Although considerable research has also been conducted on the use of mined (natural) gypsum to remediate sodic soils, relatively little information exists on the use of FGD gypsum for that purpose.

The objective of this research was to determine the efficacy of FGD gypsum for improving the stability of highly dispersive sodic soils of the lower Mississippi River Valley by increasing infiltration rates and decreasing runoff and erosion.

MATERIALS AND METHODS

This research was conducted on A-horizon samples of a Bonn silt loam (fine silty, mixed, superactive, thermic Glossic Natraqualfs) collected from the Southern Mississippi Valley Alluvium, Major Land Resource Area 131[7] near Teoc, MS (Fig. 3) at Lat. 33 deg., 34 min., 05.56 sec., N; 90 deg., 05 min., 09.42 sec., W. Land-use was conventionally tilled soybean [Glycine *max* (L.) Merr.].

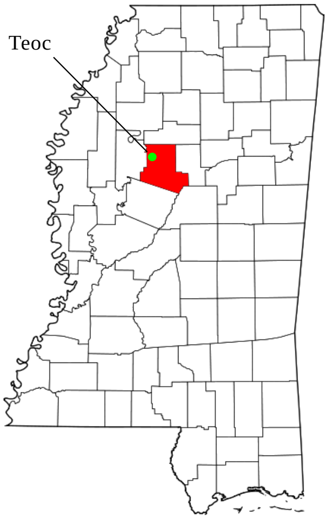

Figure 2 Location of the field sampling site near Teoc, Carroll County, MS.

Soil samples collected from three separate locations in the same field were air-dried, sieved to < 2 mm, and characterized for their basic soil physical and chemical properties. Particle size distribution and water dispersible clay (WDC) were determined by the pipette method of Day[8]. An aggregation index (AI) was calculated from the total clay and WDC data using the method of Harris[9] as follows: AI = 100 (1-WDC/total clay). Percent transmittance (% T) was measured on the same suspension used for WDC contents. After a settling time of 24 h, sub-samples from the top 3 cm were siphoned off with a pipette, transferred to test tubes that had a 16-mm path length, and read at a wavelength of 860 nm with a Spectronic 1001 Spectrophotometer. Aggregate stability measurements utilized the procedure of Kemper and Chepil[10]. Soil pH was determined using a 1:1 soil/distilled water suspension[11]. Soil organic C (OC) contents were determined with an Elementar Vario Max CNS analyzer. The exchangeable cation concentrations were determined by the NH4OAc procedure of the NRCS[12]. Cation exchange capacity (CEC) was estimated from the summation of these cations. The sodium adsorption ratio (SAR) was calculated following analysis of the extracts from a soil:water saturated paste that had been equilibrated overnight. The exchangeable sodium percentage (ESP) was determined as follows: ESP = exchangeable Na/CEC[12]. Gypsum amendment rates needed to remediate sodic soils were determined by exchangeable Na concentrations using the U. S. Salinity Lab[13] procedure.

Soil samples used to measure erodibility were air-dried, sieved to < 8 mm, and split into twelve 6.5 kg subsamples. Each subsample was then amended with FGD gypsum at rates equivalent to 0, 3.36, 6.72, and 13.44 Mg ha^{-1} (0, 1.5, 3.0 and 6.0 tons acre^{-1}), based on an acre furrow slice depth of 15.2 cm, and a weight of 2240 Mg ha^{-1} (2,000,000 lbs acre^{-1}). The air-dried FGD gypsum was thoroughly mixed with the soil samples, and wetted to saturation with distilled water. The gypsum amended soils were then dried in a forced air oven at 60° C to water contents <10 % by weight. This wetting-drying cycle was repeated twice over a two week period.

At the end of the wetting-drying cycles, individual 6.5-kg samples of the amended soil were packed to a depth of 7.6 cm in plexiglass cylinders (30.5-cm high by 26.7-cm i.d.) that were sealed at one end[14]. Simulated rainfall was applied to three replications of each FGD gypsum amendment per soil, at an intensity of 64 mm h^{-1} for 1.0 h with the multiple intensity rainfall simulator described by Meyer and Harmon[15]. All runoff (RO) and sediment generated during the simulated rainstorm were collected (Fig. 3) and weighed. Sediment samples were separated into > 2000, 2000 - 1000, 1000 - 500, 500 - 250, 250 - 125, 125 - 53, and < 53 µm fractions, oven-dried at 105°C, and weighed. Estimates of infiltration were made by weighing the fully loaded cylinders in a dry condition, and again at the end of the rainfall simulator run.

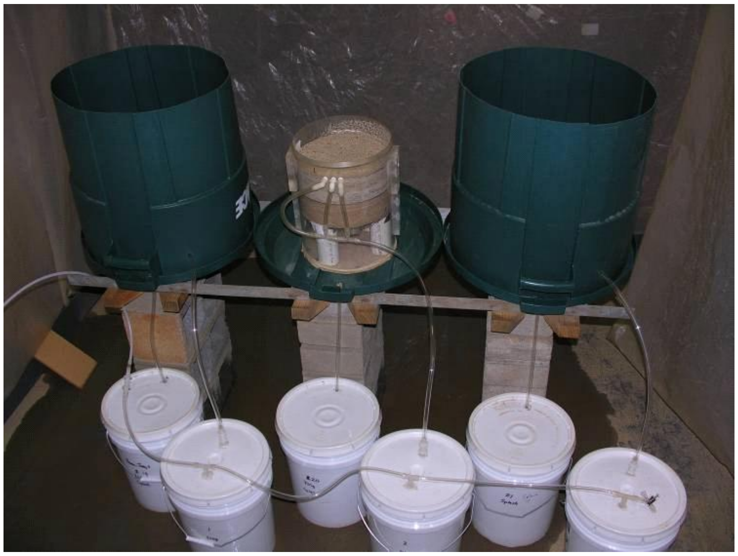

Figure 3 Cylinder and soil sample arrangement showing runoff and sediment collection systems used to evaluate FGD gypsum effects on erodibility using a rainfall simulator under laboratory conditions.

RESULTS AND DISCUSSION

The particle size data for the Bonn soil (Table 1) averaged 56, 833, and 111 g kg^{-1} for the sand, silt, and clay separates which places this soil in the silt particle size class. Water dispersible clay contents and AI averaged 85 g kg^{-1} and 23.2, respectively. An AI of this value is indicative of an unstable surface soil. The mean SAR of 48 and the ESP value of 40 % far surpass the requirements for characterization as a sodic soil, and explain the poor agronomic production of these soils.

The physical and chemical data for the FGD gypsum (Table 2) indicate that the material is relatively pure $CaSO_4$ with Ca and S contents of 23.1 % and 17.6 %, respectively, at a water content of 8.4 %. Ideally, gypsum ($CaSO_4 \cdot 2H_2O$) has Ca and S contents of 23.26 and 18.60 %, respectively. he data for aggregate stability, WDC, AI, and % transmittance versus gypsum amendment rate for the Bonn soil (Table 3) indicate an increase from 28.5 % for the untreated sample to 45.5 % at the 13.44 Mg ha^{-1} rate. Apparently, 6.72 Mg ha^{-1} (3 tons $acre^{-1}$) is the maximum rate at which this soil responds to gypsum in terms of increased aggregation.

The % transmittance data show a similar relationship for the soil-water suspensions as a function of gypsum rate (Table 3, Fig. 4). These results show that the addition of 3.36 Mg ha^{-1} (1.5 tons $acre^{-1}$) gypsum reduced the dispersibility by 44 % as indicated by a significant increase in % transmittance from 18.8 to 33.7 %. The 6.72 Mg ha^{-1} rate significantly increased % transmittance to 42.7 %, a change of 26 %. No further significant changes occurred at 13.44 Mg ha^{-1}. Apparently, the intermediate rate (6.72 Mg ha^{-1}, 3 tons $acre^{-1}$) is adequate to affect maximum flocculation/aggregation of this sodic soil.

The effects of gypsum on erodibility are clearly evident in the infiltration, runoff, and soil loss data (Table 4). These parameters were significantly ($P < 0.05$) improved over the untreated soil with each additional increase in amendment rate. Total infiltration increased 71 % from 7 to 24 mm between the 0 and 13.44 Mg ha^{-1} rates. Total runoff decreased 36 % from 50 to 32 % for the same treatments. Soil loss decreased from 23 Mg ha^{-1} in the untreated soil to 5.4 Mg ha^{-1} for the 13.44 Mg ha^{-1} amendment rate, a change of 77 %. These significant improvements in erodibility parameters are explained by the increases in Ca concentrations which progressively displace Na on the exchange complex to form a greater percentage of water stable aggregates.

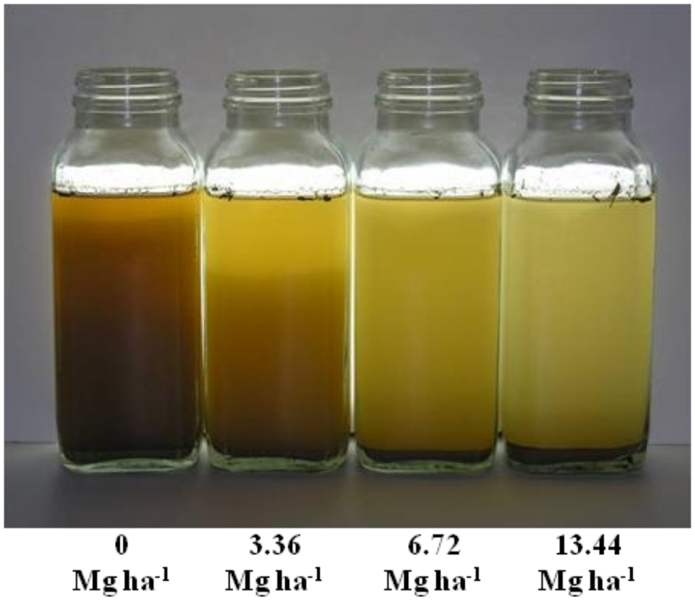

Figure 4 Suspended sediment concentrations at four FGD gypsum rates following dispersion in distilled water, and a 24 hour settling time.

These changes are evident in the sediment size distributions (Table 4, Figures 5 and 6). For ease of comparison, data from the ten sub-fractions are commonly composited to form > 250, 250-53, and < 53 µm components. In the untreated samples, the distribution of sediment between these size fractions was 15, 51, and 934 g kg^{-1}, respectively, with 798 g kg^{-1} occurring between 53 and 5 µm. With the addition of 3.36 Mg ha^{-1} gypsum to the soil, the > 250 and 250-53 µm fractions increased slightly, and the < 53 µm component decreased ($P < 0.05$). The greatest change in sediment size was the 22 % increase in the 125-53 µm fraction. This indicates that, even at the relatively low amendment rate, gypsum increased the amount of water stable aggregates in this soil.

At the 6.72 Mg ha^{-1} amendment rate, both the > 250 and the 250-53 µm fractions increased by an average of 40 %, and the < 53 µm fraction decreased by approximately 3 %. These increases in larger sediment sizes were at the expense of the 5-2 and < 2 µm fractions, both of which decreased 21 %. Again, this is an indication that the greater Ca concentrations are displacing Na on the exchange complex of the smaller size fractions to form water stable aggregates. The 13.44 Mg ha^{-1} affected an even greater change in sediment size distributions due to the increase in Ca concentrations. The > 250 µm fraction increased 64 %, the 250-53 µm increased 17 %, and the < 53 µm decreased 3.4 %.

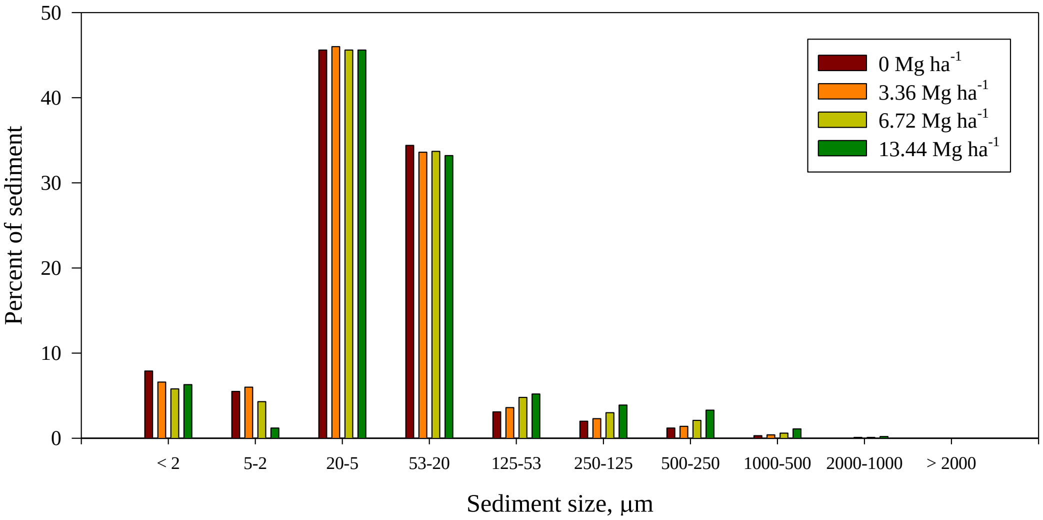

Figure 5 FGD gypsum amendment rate effects on sediment size distributions

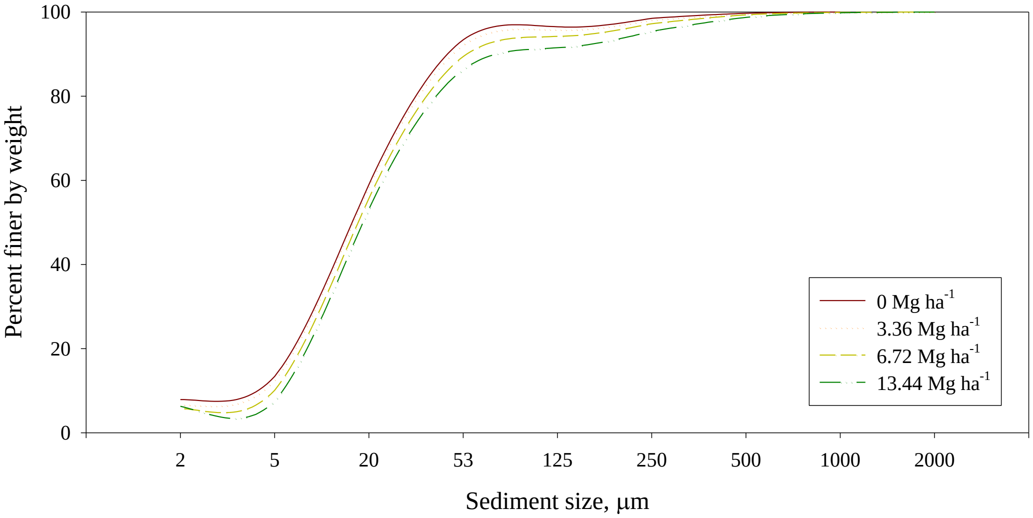

Figure 6 Cumulative sediment size distribution curves for the four FGD gyspum amendment rates.

CONCLUSIONS

The sodium-affected soils in the lower Mississippi River Valley represent a substantial problem in the region due to their dispersive properties which adversely impact the success of erosion control structures, streambank stability, and agricultural production.

Such soils are most common in arid regions where there is also an ample supply of naturally occurring gypsum which is the material most commonly used to remediate sodic soils. The use of natural gypsum to amend large areas in the eastern United States is not an economical option due to excessive costs associated with its transport. Instead, FGD gypsum, a byproduct of the coal-fired power industry is considered a viable alternative.

The data from this study indicate that the highly erodible, Na affected Bonn soil can be remediated with the addition of FGD gypsum. An amendment rate as low as 3.36 Mg ha^{-1} (1.5 tons/acre) was shown to significantly increase aggregate stability in this soil which had a SAR of 48, and an ESP of 40. The effect of these improvements in soil aggregation is demonstrated by significant increases in total infiltration, and reductions in runoff and soil loss. In addition to the decreases in soil loss, the reduction in erodibility is best evidenced by the increase in sediment sizes greater than 125-53 µm range and the accompanying decrease in the percentage of sediment in the 5-2, and the < 2 µm sizes. Further, the use of FGD gypsum as the primary component of a best management practice will improve the success rate of erosion control structures installed in dispersive soils, and aid in the development of approaches to remediate streambank erosion problems.

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Table 1. Selected physical and checmical properties of the untreated Ap horizon of Bonn silt loam.

Sample						Aggreg	Munsell Color				Exchangeable cations					
Site	OC	Sand	Silt	Clay	WDC	Index	Hue	Value	Chroma	pH	Ca	Mg	K	Na	CEC	SAR	ESP
	g kg^{-1}										cmol kg^{-1}						%
1	7.5	45	856	99	72	26.4	0.1Y	3.8	2.3	6.9	3.5	1.6	0.2	3.6	8.9	47	41
2	8	80	802	119	91	23.3	0.1Y	3.7	2.3	7.6	3.4	1.6	0.2	3.2	8.4	48	39
3	9.9	44	842	115	92	19.7	0.1Y	3.7	2.0	8.8	3.4	1.6	0.2	3.6	8.8	49	41
Average	8.5	56	833	111	85	23.2	0.1Y	3.7	2.3	7.7	3.4	1.6	0.2	3.4	8.7	48	40

WDC = water dispersible clay, OC = organic carbon, CEC = cation exchange capacity, SAR = Sodium adsorption ratio,
ESP = exchangeable NA / CEC

Table 2. Selected physisical and chemical properties of the FGD gypsum.

Water Content[1]	Insoluble Residue[2]	Ca	S	Mg	B	Fe	Mn	P	Al	As	Cr	Cu	Pb	Hg	Zn
		Water Extractable nutrients/metals[3]													
%				mg kg^{-1}											
8.4	1.4	23.1	17.6	370	50.5	212.1	7.5	78	299	<0.52	<37	<42	<26	<0.26	<21

1. After drying overnight at 60 C
2. Material remaining following extraction for 3 days in pH 3 water
3. Gypsum specimens were stirred for 3 days in pH 3 water.

Table 3. Soil aggregate stability/dispersibility as a function of gypsum amendment rate.

Gypsum amendment rate	Aggregate stability	WDC	AI	Transmittance
Mg ha^{-1}	%	g kg^{-1}		%
0	28.5 b[1]	7.5 a	32 c	18.8 c
3.36	31.6 b	5.9 b	47 b	33.7 b
6.72	33.7 b	5.0 c	55 a	42.7 a
13.44	45.5 a	5.0 c	55 a	45.3 a

[1]Means within a column followed by the same letter are not statistically different at P≤0.05 based on Duncan's new multiple range test.

Table 4. FGD gypsum amendment rate effects on infiltration, runoff, soil loss, and sediment size distributions.

Gypsum rate	Infiltration	Runoff	Soil loss	Sediment size distribution (μm)											
				2000-1000	1000-500	500-250	250-125	125-53	53-20	20-5	5-2	<2	>250	250-53	<53
Mg ha^{-1}	—— mm ——		Mg ha^{-1}	---------- g kg^{-1} ----------											
0	7 d[1]	50 a	23.0 a	0 c	3 c	12 c	20 c	31 c	340	458	59 b	77 a	15 c	51 d	934 a
3.36	13 c	44 b	12.1 b	1 c	4 c	14 c	23 c	36 b	334	459	62 a	67 b	19 c	59 c	922 b
6.72	21 b	36 c	8.2 c	1 b	6 b	21 b	30 b	48 a	332	460	49 c	53 c	28 b	78 b	894 c
13.44	24 a	32 d	5.4 d	2 a	11 a	33 a	39 a	52 a	327	459	12 d	63 b	46 a	91 a	861 d

[1]Means within a column followed by the same letter are not statistically different at P ≤ 0.05 based on Duncan's newmultiple range test.