SOIL DEVELOPMENT IN SANDY TAILINGS DERIVED FROM MINERAL SANDS MINING IN FLORIDA[1]

by

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Abstract A significant area of land containing heavy mineral sands (rutile, ilmenite, and zircon) has been proposed for mining in the upper Coastal Plain of Virginia and North Carolina. In order for us to develop appropriate reclamation strategies, it is important to gain a better understanding of the nature of soils developed in the tailings and slimes generated by mineral sands mining. Fourteen mine soils (ages 1-20 yr) and two natural undisturbed soils were described and sampled at the Associated Minerals mine in Green Cove Springs, Florida. Very young profiles (< 2 yr) exhibited little or no profile differentiation other than that resulting from topsoiling. The tailings below the topsoiled surface showed obvious stratification from wet settling and were frequently quite compact. Mine soils between 5 and 15 years in age exhibited much stronger profile differentiation, and all contained thin continuous bands of precipitated humate. The deeper C horizons often showed prominent lamination. Rooting in these soils was generally limited to less than 50 cm, and quite often to less than 25 cm. When compared with the natural soils of the pre-mining landscape, the mine soils are less acidic and appear to provide a deeper subsoil rooting medium.

Introduction

In August of 1989 we entered into a cooperative research agreement with RGC Minerals, Inc. to develop effective restoration strategies for their proposed mineral sands mining projects in Virginia and North Carolina. A significant deposit of ilmenite, rutile and zircon bearing sands has been located in the upper Coastal Plain between Richmond Virginia, and Raleigh, North Carolina. Up to 5,000 ha could potentially be mined over the next 20 years. Since much of this area is currently in row crop production, there is considerable interest in estimating the potential productivity of the post-mining landscape, and the effect of the mining operation on soil

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properties. In order to answer these questions, we entered into a study of mine soils formed in sandy tailings at the Associated Minerals mine site in Green Cove Springs, Florida. Associated Minerals is a mining subsidiary of RGC Minerals, Inc. While this mine is certainly in a very different climatic and geologic setting than the proposed sites in Virginia/North Carolina, the mining technology is quite similar to that proposed for the new areas, and it is the only area in the southeast USA suitable for such a study. Our overall objectives in this study were:

1. To describe and characterize the morphological, physical, and chemical properties of mine soils formed in tailings generated by mineral sands mining.

2. To investigate the rate and nature of mine soil genesis in an age sequence of reclaimed tailings.

3. To compare the properties of the mine soils to those of adjacent undisturbed natural soils.

Mineral Sands Mining and Reclamation

In Australia, heavy mineral sands containing rutile, monazite, ilmenite, and zircon have been mined for over 50 years. Today, Australia produces over half the world's ilmenite, rutile, and zircon, and about a quarter of the world's monazite (Brooks, 1989). Although mineral sands are mined in other parts of the world, the techniques for reclaiming the mined areas were pioneered and developed in Australia. Mineral sands are mined by a variety of techniques including conventional dry mining and wet dredging. The Green Cove Springs site used for this study employs a dredge and a concentrator which float on the water table as the mining operation migrates across the landscape (Fig. 1). The heavy minerals are separated by spiral centrifugation from the lighter host sands which are then pumped behind the mine path as tailings.

The water cycling through the floating concentrator gradually accumulates suspended clays, silts, and organic materials dependent on the type of soil substrate being processed. These fine materials are collectively referred to as "slimes" by the industry. At the Florida site this consists primarily of humates derived from the thick spodic horizon present in the native soils. This suspended humate material is settled in detention ponds and the water is then re-cycled to the working dredge pond. In areas where the native soils contain appreciable amounts of fine silt and clay, this suspended material is also referred to as "slimes" and is typically settled with the tailings whenever possible.

Prior to mineral sands mining in Australia and Florida, vegetation is cleared and the A horizon of the soil is stripped and stockpiled. The subsoil along with underlying mineralized sand is then mined with dredges. The stored topsoil is then returned to the site, and vegetation is established and stabilized (Brooks and Bell, 1984). Heavy mineral removal produces no toxic wastes, and generally results in a volume loss of less than 5% (Brooks, 1989). In Australia, mineral sands mining and subsequent reclamation have taken place on a variety of landforms and ecological systems, including dunes, coastal lowlands, forest lands, and sand plain shrubland. Most of this work has involved the re-establishment of native species. The site's landforms must be reconstructed to follow the original topography of the landscape, with emphasis on drainage.

Research Methods

Fourteen representative mine soils developed in sandy tailings at the Green Cove Springs mine in Clay County, Florida, were described and sampled in November 1989 and again in March 1991. The sites ranged in age from less than 1 year to approximately 20 years since reclamation, and the ages were verified through the company mining records. At least two pedons in each age class were described. Two representative pedons of the dominant native soil (Leon series: sandy, siliceous, thermic, Aeric Haplaquods) were described and sampled in undisturbed areas adjacent to the mining path. Careful descriptions were made of soil morphology and plant rooting patterns. The bulk density of each major delineated horizon was carefully measured with an intact core sampling device. Each major morphological soil horizon from each pedon was sampled. All soil samples were air-dried and passed through a 2mm sieve to remove coarse fragments. All analyses were performed on the <2mm fraction. Particle size analysis was performed by the pipette method (Day, 1965).

Soil pH was determined in a 1:1 soil:water slurry (McLean, 1982). Exchangeable Ca, Mg, and K were determined

Figure 1. Mining dredge at Associated Mineral's mine in Florida. The original topsoil has been removed from the site and the dredge processes the entire subsoil plus mineralized sands to the depth of 10 m. Sandy tailings are deposited behind the dredge and form the subsoil of the new mine soils.

by atomic absorption spectrophotometry after extraction with N NH_4OAc buffered at pH 7 (Thomas, 1982). Exchangeable Al was extracted with N KCl (Barnhisel and Bertsch, 1982) and exchangeable acidity was determined using the $BaCl_2$-TEA method of Peech (1965). Cation exchange capacity (CEC) was determined by the summation of extractable Ca, Mg, K, and exchangeable acidity (Chapman, 1965), and effective CEC was determined as the sum of extractable bases plus exchangeable Al.

Results and Discussion

During our original investigations of these mine soils (in 1989) we sampled 6 pedons and were impressed by the occurrence of thin continuous humate bands in all but the youngest mine soils (Fig. 2). We originally believed this to be a depositional phenomenon or a function of grading, but these mechanisms would not explain why the layer appeared to become more distinct with mine soil age, and did not occur in recently deposited tailings. On our second visit (in 1991) we sampled an additional 8 pedons with a similar age distribution to the 1989 sampling, and observed the same morphology and age trends. It is important to note that when we first observed these soils in the fall of 1989, northern Florida had suffered a protracted drought and the regional water table was quite low. Free water was observed within 1 m of the surface in only one of the six pits opened in 1989, and that pit appeared to be receiving subsurface flow from a nearby humate impoundment. By 1991 the regional water table had returned to normal levels and was observed in almost all pits at a depth 45 to 90 cm, even though several of these pits were dug in close proximity to the original 1989 pits.

The findings discussed in this paper reflect the entire set of pedons observed, but we

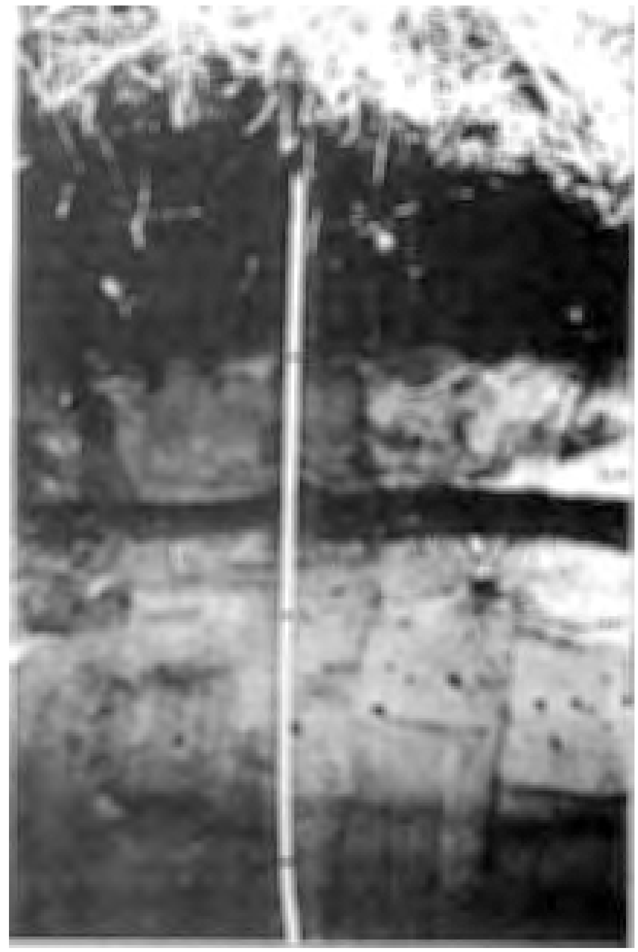

Figure 2. Ten year-old mine soil with prominent precipitated humate horizon at approximately 50 cm. This pedogenic feature appears to be associated with water table fluctuations and is very similar to the spodic horizon found in local undisturbed soils. The topsoiled surface layer is quite distinct.

have chosen representative examples for discussion (Table 1). Three pedons in recently topsoiled tailings were studied, and these young soils exhibited little or no profile differentiation other than that resulting from topsoiling and were described as A-C soils. The tailings below the topsoil layer showed obvious stratification due to wet settling, and were frequently quite compact. The C horizons in these soils varied considerably in color hue, but none contained distinct humate bands. Several profiles were quite compacted just below the topsoil layer, and the bulk density in the deeper subsoils often approached 1.7. These tailings are commonly "walked" with a bulldozer to enhance dewatering, and they also receive considerable traffic during topsoiling operations. The combination of wet settling and traffic is most likely responsible for the observed density of these C horizons, but it is unclear whether or not this density is sufficiently high to limit rooting.

We examined seven mine soils between 5 and 10 years-old. All exhibited much stronger profile differentiation than the youngest soils, and nearly all contained a thin (0.5 - 5 cm) continuous band of humate within 50 cm of the surface (Fig. 2), often accompanied by an Fe-stained zone as well. We described these as Bh and Bs horizons when their morphology was sufficiently strong enough to warrant their delineation. The one pedon in this age class that did not contain the humate horizon occurred on a well-to excessively-drained convex ridge with a deep water table (> 2.0 m). Several pedons contained two distinct humate bands, one within 40 to 50 cm of the surface, and a second one near the bottom of the pit. These layers appear to be the result of humate+Fe precipitation, presumably associated with a fluctuating water table.

It seems quite remarkable that this spodic-like horizon could form within 5 years, but not totally unexpected since the pore waters of the sandy tailings contain a considerable load of humate and iron liberated from the spodic horizon of the Leon soil as it is processed. The topsoiling material used is also enriched in humates and is often a blend of upland topsoils and muck-like materials from somewhat poorly drained areas. The deeper C horizons in these soils were often well differentiated and showed prominent lamination. Several of the subsurface layers were also quite compact.

The strongest subsoil differentiation was observed in several 13 to 15 year-old soils that occurred in landscapes with low relief. These soils contained distinct humate bands within 50 cm of the surface, often with reddened zones of Fe-accumulation just above the humate. Two pedons contained a second humate horizon at or just below the water table which was considerably thicker and higher in humate than the first horizon. This double humate layer morphology is remarkably similar to that of the natural Leon soil (Table 2, Fig. 3).

The two oldest mine soils

Table 1. Mine soil descriptions from Green Cove Springs site. All colors are 10YR unless noted.

Horizon	Depth (cm)	Description
		One Year-Old Mine Soil (RGC #5)
A	0-15	Dark grayish brown loamy sand.
C	15-122+	Banded yellowish brown and pale brown sand.
		Comments: Roots to 61 cm; Bulk density of A = 1.43; C = 1.57.
		Five Year-Old Mine Soil (RGC #1)
A	0-15	Black loamy sand.
A&C	15-28	Dark brown and black laminated humate and sand.
C1	28-46	Brown sand.
C2	46-76	Yellowish brown sand.
C3	76+	Dark yellowish brown sand.
		Comments: Roots to 28 cm. Bulk density of A = 1.42; A&C = 1.39; C2 = 1.59.
		Thirteen Year-Old Mine Soil (RGC #3)
A	0-23	Grayish brown loamy sand.
Bs	23-41	Strong brown (7.5YR 5/6) sand.
Bh	41-51	Black laminated humate.
C1	51-91	Light gray sand.
C2	91+	Strong brown sand.
		Comments: Well developed spodic-like layer. No roots below 41 cm.
		Twenty Year-Old Mine Soil (RGC #4)
A/E	0-23	Dark grayish brown loamy sand.
Cn	23-102+	Light yellowish brown sand with prominent brownish yellow lamellae.
		Comments: Soil formed in deep, dry tailings. Common small (1-2 mm) Fe/Mn concretions. Roots to 71 cm.

TABLE 2. Comparison of Mine Soil and Natural Soil from Green Cove Springs, FL Mine Site.

Pedon Number: GCS-6.
Vegetation: Longleaf pine and grasses.
Parent Material: Reclaimed mine tailings. Area was mined in January of 1985.
Physiography: Footslope.
Relief: Nearly level.
Slope: 3%.
Aspect: NW 280 degrees.

Ap -- 0 to 8 inches (0 to 20 cm); black (5Y 2.5/1) fine sand; weak fine granular and weak medium and coarse subangular blocky structure; very friable, non-sticky, non-plastic; many medium and common fine and coarse roots; extremely acid; abrupt smooth boundary.

Bh -- 8 to 16 inches (20 to 40 cm); very dark brown (10YR 2/2) fine sand; massive; friable, non-sticky, non-plastic; common fine and medium roots; very strongly acid; abrupt wavy boundary.

C -- 16 to 48 inches (40 to 122 cm); brown (10YR 5/3) fine sand; massive; very friable, non-sticky, non-plastic; few fine and few coarse roots; extremely acid; gradual smooth boundary.

Bh' -- 48 to 50+ inches (122 to 127 cm); black (10YR 2/1) fine sand; massive; friable; non-sticky, non-plastic; extremely acid.

Pedon Number: GCS-Leon 2.
Vegetation: Slash pine, saw palmetto, galdberry, wiregrass.
Parent Material: Fluviomarine sediments (natural soil).
Physiography: Broad flat (flatwoods).
Relief: Nearly level.
Slope: 1%.
Aspect: S 180 degrees.

Ap -- 0 to 5 inches (0 to 13 cm); dark gray (10YR 4/1) fine sand; weak fine granular structure; very friable;, many fine and medium and common coarse roots; extremely acid; clear wavy boundary.

E -- 5 to 16 inches (13 to 41 cm); gray (10YR 6/1) fine sand; single grain; loose; common fine and medium and few coarse roots; very strongly acid; abrupt smooth boundary.

Bh1 -- 16 to 19 inches (41 to 48 cm); black (5YR 2.5/1) fine sand; massive; friable; few fine roots; extremely acid; clear wavy boundary.

Bh2 -- 19 to 22 inches (48 to 56 cm); dark reddish brown (5YR 3/4) fine sand; massive; friable; few fine roots; extremely acid; gradual wavy boundary.

BE -- 22 to 30 inches (56 to 76 cm); brown (10YR 5/3) fine sand; single grain; loose; few fine roots; extremely acid. gradual wavy boundary;

B'h1 -- 30 to 36 inches (76 to 91 cm); dark brown (7.5YR 3/2) fine sand; massive; very friable; few fine roots; very strongly acid; gradual wavy boundary.

B'h2 -- 36 to 42 inches (91 to 107 cm); dark reddish brown (5YR 2.5/2) fine sand; massive; friable; few fine roots; very strongly acid; gradual wavy boundary.

B'h3 -- 42 to 50 inches (107 to 127 cm); black (5YR 2.5/1) fine sand; massive; friable; few fine roots; very strongly acid; gradual wavy boundary.

B'h4 -- 50 to 80 inches (127 to 203 cm); black (5YR 2.5/1) fine sand; massive; friable; few fine roots; very strongly acid.

observed were formed in excessively drained upland tailings that were approximately 20 years old. Both pedons contained areas of very thin humate laminations which appeared to follow textural bands in the sands, but the humate layers were not nearly as thick or distinct as those observed in soils with high water tables. Prominent Fe-precipitate banding (lamellae) was observed in the C horizons, which were also riddled with fine iron-stone concretions. Apparently, these lamellae can form fairly rapidly under these conditions since they were easily observable by 1991 in the upper 50 cm of fill in the soil pit that had been closed in 1989.

Rooting in these soils was generally limited to less than 50 cm, and quite often to less than 25 cm. Rooting was seldom observed below the humate horizon in most pits, further reinforcing our hypothesis that its formation is associated with the high water table which would also limit perennial rooting. In the two natural Leon pedons observed, rooting was limited by the upper spodic layer which was quite dense, and few roots were observed in deeper layers (Table 2). The lack of rooting in the deeper layers of the mine soils may also be due to compaction, or a combination of compaction and wetness. The compaction observed high in the profile appeared to be due to final grading operations during topsoiling, while that lower in the profile appears to be due to wet settling and fill consolidation. The soils associated with the topsoil layers and upper parts of the sandy tailings developed reasonable structural aggregation within five years, but the deeper tailings remained massive.

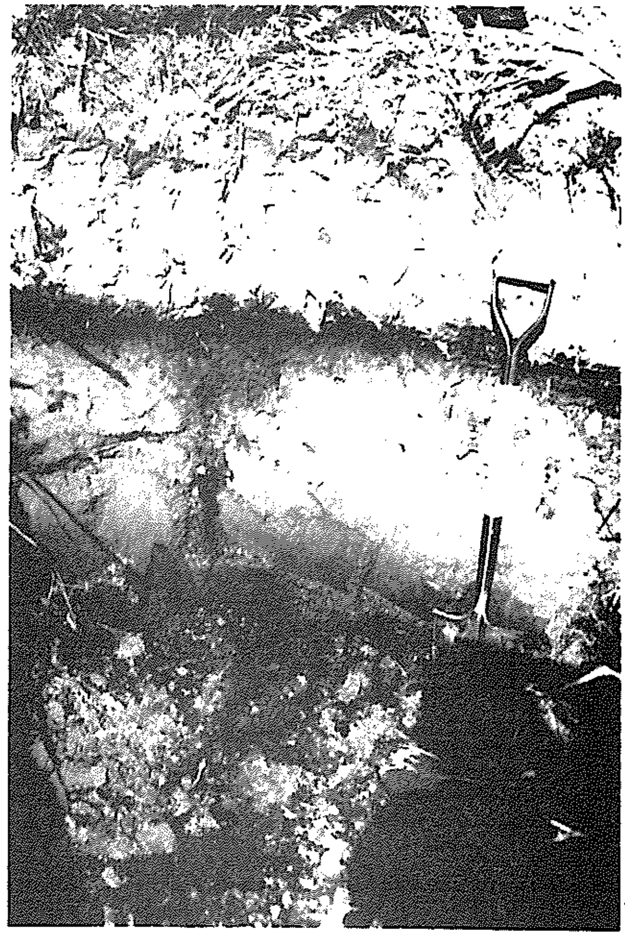

Figure 3. Profile of the naturally occurring Leon soil. This soil is typically very strongly acid throughout with two organic enriched spodic horizons. The first spodic is weakly developed at approximately 50 cm and the second is quite strong and is just visible at the bottom of the profile.

The texture of the mine soils was relatively uniform with age and reflects the homogenizing influence of the mining operations (Table 3). The topsoil layer was higher in silt+clay than the underlying

TABLE 3. Physical and Chemical Data for RGC Mine Site at Green Cove Springs, Florida.

PEDON	HORIZON	DEPTH (cm)	%TOTAL SAND	%TOTAL SILT	%CLAY	pH	Ca	Mg	K	H	Al	CEC	ECEC	% BASE SATURATION	%EFFECTIVE BASE SAT'N
							cmol(+)/kg soil								
							One Year-Old Mine Soil								
RGC #5	A	0-15	88.4	7.4	4.2	4.24	0.50	0.08	0.03	9.00	1.65	9.61	2.26	6.35	26.99
	C	15-122	95.9	2.4	1.7	4.72	0.04	0.01	0.01	2.80	0.35	2.86	0.41	2.10	14.63
							Five Year-Old Mine Soil								
RGC #1	A	0-15	87.9	8.1	4.0	4.40	0.60	0.27	0.05	12.80	1.95	13.72	2.87	6.71	32.06
	A+C	15-28	91.0	5.9	3.1	4.60	0.52	0.18	0.02	9.60	1.25	10.32	1.97	6.98	36.55
	C1	28-46													
	C2	46-76	97.7	2.3	0.0	5.02	0.05	0.02	0.01	1.40	0.25	1.48	0.33	5.41	24.24
	C3	76+													
							Thirteen Year-Old Mine Soil								
RGC #3	A	0-23	92.1	5.0	2.9	5.70	4.15	1.01	0.01	1.60	0.05	6.77	5.22	76.37	99.04
	Bs	23-41	98.6	1.4	0.0	5.22	0.27	0.12	0.01	5.80	0.25	6.20	0.65	6.45	61.54
	Bh	41-51	94.2	5.8	0.0	4.92	0.16	0.06	0.01	12.20	1.05	12.43	1.28	1.85	17.97
	C1	51-91	99.8	0.2	0.0	5.40	0.02	0.01	0.01	1.40	0.20	1.44	0.24	2.78	16.67
	C2	91+	99.3	0.7	0.0	5.01	0.03	0.02	0.01	3.00	0.25	3.06	0.31	1.96	19.35
							Twenty Year-Old Mine Soil								
RGC #4	A/E	0-23	93.5	6.5	0.0	5.00	1.47	0.18	0.03	2.60	0.10	4.28	1.78	39.25	94.38
	Cn	23-102+	99.1	0.9	0.0	5.16	0.06	0.01	0.01	3.20	0.55	3.28	0.63	2.44	12.70
							Natural Soil								
Leon #2	A	0-13	95.1	4.9	0.0	4.18	0.20	0.06	0.02	3.80	0.65	4.08	0.93	6.86	30.11
	E	13-41	96.9	2.2	0.9	4.53	0.05	0.02	0.02	0.60	0.15	0.69	0.24	13.04	37.50
	Bh1	41-48	88.2	5.8	6.0	4.14	0.06	0.04	0.02	26.40	4.65	26.52	4.77	0.45	2.52
	Bh2	48-56	91.0	5.3	3.7	4.30	0.03	0.01	0.01	17.00	2.55	17.05	2.60	0.29	1.92
	BE	56-76	91.5	4.0	4.5	4.32	0.03	0.01	0.01	11.60	1.85	11.65	1.90	0.43	2.63
	B'h1	76-91	94.1	5.0	0.9	4.58	0.02	0.01	0.01	4.00	0.55	4.04	0.59	0.99	6.78
	B'h2	91-107	89.6	8.3	2.1	4.64	0.02	0.01	0.01	8.00	0.45	8.04	0.49	0.50	8.16
	B'h3	107-127	96.6	3.1	0.3	4.70	0.02	0.00	0.01	7.40	0.65	7.43	0.68	0.40	4.41
	B'h4	127-203	97.1	2.6	0.3	4.62	0.02	0.00	0.01	6.60	0.65	6.63	0.68	0.45	4.41

NOTE: Soils and spoils were essentially devoid of coarse fragments.

washed tailings as would be expected. The overall texture of the mine soils was quite similar to that of the original Leon soil, both ranging from 90 to 97% sand. The chemical properties of the mine soils do appear to be more suitable for plant growth than those of the natural Leon soil, however. The pH of the mine soils ranged from 4.2 to 5.7, but was generally between 4.6 and 5.2 in the upper 50 cm, while the pH of the Leon soil was typically less than 4.5. The CEC of the surface horizons in the mine soils was typically higher than the Leon soil (Table 3). The CEC of the topsoil layers was also higher than that of the underlying tailings, and the subsurface humate (Bh) layers exhibited higher CEC and lower pH values than their surrounding horizons. This behavior is also seen in the Leon spodic horizons.

These differences in mine soil pH and CEC may reflect changes in soil acidity and surface charge due to the wet processing of the original soils along with their underlying sediments, and the fact that the majority of the mine soils studied were under grass vegetation which is less acidifying than the thick pine/palmetto cover over the Leon soils. On the other hand, the topsoil horizons from the two Leon pedons sampled may not be reflective of the blend of topsoils from the overall landscape which are salvaged and re-applied to the graded tailings.

Conclusions

These mine soils, formed in re-applied topsoil over sandy tailings, become well differentiated with distinct subsoil humate+Fe horizons within 5 to 10 years. The subsoil humate band appears to be very similar in morphological and chemical properties to the spodic horizon of the native Leon soil. The precipitated band of humate appears to be associated with fluctuating redox and drying conditions at the top of the winter water table, and a second humate layer is often found lower in the profile. The genesis of this lower layer is unclear, but may result from longer term contact of the tailings with the humate laden pore waters. Again, this morphology is very similar to the native Leon soil.

The physical and chemical properties of the post-mining soil appear to be more suitable for plant growth than the original soil, but subsurface compaction may limit rooting in the massive subsoils. The combination of wet settling and topsoil re-application with heavy machinery can lead to moderate to high bulk density in these materials. Topsoiling has a very beneficial influence on the physical and chemical properties of the surface soil after mining in addition to its well known biological benefits. The original soils in this mining landscape are very low in silt+clay and therefore do not generate mineral slimes. The soils in the proposed mining area in Virginia and North Carolina are quite high in silt+clay, so any effort at application of these findings to those areas must acknowledge that fundamental difference.

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