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Organic matter and polyacrylamide amendment of Norfolk loamy sand

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Abstract

Loamy sand soils of the southeastern USA Coastal Plains often have poor physical properties because they contain cemented subsurface hard layers that restrict root development and yield. Their physical properties can be improved by adding amendments. Polyacrylamide (PAM) amendments and/or organic matter (OM) in the form of ground wheat (*Triticum aestivum* L.) stubble or pecan (*Carya illinoensis*) branches were mixed into a blend of 90% E horizon and 10% Ap horizon (to assure microbial presence) obtained from a Norfolk soil (Acrisol or fine-loamy, siliceous, thermic *Typic Kandiudult*). We hypothesized that incorporation of these amendments would improve soil physical properties by reducing strength and improving aggregation. Amended treatments contained 450 g of soil, OM, and 30 or 120 mg kg^{-1} of PAM (12 mg mol^{-1}, anionic, and 35% charge density); treatments were incubated for 96 days at 10% (w/w) water content. Twice during the incubation period, treatments were leached with 1.3 pore volumes of deionized water. After leaching and equilibrating to stable water contents, treatments were analyzed for bulk densities and probed with a 5-mm diameter flat-tipped bench-top penetrometer to measure penetration resistances. Though penetration resistances increased for the highest level of PAM amendment, they showed no significance when both PAM and OM were added to the soil. When compared to controls, treatments with PAM at 120 mg kg^{-1} had decreased bulk densities. Treatments with both rates of PAM had decreased requirements for water needed to maintain treatments at 10% water contents. Aggregation increased with increasing amounts of PAM but showed no consistent trend when both PAM and OM were added to the soil. Because PAM increased aggregation and water holding capacities in these coastal soils, it could reduce the need for deep tillage. However, more work needs to be done to determine an effective mix of PAM and OM.

Keywords: Soil amendment; Polyacrylamide; Soil strength; Aggregate

1. Introduction

In many agriculturally productive southeastern Coastal Plain soils, the top two horizons (the Ap and E) have massive structure, sandy texture, and low OM contents. These horizons, especially the E, can have soil strengths high enough to reduce or prevent root growth (Busscher et al., 2002), even when soil water contents are at field capacity (Campbell et al., 1978). Though these horizons soften when they rewet, the amount of water needed to soften the soils results in conditions so near water saturation that oxygen depravation either exists or is imminent. As a result, water cannot normally be used to manage the hardness of the subsurface horizon (Camp et al., 2000).

The usual management practice for these soils is to physically disrupt the E horizon with non-inversion deep tillage. Disruption shatters the E horizon allowing for increased root growth and yield

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(Busscher et al., 2002; Raper et al., 2000). Once the roots penetrate the E horizon, they can grow into the B horizon that has weak blocky structure. Even when the B horizon hardens as it dries, roots can grow along the weaker fracture planes such as the faces of the aggregated structural units.

Over time the loosening effects of tillage diminish as the E horizon reconsolidates (Raper et al., 2000; Shukla et al., 2003) reducing yields (Arvidsson et al., 2001; Lapen et al., 2001; Radford et al., 2000). Although the effects of deep tillage can be seen for years afterward (Busscher et al., 2002; Munkholm et al., 2001), yields are reduced as incomplete reconsolidation from one growing season to the next increases soil strength enough to restrict root growth. For example, in these soils, each MPa increase in soil strength reduces the yield of wheat (*Triticum aestivum* L.) by 1.5–1.7 mg ha^{-1}; soybean (*Glycine max* L. Merr.) by 1.1–1.8 mg ha^{-1} and maize (*Zea mays* L.) by 1.1–2.4 mg ha^{-1} (Busscher et al., 2000a). As a result, deep tillage for these soils is recommended annually, either in spring (Busscher et al., 2000a; Threadgill, 1982) or fall (Porter and Khalilian, 1995) or possibly both with double cropping (Frederick et al., 1998).

Reducing soil strength with deep tillage is expensive; it requires large tractors (14–20 kW per deep tillage shank), 20–40 min ha^{-1} of labor, and 20–25 L ha^{-1} of fuel (Karlen et al., 1991). With the cost of fuel escalating, it would be advantageous to have an alternative to deep tillage that would amend the soil and provide a longer-lasting solution to loosening the soil. Researchers have long known that OM additions improve soil tilth (Waksman, 1937) and reduce strength (Free et al., 1947), even for sandy loam soils such as those found in Coastal Plains (Ekwue and Stone, 1995). Unfortunately, added OM oxidizes rapidly in soils with high summer temperatures (Parton et al., 1987; Wang et al., 2000). As a result, in SE US Coastal Plain soils, residues from row crops either do not increase OM from year to year or increase it only in the top few centimeters (Hunt et al., 1996; Novak et al., 1996).

Polyacrylamide (PAM) and other soil conditioners were found to improve plant growth by improving soil physical properties; older PAM formulations were used in the early 1950s to stabilize aggregates in the surface 30- to 40-cm depths (Weeks and Colter, 1952). Unfortunately, these early formulations required hundreds of kilograms of PAM per hectare with multiple spraying and tillage operations. Newer longer-chain polymers with higher purities have improved PAMs, making them more effective at lower concentrations (Wallace and Wallace, 1986). Water soluble PAM was identified as a highly effective erosion-preventing and infiltration-enhancing polymer when applied at rates of 1–10 mg L^{-1} in furrow irrigation water (Sojka and Lentz, 1997; Sojka et al., 1998). PAM stabilized aggregation in the surface few millimeters when applied at application rates of 1–2 kg ha^{-1} per irrigation.

If mixing PAM into this coastal soil can develop aggregates, it would disrupt the massive structure, reducing the need for deep tillage. Aggregates would also have the potential to increase OM more permanently because they can protect it from decomposition (Goebel et al., 2005; John et al., 2005). Our objectives were (a) to improve the physical properties of sandy coastal soils by adding PAM with OM (where the PAM could enhance the ability of the OM to produce aggregates because of PAM's capability to flocculate soil) and (b) to improve aggregation thereby decreasing soil strength. We hypothesized that (a) adding PAM with OM would develop more aggregates than either one alone and (b) adding low concentrations of PAM could increase aggregation thereby decreasing soil strength and bulk density.

2. Materials and methods

2.1. Soil

The soil used in this experiment was Norfolk loamy sand (fine-loamy, siliceous, thermic *Typic Kandiudult* in the USDA classification or an Acrisol in the FAO classification); it was collected from a field 2 km northwest of Florence, SC, USA, sieved while still at field moisture through a 10-mm sieve to remove debris, and air dried. Norfolk soil series formed with Coastal Plain marine sediments as parent materials. It was well drained with seasonally high water tables at 1.2–1.8 m depth. Over the years, the Ap horizon had been tilled to a depth of about 0.20 m. Below the plow layer, the soil had an eluviated E horizon that can restrict root growth. The E horizon typically extended to a depth of 0.30–0.45 m overlaying a sandy clay loam Bt horizon that extended beyond 0.6-m depth. General characteristics for Ap and E horizons were similar with differences based mainly on previous tillage that mixed surface organic matter into the Ap. The Ap and E horizons had 1–3 cmol kg^{-1} cation exchange capacity, 20–80 g kg^{-1} clay, and 2–20 g kg^{-1} of organic matter (Soil Survey Staff, 2005). For this experiment, 90% E and 10% Ap horizon on a dry weight basis were mixed together in a twin shell dry blender[1] (Patterson-Kelley Co. Inc., East Stroudsburg, PA, USA) for 15 min and used as the soil medium. The E horizon was the intended medium of study; a small amount of the Ap horizon was added to assure that the soil would have microbial presence whose activity could decompose OM. When analyzed for particle size (Miller and Miller, 1987), the final soil mix had 665 g kg^{-1} sand, 297 g kg^{-1} silt, and 38 g kg^{-1} clay; it had an organic matter content of 3.2 g kg^{-1}.

2.2. Treatments

From our experience, the bulk density of this soil can vary from 1.0 to 1.6 g cm^{-3}, depending on timing of tillage, surface traffic, and rainfall. To avoid excessive compaction forces and yet be realistic, soil was packed to a bulk density of 1.2 g cm^{-3}. Four hundred and fifty grams of soil were packed into 10 cm diameter pots by pouring it loosely into the pot and tapping the pot on a laboratory table until soil settled to a preset line drawn on the inside of the pot. Soils were packed with a 20 mesh nylon screen on the bottom to prevent loss from drain holes in the bottom of the pot. Fifteen treatments included all combinations of soil mixed with five treatments of organic matter that had been ground to a fine powder in a Wiley Mill (6 mm mesh opening, Arthur Thomas Co., Philadelphia, PA, USA) and three polyacrylamide levels. Organic matter treatment levels were 0 g kg^{-1} (n), 3.22 g kg^{-1} (w1) and 6.44 g kg^{-1} (w2) ground wheat stubble, and 3.52 g kg^{-1} (p1) and 7.04 g kg^{-1} (p2) ground pecan (*Carya illinoensis*) branches. Soil C:N ratios were brought to 20:1 by adding NH_4NO_3 in amounts of 0.157, 0.307, 0.456, 0.318, and 0.476 g kg^{-1} to treatments, respectively. Wheat and pecan were chosen as OM treatments because both are plentiful and while wheat straw will deteriorate relatively quickly pecan wood will deteriorate slowly.

PAM treatment levels were 0, 30, and 120 mg kg^{-1}. The PAM used was a currently commercially available formulation of 1–2 mm dry granules of 12 mg mol^{-1}, anionic, and 35% charge density (SNF Inc., Riceboro, GA, USA). Because so little PAM was added to the soil, it would not mix uniformly in a dry state. For each treatment, an appropriately diluted solution was sprayed onto soil that had been spread out on a table; soil with or without OM and solution were gently mixed on waxed paper. Treatments without PAM addition were sprayed with water only. Each treatment had three replicates.

Treatments were incubated for a period of 96 days in a lab that was maintained at 20–22 °C and ambient humidity with a mean of 47% ranging from 33 to 75%. Treatments were maintained at 10% (±0.6%) soil water content on a dry weight basis by weighing and adding deionized water two to three times a week. Water was added by placing a screen on the surface to prevent erosion and to disperse water that was poured onto it. Deionized water was used to prevent additions of unwanted or unknown chemicals from commercial water sources. Ten percent water content was chosen as an approximate value of field capacity for this soil (Peele et al., 1970).

2.3. Measurements

Treatments were leached with 1.3 pore volumes (147 g) of water at 47 and 82 days after the beginning of the experiment. After leaching, penetration resistances and bulk densities were measured to determine soil strength and settling. At 69 and 90 days, soil bulk densities were calculated by first measuring distances from the top of the pot to the soil surface at three points along the side of the pot and one point in the center and taking an average. These measurements were used to calculate volume of soil. Distances along the side of the pot were calibrated against volume by sealing the drain holes at the bottom and filling the pot with water to several depths, giving a relationship $V = 28.0\,d^{1.3322}$ ($r^2 = 0.99$) where V is volume of the pot filled with water and d is depth of water in the pot. To calculate bulk densities, volumes were combined with known dry weights of soils or soils and amendments.

After treatments were leached, they were covered with plastic wrap to allow soil to come to equilibrium without evaporation from the surface. At 64 and 96 days, the plastic wrap was removed and penetration resistance (PR) was measured on the soil surface with a 5-mm-diameter, stainless-steel flat-tipped probe. The probe was attached to a strain gauge and a motor geared to penetrate the soil at a constant rate of 0.28 mm s^{-1}. Strain gauge output was expressed in millivolts recorded at a rate of 100 Hz on a CT-23X Micrologger (Campbell Scientific Inc., Logan, UT, USA) while the probe penetrated the top 5 mm of the core. Output was uploaded to a desktop computer. After probing to 3–4 mm depth, output generally reached a plateau or

[1] Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

peaked and receded. In either case, the mean of the 10 highest values was used as the measurement for each probing. Three probings were taken on the soil surface approximately half way from the center to the edge of the pot at equally spaced positions around the circumference; data for the three probings were averaged and treated as a single data point. Data were converted from millivoltage to penetration resistance using a calibration $PR = 0.512\ V - 0.021$ ($r^2 = 0.99$) previously developed (Busscher et al., 2000b) where PR is probe resistance and V is voltage. The equation takes into account both the probe size and strain gauge calibration.

At the end of the experiment, aggregate sizes were measured using the procedure of Sainju et al. (2003). To break up large clumps, 100 g of air-dry soil were passed through a 4-mm sieve and placed into a nest of 20-mm diameter sieves with openings 2, 1, 0.5 and 0.25 mm that was shaken at a rate of 60 Hz with amplitude of approximately 3 mm for 1 min using an Octagon Digital Sieve Shaker (Endecotts Inc., London). Aggregate data were corrected by rerunning samples of the original soil dispersed with sodium hexametaphosphate ($Na_6P_6O_{18}$) and subtracting non-aggregated particles that were retained on the sieves.

2.4. Data analysis

Data were analyzed using analysis of variance and least significant difference mean separation procedure (SAS Institute Inc, 2000). Data were analyzed as a randomized complete block design with OM and PAM treatments as cofactors. When data were taken over several dates, a split plot design was used with measurements as splits. When data were taken in the nest of sieves, a split plot design was used with measurements in the sieves as splits. Data were tested for significant differences at the 0.05 level.

3. Results

3.1. Bulk density

Since there were no interactions of treatments with date, bulk densities were analyzed with both dates together. Treatments were formed at a bulk density of 1.2 g cm^{-3}; differences between measured bulk densities and initial values indicated settling. Bulk densities varied by date of measurement and treatment. They increased to 1.28 g cm^{-3} at 69 days. After that, they did not differ significantly; at 90 days they averaged 1.29 g cm^{-3} indicating that settling continued until the first leaching and remained relatively constant after that. Except for treatment p1 which showed no effect, bulk densities decreased with an increase of organic matter (Table 1), as would be expected. Bulk densities also decreased with increasing amounts of PAM; but the difference was only significant for the treatment with 120 mg kg^{-1} added. In a study by West et al. (2004), bulk densities increased with addition of anionic PAM because it flocculated the dispersed clay in fabricated soils. In our sandy soils with only 38 g kg^{-1} clay content, bulk densities decreased with PAM probably because the massive structure was disrupted by increased aggregation which could increase soil volume.

3.2. Penetration resistance

Penetration resistances were taken about 2 weeks after leaching because soils were too wet to give significant measurements before those dates. Also, penetration resistances could be affected by water contents if they differed among treatments with wetter soils having naturally lower readings. However, after 2 weeks of drainage during which time pots were covered with plastic wrap, water contents were not significantly different among treatments with values ranging from

Table 1
Bulk densities (g cm^{-3}) for treatments with organic matter or PAM added to the soil at 69 and 90 days

	Organic matter*					PAM* (mg kg^{-1})		
	None	w1	w2	p1	p2	0	30	120
Day 69	1.32	1.28	1.26	1.33	1.25	1.30	1.29	1.28
Day 90	1.31	1.28	1.24	1.32	1.26	1.30	1.28	1.27
Mean	1.32a**	1.28b	1.25c	1.33a	1.26c	1.29a	1.28ab	1.27b

Initial bulk densities were 1.2 g cm^{-3}.

* Organic matter added was of 0 g kg^{-1} (none), 3.22 g kg^{-1} (w1) and 6.44 g kg^{-1} (w2) ground wheat stubble, and 3.52 g kg^{-1} (p1) and 7.04 g kg^{-1} (p2) ground pecan. PAM added was 0 mg kg^{-1}, 30 mg kg^{-1}, and 120 mg kg^{-1}.

** Means with the same letter are not significantly different using the LSD test at 5%. The LSD for the interaction of day and treatment is 0.04 g cm^{-3} for organic matter and 0.03 g cm^{-3} for PAM.

Table 2
Penetration resistances (MPa) averaged over readings taken after 64 and 96 days

Treatment*	Organic matter					Mean
PAM ($mg\ kg^{-1}$)	None**	w1	w2	p1	p2	
0	0.611	0.452	0.612	0.487	0.482	0.523c
30	0.793	0.519	0.594	0.517	0.647	0.614b
120	1.001	0.551	0.612	0.951	0.560	0.737a
Mean	0.829a	0.507d	0.606bc	0.652b	0.563cd	

* Organic matter added was 0 $g\ kg^{-1}$ (none), 3.22 $g\ kg^{-1}$ (w1) and 6.44 $g\ kg^{-1}$ (w2) ground wheat stubble, and 3.52 $g\ kg^{-1}$ (p1) and 7.04 $g\ kg^{-1}$ (p2) ground pecan. PAM added was 0, 30, and 120 $mg\ kg^{-1}$.
** Means with the same letter are not significantly different using the LSD test at 5%. LSD is 0.150 for the interaction.

0.095 to 0.100 $g\ g^{-1}$ for the measurements taken at 63 days and 0.094–0.097 $g\ g^{-1}$ at 95 days.

Penetration resistances were higher at the second reading possibly because of more settling and slightly higher bulk densities of the soil. However, penetration resistances had no interactions of treatments with date; so, they were analyzed with both dates together.

Penetration resistance measurements were significantly different for the PAM and OM treatments and their interactions. Penetration resistances were generally lower for treatments with OM added (Table 2), as seen by other researchers (Ohu et al., 1985; Sanchez et al., 2003), though here penetration resistances did not differ consistently with amounts or types of organic matter.

Penetration resistances appeared to increase with amount of PAM. However, the increase was caused by readings for the treatments without OM; this was true whether or not the non-significantly different p1 treatment was included in the analysis (Table 2). Penetration resistances for treatments with OM only (without the 0-OM treatment) showed no general trend with increasing amounts of PAM in contrast with Lu et al. (2002). In this study, organic matter generally reduced penetration resistances but not necessarily in proportion to the amount added and not necessarily more effectively with more or less PAM.

3.3. Cumulative water added

Cumulative water added was the sum of the amount added to each pot two to three times a week to maintain 10% water content. Over the course of the experiment, cumulative water was added to the treatments in the order p2 > p1 > n > w1 > w2 (Fig. 1a). After Day 34, water added to the pecan treatments was greater than that added to the other treatments. After Day 41, water added to the treatment with no amendment (n) was greater than that added to w2. Water added to treatments with wheat decreased with increasing wheat content suggesting that the wheat organic treatments were more effectively holding water against evaporation and/or drainage than the pecan. This would be consistent with the fact that wheat would rapidly degrade and the degraded wheat would hold water; but does not explain why the pecan treated soils would have required more water than the treatment with no amendment.

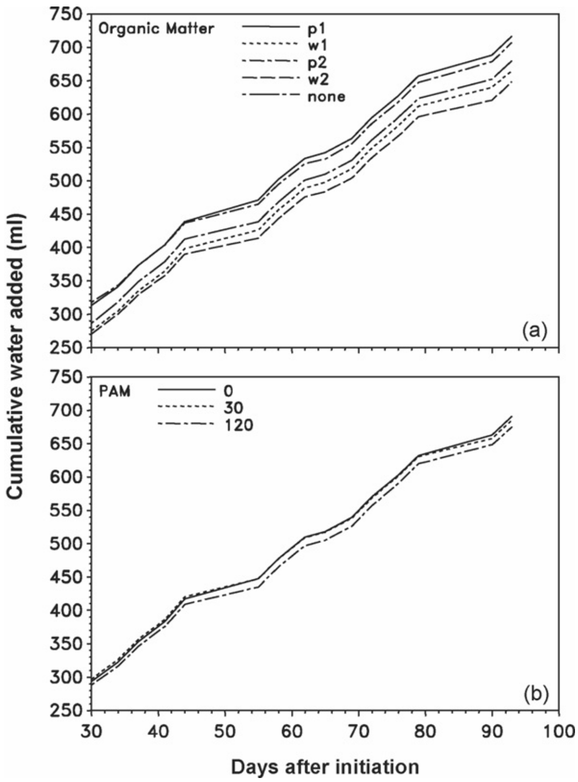

Fig. 1. Cumulative amount of water added over the study shown from Day 30 to the end of the experiment for the (a) OM treatments and (b) PAM treatments. Organic matter added was of 0 $g\ kg^{-1}$ (none), 3.22 $g\ kg^{-1}$ (w1) and 6.44 $g\ kg^{-1}$ (w2) ground wheat stubble and 3.52 $g\ kg^{-1}$ (p1) and 7.04 $g\ kg^{-1}$ (p2) ground pecan, averaged over PAM treatments. PAM added was 0, 30, and 120 $mg\ kg^{-1}$, averaged over OM treatments.

PAM treated soils decreased the amount of water added to maintain 10% water content, suggesting that PAM treated soil probably was also holding water against evaporation and/or drainage. Though the differences were small (Fig. 1b), they suggest that the PAM was altering the soil by increasing aggregation, similar to the study of Green et al. (2004) where PAM stabilized aggregation in a crusting/erosion study. Data analyzed over all dates of the studies averaged 26.9 ml water added to the treatment with no amendment, >26.4 ml added to treatments with 30 mg kg^{-1} PAM, and ~26.3 ml for 120 mg kg^{-1} PAM (LSD at 5% = 0.3). The relatively larger amount of water added to the treatment with no amendment could have also led to its greater penetration resistance as a result of more settling, as also in field studies with these soils (Busscher et al., 2002).

3.4. Aggregation

Though aggregates were measured on a nest of sieves (2 mm, 1 mm, 0.5 mm, 0.25 mm), the fractions that remained on the 2-mm sieve and the fraction that fell through the 0.25-mm sieve were not analyzed as aggregates because materials on the 2-mm sieve were a mixture of aggregates and loose OM; materials that fell through the 0.25-mm sieve were small aggregates mixed with individual particles. Aggregates that were analyzed fell in the ranges 2–1 mm, 1–0.5 mm, and 0.5–0.25 mm with the smallest size having significantly more aggregates with 17% (Table 3) of the sample than the other two sizes with about 15% each (Pr = 0.03).

Treatments analysis for aggregates showed significant differences for PAM amendment, OM amendment, and their interaction. When the interaction was analyzed, treatments with both OM and PAM amendments showed no significant or overall trend while the treatments with only PAM added showed a difference. The overall means for all OM levels and the means with no OM added (Table 3) showed an increase in aggregation with increasing amounts of PAM as others have seen in the past (Sojka et al., 1998). Within the PAM treatments, the fact that the treatments with 30 mg kg^{-1} PAM added were not different from those with 120 mg kg^{-1} added was encouraging because using the lower amount would be less expensive to treat the soil.

PAM typically costs US$3 to $4 kg^{-1} (Personal Communication, James Dillard, Chemtall, SNF). If PAM is applied at rates of 30 and 120 mg kg^{-1} (60 and 240 kg ha^{-1}), it would cost an estimated $180 to $960 per hectare.

For PAM induced aggregation to be cost effect, it would have to be permanent or semi-permanent eliminating or significantly reducing the need for deep tillage which costs an estimated $30 to $50 per ha per year plus adjustments for fuel cost increases (Khalilian et al., 2002). To be cost effective, aggregation from PAM would have to eliminate tillage for at least 6 years.

When incorporated into soil, PAM would theoretically be effective for a relatively long period of time. It degraded at rates of 10% per year as a result of physical, chemical, biological and photochemical processes and reactions (Azzam et al., 1983; Wallace et al., 1986). Because PAM is highly susceptible to UV degradation, mixing it into the soil would slow its breakdown. PAM is also slow to break down because it cannot act alone as a C substrate; microbial and chemical attacks are only on the ends of the polymers (Kay-Shoemake et al., 1998). Finally, when PAM breaks down, it does not revert to its toxic monomer, AMD (Abdelmagid and Tabatabai, 1982; Ver Vers, 1999), adding to its environmental safety.

Finally, the effect of overburden pressure on the aggregates is unknown. Because the aggregates would have to be developed in the subsoil, overburden could

Table 3
Aggregates of sizes 0.25–2 mm as percentage of the total soil for treatments with organic matter or PAM added averaged over the three particle size groupings

Treatment[*]	Organic matter					Mean
PAM (mg kg^{-1})	None	w1	w2	p1	p2	
0	15.2[**]	15.4	14.4	11.7	13.0	13.9b
30	16.4	14.4	15.6	13.2	13.1	14.4ab
120	17.0	15.5	13.1	15.2	12.8	14.7a
Mean	16.3a	15.1b	14.4b	13.4c	13.0c	

[*] Organic matter added was of 0 g kg^{-1} (none), 3.22 g kg^{-1} (w1) and 6.44 g kg^{-1} (w2) ground wheat stubble, and 3.52 g kg^{-1} (p1) and 7.04 g kg^{-1} (p2) ground pecan. PAM added was 0, 30, and 120 mg kg^{-1}.
[**] Means with the same letter are not significantly different using the LSD test at 5%. LSD at 5% for the interaction was 1.6%.

fracture fragile aggregates. More research needs to be performed to determine the effects of long-term degradation and overburden pressure on the stability of the aggregates.

4. Conclusions

PAM formulation of 12 mg mol^{-1}, anionic, and 35% charge density at both 30 and 120 mg kg^{-1} rates of soil amendment decreased the amount of water that was needed to bring the treatments to 10% indicating that more water was being held in the soil against leaching or evaporation, suggesting that the PAM was increasing aggregation and holding more water.

Addition of PAM to the soil increased penetration resistances and decreased bulk density for the highest level of amendment. Strengthening the soil while increasing the volume would be consistent with the fact that PAM can improve aggregation, causing compact aggregates with larger inter-aggregate spaces though this result could be singular to this study or condition. Penetration resistances were lower for treatments with OM added, though they did not differ among amounts or types of organic matter. Penetration resistances showed no significant differences when both PAM and OM were added to the soil. Aggregation increased with increasing amounts of PAM but not when both PAM and OM were added to the soil. More research needs to be performed to determine proper PAM and OM treatment mixtures and interactions and to verify the aggregate spacings.

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