SOIL RECONSTRUCTION ON SURFACE MINED LAND USING A PROTOTYPE MECHANICAL SYSTEM.[1]

J.P. Fulton and L.G. Wells[2]

Abstract: Soil compaction due to heavy earth moving equipment remains an impediment for the surface mining industry to return prime farmland back to pre-mining performance. The purpose of this investigation was to fabricate and evaluate a mechanism, called the “Soil Regenerator”, for constructing the top- and sub-soil profiles without the introduction of machinery traffic in order to minimize compaction during reclamation. The prototype system was mounted on the front of a bulldozer. Windrows of soil were constructed using a scraper or bulldozer for the mechanism to process. The bulldozer engaged the windrows allowing soil to rise up the blade and be agitated, transported, and deposited by a helicoid auger resulting in a 0.9 m deep berm adjacent to the bulldozer. An uncompacted soil medium was built by making successive parallel passes. Testing resulted in processing capacities ranging from 330 to 804 m^3/hr for the prototype, which was much less than the projected theoretical design capacity of 2680 m^3/hr. However, dry bulk densities equal to or less than 1.0 Mg/m^3 were produced along with penetrometer measurements below 0.7 MPa. These results proved that the ‘Soil Regenerator’ was capable of eliminating soil compaction during reclamation of surface mined land.

Additional Keywords: Reclamation, Surface Mining, Soil Handling System, Soil Profile, Reclamation and Excavating Equipment.

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Introduction

For years, many agricultural communities faced the problem of having coal reserves overlain by productive cropland. Bernard (1979) predicted that coal surface mining may involve as much as 182,100 hectares (450,000 acres) in the Corn Belt by the year 2000, with approximately 51,400 hectares (127,000 acres) involving prime farmland. Another report published in 1979 estimated 20 million hectares (48.5 million acres) of prime farmland was underlain by strippable coal reserve base (Harper, 1979). It has been recently estimated that approximately 10 percent of this has been mined (Vories, 1997); leaving over 16 million hectares (40 million acres) of potential mineable prime farmland.

The major regulations governing prime farmland reclamation in Kentucky are The Surface Mining Control and Reclamation Act of 1977, Public law 95-87 (SMCRA, 1977), at the federal level, and The 1992 Kentucky Surface Mining Law -KRS 350- (KSML, 1992) and 405 KAR Chapter 7 through 24 (KPPR, 1986), at the state level. These regulations govern permitting and performance standards for surface coal mining and reclamation especially on land designated as prime farmland. The purpose of the regulations is to ensure that surface mined land is adequately reclaimed.

Several aspects of these regulations relate to mining and reclamation of prime farmland. First, the A- and B-horizons must be segregated and stored separately upon removal. Second, these horizons must be replaced during reclamation to develop a uniform depth of 1.2 m (4 ft) of rooting zone with 0.3 m (1 ft) of topsoil over .91 m (3 ft) of subsoil. Third, overburden must be graded to approximate contour and the post-mine landscape must blend into the surrounding undisturbed terrain. Finally, land designated as prime farmland must be capable of supporting successful revegetation based on pre-mining crop production from approved reference areas or other procedures, which pertain to reclamation. Therefore, timely crop production must follow soil replacement and target yields must be met in order to avoid forfeiture of surety bond.

The primary factor inhibiting successful reclamation is excessive compaction within the rooting zone occurring during soil reconstruction. The impact of compaction on agricultural soils has been studied and documented over the years. Farmers, foresters and others who cultivate the land have found the existence of soil compaction to be a cumbersome problem. Compaction on surface mined land results in high bulk densities that are in excess of those found on natural soils (Hooks and Jansen, 1986). Vance et al. (1987) reported that the degree and depth of compaction in mine soils varies with reconstruction methods. The existence of soil compaction after surface mine reclamation is due to heavy excavation equipment used during the reconstruction process. Earthmoving equipment applies large surface pressure generating an increase in soil density (Dollhopf and Postle, 1988). These vehicles are heavy owing to their payload capacity and final grading capabilities thereby transmitting extremely high loads to the soil via their running gear.

Jansen et al. (1985) and Dunker et al. (1991a) reported that the physical properties of reconstructed soil are the major factor affecting crop performance. The physical state of reclaimed soil is a direct result of the method and equipment used for soil replacement. Bulk density and soil strength are two primary physical properties which quantify soil compaction. Currently, no general rule of thumb exists stating that a certain bulk density or penetrometer strength limits plant productivity. However, some studies have been conducted which address these two parameters in predicting detrimental effects on plant growth.

Bowen (1981) suggested a general rule (with many exceptions) that bulk densities of 1.55, 1.65, 1.80 and 1.85 Mg/m^3 can impede root growth and thus will reduce crop yields in clay loams, silt loams, fine sandy loams, and loamy fine sands, respectively. Bulk density greater than 1.2 Mg/m^3 for clay soil, 1.6 Mg/m^3 for loam soil, and 1.8 Mg/m^3 for sandy loam adversely affected the root growth of rice (Kar et al., 1976). Singh et al. (1992) proposed a bulk density less than or equal to 1.3 Mg/m^3 as non-limiting to crop growth, in any soil type. However, due to the lack of research literature, they suggested that a maximum bulk density of 2.1 Mg/m^3 in any type of soil is unusable by plants.

The above references suggest that a dry soil bulk density (DBD) equal to or exceeding 1.6 Mg/m^3 can be excessive in agricultural soils and should be managed in some way. Anything above this value has the potential to greatly reduce crop yields, especially when the DBD reaches 2.0 Mg/m^3. Within the range of 1.6 to 2.0 Mg/m^3, some type of tillage or other physical manipulation should be applied. Around 2.0 Mg/m^3, a critical bulk density for soils exists at which roots are unable to penetrate and develop.

Soil strength can be a better predictor of detrimental soil compaction than bulk density since it more accurately predicts the resistance plant roots encounter during elongation (Phillips and

Kirkham, 1962; and Blancher et al., 1978). Some researchers have concluded that soil strength, not bulk density, is the critical limiting factor reducing root growth (Taylor and Garner, 1963; and Taylor et al., 1964). Vance et al. (1992) showed that penetrometer data correlated well with corn and soybean yields on reconstructed soils. The lowest yields were observed in reclamation treatments with the highest soil strength.

The predominant method of assessing soil strength in the field is through the use of the soil cone penetrometer (ASAE, 1997). The force required to push a 30^o cone into the soil at 3 cm/sec is divided by the base area of the cone and reported as soil cone index (CI) in units of MPa or psi.

Penetrometer resistance that is limiting to root growth depends upon the soil conditions and characteristics and the crop. Ayers and Perumpral (1982) pointed out that dry density had a considerable influence on CI at low moisture contents for soils containing a certain percentage of clay. Cone index became less dependent on dry density at higher moisture contents. Sojka et al. (1990) studied the effect of CI on sunflowers. A penetrometer measurement of 2 MPa produced some restriction to root growth and a resistance of 3 MPa created a total barrier to root elongation. Murdock et al. (1995) suggested a CI of 2.1 MPa as indicative of severe compaction for Kentucky soils. The literature suggests that CI values measured with a 13-mm, 30-degree cone tip above 2.5 to 3.0 MPa limits root growth in most soils (Busscher and Sojka, 1987).

Excessive compaction leads to the reduction in plant growth and crop yield. Such yield reduction can have serious consequences in reclaiming surface mines. If crop yields fall below 90% of pre-mining target yields on prime farmland soils, bond forfeiture can occur. Philips and Kirkland (1962) and Morris (1975) reported corn yield reductions of 10 to 22 percent due to compaction. Canarache et al. (1984) reported that each 0.1 Mg/m^3 increase in bulk density created an 18% decrease in maize grain yields compared to the yield on a non-compacted plot. Nielson and Miller (1980) compared corn yields on strip-mined soils and native soils. Depending upon topsoil replacement method and time after reclamation, their research showed a 4 to 90 percent reduction in yields on mined soils. These results illustrate the potential for compaction to depress crop yields.

Deep tillage and other soil loosening procedures have been implemented after reconstruction to improve soil productivity, but none have been fully successful. Research on reconstructed mine land has demonstrated that deep tillage improves yield, especially in corn, and that yield increased with tillage depth (Bledsoe et al., 1992; Dunker et al., 1992a). Dunker et al. (1992a) produced yields at 122 cm (48 inch) tillage depth comparable to an undisturbed plot in three of four years and equaled the adjusted target yield for the county in all four years. However, other research has shown minimal benefit of deep tillage for short periods. Gaultney et al. (1982) found subsoiling was ineffective in reducing the effects of compaction on a silt loam soil in Indiana. After an area has been tilled, the tilled soil can return to its compact state. Barnhisel (1988) reported a tendency for bulk density to increase over a period of two years in both ripped and non-ripped areas. Elkins et al. (1983) also noted that subsoiling has short-term beneficial effects but undesirably mixes soil horizons. Subsequent cultivation operations requiring machinery traffic, along with the natural settling of the soil particles, can lead to a reduction on pore space that was created by deep tillage (Larney and Fortune, 1986; and Kouwenhoven, 1985). Therefore, some soils may require yearly subsoiling to help reduce soil strength and bulk density and enhance plant growth. Deep tillage requires large energy input and may not be economically feasible on an annual basis.

Some innovative material handling schemes have been devised to limit vehicular traffic on reconstructed rooting media or subsoil (B-horizon). Dunker et al. (1991b) proposed a process using large dump trucks to back-fill a mined area. Dump trucks would be loaded by filling the front with topsoil and the rear with subsoil. The mixture would then be back-dumped onto a graded spoil base, allowing most of the topsoil to remain at the top of the soil pile. By replacing the topsoil and subsoil with a single dump, the subsoil material would not be subjected to continual traffic. Using light dozers for final surface grading would minimize surface traffic, but still could create bulk densities that impede plant growth.

Another method utilized a large mining wheel-conveyor-spreader system, developed in Germany, to transport soil onto graded spoil. These large bucket wheel excavators removed and mixed the A and B horizons. A rotating bucket digs soil from an embankment and a belt conveyor then transports the mixed soil horizons to a spreader that places it onto graded spoil. The use of this type of system still requires minimal grading (Dunker et al., 1992b; and McSweeney et al., 1987). Soils reconstructed by the wheel-conveyor produced higher yields than those replaced by scrapers (Dunker et al., 1992b) and produced 4-year average yields as good as those on natural soils (McSweeney et al., 1987). Dunker et al. (1992b) showed that this method produced productive soils upon completion of reclamation, but proved to be too costly for use in most surface mining situations, especially small mines found in the Midwest.

As prime farmland continues to be surface mined, a technique is needed to better assist mining companies in returning prime farmland land to pre-mining crop productivity. Therefore the objectives of this paper are:

- To describe a prototype mechanism for reconstructing soil after the completion of surface mining for agricultural lands without introducing surface traffic.
- To describe the soil handling process to be used with this prototype mechanism.
- To test and evaluate the performance of the soil regenerator with respect to operational capacity (m^3/hr) and efficacy of operation.
- To evaluate the physical condition of the resultant reconstructed soil.

A cost analysis between the ‘soil regenerator’ and conventional reclamation methods was not performed for this paper. The focus of the paper is on describing the ‘soil regenerator’ and the resulting physical condition of the soil medium reconstructed by it with comparisons made to the physical state of soil reconstructed using a conventional reclamation process.

Methodology

Fabrication of the prototype mechanism, called the 'Soil Regenerator,’ occurred in the Agricultural Machinery Research Laboratory (AMRL) at the University of Kentucky, Lexington, Kentucky. Fig. 1 presents the ‘Soil Regenerator’ built to reconstruct soil profiles after surface mining without introducing detrimental traffic compaction. The soil regenerator system was mounted on a Caterpillar D7 bulldozer. With a maximum power requirement of 75 kW for the auger, an auxiliary engine was needed to drive the auger system. However, enough power was available from the bulldozer engine to operate auxiliary hydraulic actuators for controlling auger height. The auger serves three purposes. The first is to agitate and break-up dense soil through its spiraling action. Secondly, the auger transports soil from in front of the blade and deposits it in a berm adjacent to the windrow. Finally, the action of the auger aids in leaving a level berm.

Figure 1. The 'Soil Regenerator."

The original bulldozer semi-universal (SU) 3.3 m wide blade was modified from its original configuration to provide easier lateral soil displacement (Fig. 2). This modification was accomplished by removing the curved right side of the blade and replacing it with a straightened section to help facilitate soil movement to the right (the side where the auger deposited soil). To help retain soil in front of the blade during operation, the blade height was increased. A helicoid auger was fabricated to extend approximately 2.2 m beyond the right end of the modified blade.

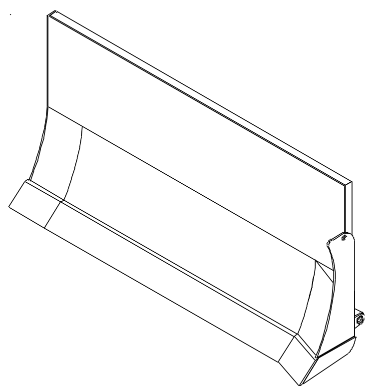

Figure 2. The modified SU blade.

A D333C (3306), 6-cylinder Caterpillar diesel engine was used for auxiliary power to drive the auger and other hydraulic components on the prototype. The auxiliary engine was mounted at the rear of the bulldozer to minimize visual obstruction for the operator. Fuel and power for the auxiliary engine was supplied by the fuel tank and battery on the bulldozer, respectively.

A hydrostatic system was selected to power the auger since it provides infinite speed control, reversibility, and dynamic braking. A gear reducer was selected to provide the desired speed and torque to the auger and was coupled directly to the auger by a flexible drive coupler. The hydrostatic transmission consisted of a fixed displacement, axial piston motor and a variable displacement, axial piston pump. The pump was connected directly to the flywheel of the auxiliary engine using a pump drive.

A support structure was designed and fabricated to mount the auger and drive system on the bulldozer. Fig. 3 shows the structure, auger and drive components along with the modified blade. The auger support structure was mounted on the side arms of the bulldozer. The central element of the auger support structure was the main support beam, which is shown with left and right end plates. The main framework was constructed of steel tubing with steel plating used for mounting the bearing and gear reducer. Due to the large thrust force generated by the auger, a wear plate was added between the structure and blade to transfer this lateral force to the blade. The beam was connected to the left and right support arms via quick couplers that allowed the main beam and auger assembly to be detached from the arms for transportation. The gear reducer and hydrostatic motor were mounted rigidly to the left end plate. The auger was then connected to the gear reducer via a specially designed flexible coupler, which accommodated any misalignment between shafts yet transmitted the necessary thrust force during soil conveyance.

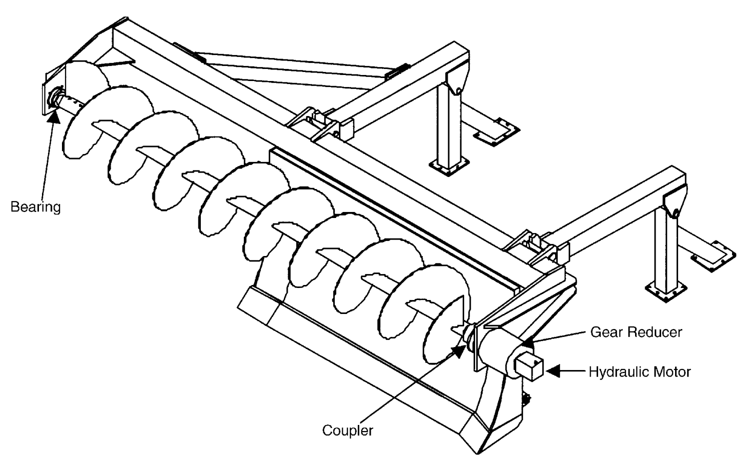

Figure 3. Illustration of support structure, helicoid auger, and drive components.

Two hydraulic cylinders were connected in series and sized appropriately to adjust the vertical position of the auger; one attached to each arm. The series cylinders insured synchronized movement of the two sides of the structure during extension and retraction. The blade tilt-cylinder hydraulic system on the bulldozer was used to actuate the series cylinders.

The intended soil handling process starts by placing soil or other rooting media atop graded spoil in long, narrow windrows (approximately 46 cm deep by 3.7 m wide) with scrapers or dump trucks (Fig. 4). As the bulldozer pushes into such a berm or windrow, material rises up the blade where the auger grinds and displaces the material perpendicular to the direction of bulldozer travel. The disturbed soil is deposited and leveled in a berm adjacent to one side of the bulldozer, which is narrower and deeper, approximately 1.1 m deep and 1.2 to 1.8 m wide. Once a berm of subsoil is reconstructed, the same method is implemented to place topsoil on top of the subsoil prior to formation of the next berm. It is expected that in most prime farmland regions, approximately 30 cm of A-horizon will be placed over 90 cm of B horizon. Successive parallel passes of the mechanism results in the construction of a non-compacted rooting layer (Fig. 5).

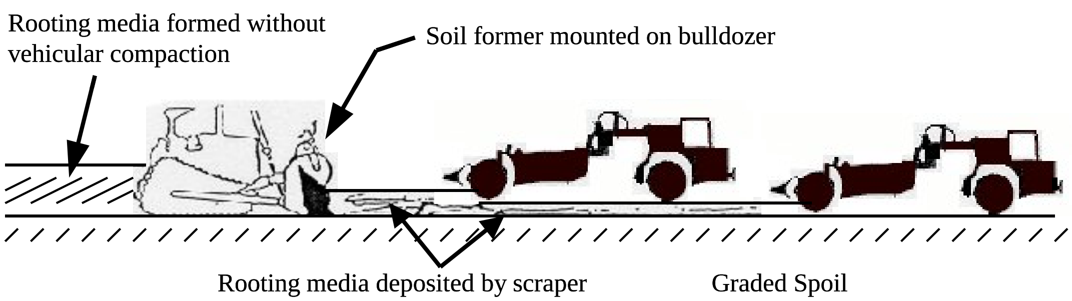

Figure 4. Soil handling process with mechanism loosening and reconstructing soil deposited in a windrow.

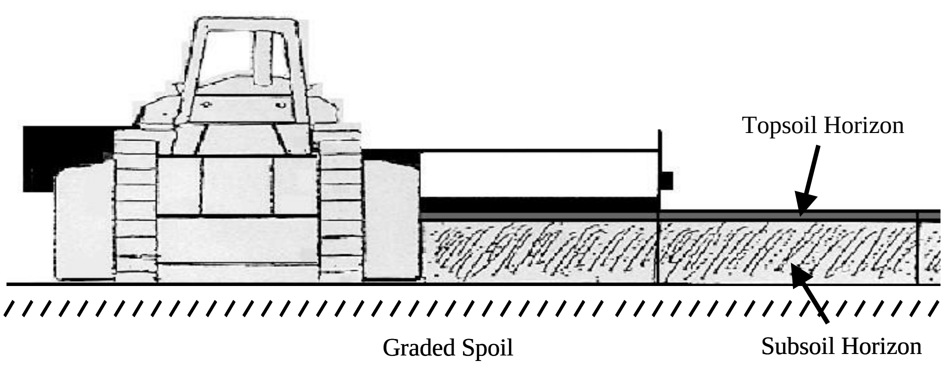

Figure 5. Soil placement from successive parallel passes.

Evaluation of the ‘Soil Regenerator’ occurred at the Grand Eagle surface mine located in Henderson County, Kentucky. Grand Eagle Mining is owned by The Patriot Coal Company, a subsidiary of the Peabody Group. A 2.0 ha site was provided for testing which was classified as nonprime farmland. The area was relatively level with overburden material already brought to desired grade. A minimum of 1.2 m for soil replacement was required on this area. An agreement was reached such that the prototype system was used to replace about 0.9 m of soil with the uppermost 0.3 m of soil being placed by mine bulldozers. The site was approximately 76 m in length with a silt loam soil already deposited and graded to approximately 0.6 m deep on one side of the area. The other side of the site contained a long stockpiled berm of silt loam soil to be used to complete soil replacement in this area. Instead of placing soil with scrapers or trucks, soil was pushed out of the stockpile berm by a bulldozer and used to test the performance of the soil regenerator. Though the procedure was different than originally proposed for the machine, this provided the best alternative testing method.

Soil was excavated from the soil bank with two or three passes of the soil regenerator to form a windrow approximately 1.8 m wide by 0.6 m deep (Fig. 6). After placing enough soil in the windrow, a final pass was made to construct a 0.9 m deep berm (Fig. 7). The final width of the berms varied as the volume of soil in front of the blade changed and the machine was steered in and out of the berm to change the fill zone width. Thus, changing the bulldozer heading was used to help form a level berm. Though many problems occurred with controlling the prototype, continued testing improved familiarity with the machine and its operation, correcting some of these control problems.

Figure 6. Building windrow.

Figure 7. Processing windrow.

Successive passes of the machine produced a relatively uniform reconstructed soil (Fig. 8). Several tests were conducted over the investigation period to collect power, hydraulic system pressure, and capacity measurements. The capacity of the soil regenerator was determined by taking random width and depth measurements along the final constructed berm over a measured distance. Flags were used to mark the beginning and end of each run. Time to complete each pass was kept using a stopwatch. Multiplying the average berm depth and width by its length calculated the volume of soil displaced. This volume divided by the time required to complete the final pass computed the finishing capacity.

Figure 8. Reconstructed soil profile after several passes.

A total of eight passes were used to collect various power and capacity data. Hydraulic system pressure and auger speed data were collected on five final passes by using a video camera to record the digital pressure and speed indicators located within the operator’s station on the bulldozer. More passes were video taped, but sunlight reflected on the indicators hindering the camera's ability to clearly record readings. The auger speed was set at approximately 130 rpm before starting a pass. Minor speed adjustments were made during soil reconstruction to help form uniform berms.

For comparison, soil bulk density and strength measurements were collected from both soil reconstructed by the soil regenerator and the conventional reconstruction techniques employed at the Grand Eagle Mine. An area recently reclaimed by Grand Eagle, adjacent to the test area, was selected for comparison. The Grand Eagle mine utilizes a shovel/truck mine operation. Rock trucks dump soil on top of graded spoil leaving piles of soil and then wide track bulldozers (for low ground pressure) grade the soil to approximate contour. Prime farmland areas receive additional topsoil by allowing the trucks to drive only on specified paths to minimize trafficking of subsoil and using wide track dozers to spread and grade the surface soil.

A hand soil cone penetrometer with a 12.7 mm (firm soil) diameter cone tip was used to measure penetrometer resistance on Grand Eagle's reclaimed site. A penetration rate of 30 mm/sec was maintained as outlined in ASAE Standard S313.2 (ASAE, 1997). The maximum reading was recorded over depth intervals of 0 to 15.2 cm, 15.2 to 30.5 cm, and 30.5 to 45.7 cm at five different random locations.

Three soil cores were extracted from vertical increments of 0 to 15 cm, 15 to 31 cm, 31 to 46 cm, and 46 to 70 cm at each location of penetrometer measurements on Grand Eagle's reclaimed site. A soil-sampling probe, 1.91 cm diameter, was used to extract 15 cm long samples. Extracted cores were placed in plastic bags, sealed and labeled to coincide with penetrometer readings. The samples were weighed, dried (at 105º C), and then reweighed to calculate dry bulk density (DBD) and moisture content. A total of 15 cone penetrometer readings (three depths at each of the five locations) and 60 soil cores (five locations, three corings at each site, and four depth ranges) were collected.

For soil reconstructed using the soil regenerator, bulk density and hand penetrometer measurements were also made on three newly constructed berms. After berm completion, nine random penetrometer measurements were collected using the 19.1 mm cone tip. Bulk density was determined from soil cores collected at five random locations along each berm. A 1.33 cm diameter probe was used to collect density cores. Three cores were collected at depths of 25, 51 and 76 cm. Cores were collected horizontally on the side of each berm to maintain a constant depth with each sample placed in a sealed bag and labeled according to location and depth. Overall, 135 density samples and 81 cone penetrometer readings were collected for analysis.

The same weighing and drying procedure was used to compute dry bulk density and soil moisture content.

Results and Discussion

Field testing indicated that controlling the soil regenerator was cumbersome at times. The addition of the auger system generated two more tasks for the operator, varying auger speed and height, in addition to basic bulldozer operation. The soil regenerator was operated at a continuous slow pace to properly displace soil, with various adjustments needed during operation to facilitate the formation of a consistent berm. Non-uniformity of the windrows occurred since it was difficult to control the depth and width of placement. This situation produced excessive or inadequate amounts of soil at the blade. The penetration of the blade into the base material also caused problems if one side of the blade started to cut deeper than the other. There was no blade tilt function on the bulldozer, since this system was re-routed for control of the auger height. These problems were addressed by making adjustments to one or more of the following machine control settings: blade height, position of the bulldozer relative to the windrow, ground speed, or auger speed.

As soil accumulated in front of the blade and slowed the bulldozer, the blade was raised to increase speed. Lowering the blade pushed more soil, which could stall the bulldozer by creating too much pushing force. Increasing engine speed provided more power to the tracks and helped at times, but sometimes caused an undesirable increase in ground speed. Driving too fast did not provide enough time for soil to reach the end of the auger and fill the berm evenly. A berm depression developed when the auger did not convey enough soil. Any height adjustment of the blade required an opposite modification in auger height to maintain a uniform berm depth.

Changing the bulldozer heading increased or decreased the size of the fill zone to offset non-uniformity in the windrow. If a depression started to develop in the berm, the bulldozer was steered into the berm to reduce the size of the fill zone and keep the surface of the berm level. Conversely, too much soil transported to the fill zone created a mound at the end of the auger. Backing up usually provided the best approach to steer the dozer since it was difficult to turn when pushing a blade full of soil.

Windrows deeper than 30.5 cm only created problems for the bulldozer since it tried to deviate from its intended path and, at times, the magnitude of the soil being pushed caused the tracks to slip and stop forward progress. Therefore, 30.5 cm was chosen as the nominal depth to conduct testing. A speed of 130 rpm appeared to be the optimal speed for auger operation with much higher speed causing material to be thrown forward instead of conveying it to the fill zone.

Modifications of the regenerator could increase the rate of soil reconstruction compared to that described above. First, instead of being mounted perpendicular to the bulldozer axis of symmetry or direction of travel, the blade could be remounted at a small angle such that the forward motion of the bulldozer blade would displace soil laterally. Thus, the capacity of the auger would be more fully utilized in displacing and leveling soil beyond the end of the blade. Secondly, a hinged extension could be added to the right side of the blade whereby the effective width of the blade could be adjusted by extending or retracting a hydraulic cylinder. This would allow an operator to more easily control the flow of soil into the soil berm fill zone without leaving cavities or mounds on the surface when the volume of soil being displaced varies. Finally, mechanical stops could be inserted into the cylinders that lift the bulldozer blade to prevent the blade from tilting or being positioned below the bottom of the tracks. This would free the operator to control the height of the auger and the effective width of the blade.

Fig. 9 presents the power measured on passes 1, 4, 6, and 8. As observed by Fulton et al. (2002), the power varied during soil conveyance and placement by the auger. The power ranged between 5.1 to 55.4 kW with an overall average of 18.6 kW. Many of the low values corresponded to backing up to change the bulldozer's heading. Thus, the machine disengaged from the soil and the auger had no resistance. The lowest values tended to fall on a straight line representing auger power at no load. This occurred at about 7.0 kW and 3.3 MPa, but depended on the auger speed. Disregarding these lower numbers showed that a high percentage of the time the auger required between 15 to 35 kW. Passes 6 and 8 produced the highest values of measured power. The higher soil moisture content of 21% for these two passes can explain the elevated power requirements.

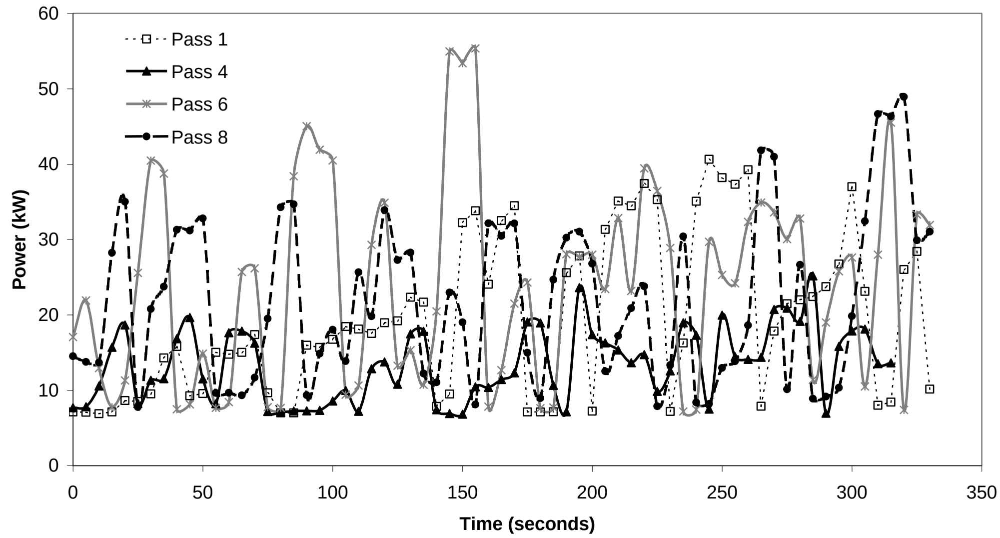

Figure 9. Auger power versus reconstruction time collected for several passes.

Fig. 10, along with Table 1 presents the average auger power measured over five runs. Table 1 also includes the soil moisture content for each berm. As expected, the moisture content increased during the testing period since testing occurred late in the fall. Looking only at passes 4, 5, 6 and 8 indicated that required auger power increased as moisture content increased because soil weight increased. However, pass 1 occurred at the lowest moisture content while producing a higher power requirement than Passes 4 and 5. This higher power was caused by a higher volume of soil displaced during Pass 1, than for Passes 4 and 5.

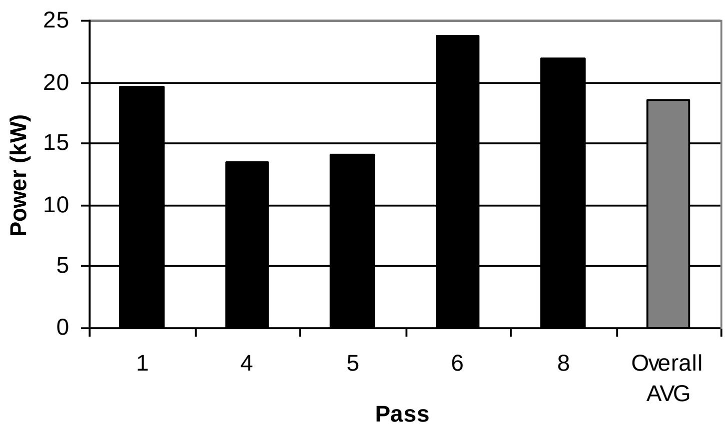

Figure 10. Average power and overall average for Passes 1, 4, 5, 6 and 8.

Table 1. Calculated data for several passes.

Pass	Soil Moisture (%)	Power (kW)	Finishing Capacity (m^3/hr)	Power/Capacity (kW·hr/m^3)
1	18.2	19.6	803.6	0.0244
2	18.2		680.2	
3	19.6		674.2	
4	19.3	13.4	582.4	0.0230
5	19.3	14.2		
6	20.9	23.8	516.8	0.0460
7	20.2		489.6	
8	20.5	21.9	527.5	0.0416
	AVG	18.6	610.6	

Measured power never nears the maximum design output power (74.5 kW) of the hydrostatic system during any of the passes. Only a few measurements were greater than 40 kW. Therefore, the drive system provided sufficient auger power during soil reconstruction. If the system is used to displace highly consolidated soil, then available auger power may be exceeded.

Table 1 also presents a measurement defined as finishing capacity. This term is used because the original design envisioned constructing a soil berm with a single pass of the soil regenerator. However, the soil regenerator required two or more passes to construct a berm at the designed depth. Thus, finishing capacity represented the formation rate of soil berms during a final finishing pass. Table 1 presents the finishing capacity measurements for seven of the eight passes. These results showed that the finishing capacity of the machine decreased as soil moisture content increased. A linear regression was performed and plotted in Fig. 11 along with the measured finishing capacities. Although some scatter exists, the data has a linear trend. The linear model seemed to describe the relationship with a R^2 value of 0.75 and standard error of 62.7. This relationship would be expected since as soil moisture content increased, soil became heavier and more difficult to convey. Fig. 12 illustrates such a conclusion by displaying a linear trend of power versus moisture content when normalized by finishing capacity. These data were collected in four passes and are shown in Table 1.

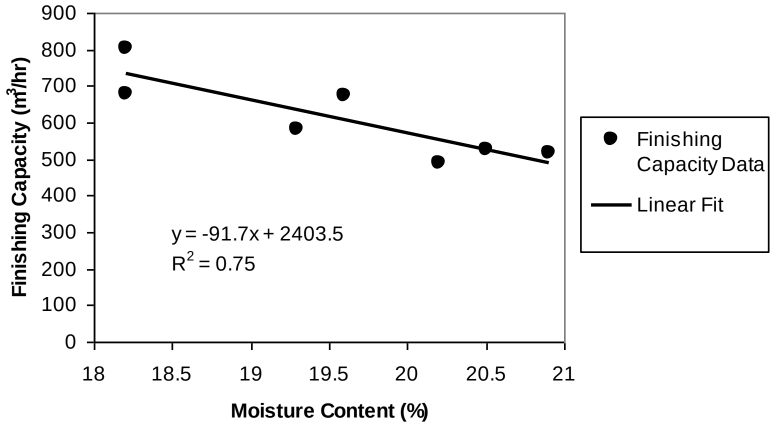

Figure 11. Finishing capacity versus moisture content.

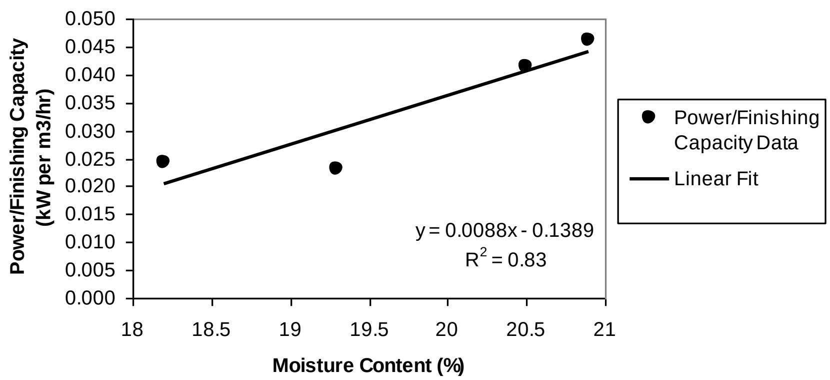

Figure 12. Power/finishing capacity versus moisture content.

Soil reconstruction rates measured at approximately 18% moisture content produced the best constructed berms. Around 18% moisture content, the machine was easier to operate and maneuver. Thus, a more uniform, level soil profile resulted with the least number of depressions and mounds. As the soil moisture content increased, soil was more difficult to convey and move around, not permitting timely adjustments to facilitate uniform placement. Many times a change was desired, but high moisture soil delayed proper adjustment. For example, a direction change for the dozer was desired to reduce the fill zone size, but due to the amount of material being pushed, the dozer would not turn. Therefore, the machine moved past the point where the necessary adjustment was desired causing a non-uniform section of berm. Based on these findings, the prototype should be used during the late spring, summer, and early fall months to achieve maximum output and produce the best results.

Table 2 presents the average moisture content for each berm. Predominantly, the soil moisture contents were consistent for all three berms ranging between 20 and 21 percent. Table 3 presents the mean DBDs for each depth and berm combination plus an overall mean for each berm and depth. At first glance, one notices that the results are impressive with a high percentage of the means less than 1.00 Mg/m^3. This is much less than typical DBD on agricultural soils, which range between 1.2 and 1.8 Mg/m^3 in the rooting zone. The overall mean of the samples taken at the 25 cm depth (0.66 Mg/m^3) was the lowest while the mean of those taken at the 76 cm depth (0.94 Mg/m^3) were highest. The increase in DBD with depth was expected due to the accumulative increase with depth of static soil weight. Mean DBD at a given depth differed only 0.15 Mg/m^3 between berms. The data clearly revealed that the prototype eliminates soil compaction associated with surface mine reclamation; both at the surface and lower in the profile. Thus, amelioration using tillage would not be required for a soil medium with these physical characeristics.

Table 2. Average moisture content for each berm.

Berm	AVG MC (%)
1	20.9
2	20.2
3	20.5

The procedure PROC MIXED within SAS (1998) was used to analyze the variance of DBD measured in the three berms reconstructed by the ‘Soil Regenerator.’ The analysis was performed at the 0.05 level for comparison of berms and depths along with determining the existence of potential interaction between berms and depths. The discussion of the SAS results follows.

Table 3 contains the resulting statistical analysis to comparing the overall DBD means for each berm and then comparing the overall depth means. These results showed that a statistical difference existed between each depth and that DBD increased with depth. Fig. 13 illustrates this by showing a linear relationship between DBD and depth. Again, the increase in DBD with depth was expected due the increase of static weight with depth. Extrapolations would predict a bulk density of 1.08 Mg/m^3 at the base of a 102 cm deep berm constructed by the soil regenerator. Even at this depth, the DBD density was well below the magnitude associated with potential compaction problems. Since the DBD was lowest at 25 cm, it can be concluded that the auger applies only minimal vertical force on the soil during placement. Many operations, such as grading with a bulldozer, compact soil most near the surface. High bulk density at the surface effects crop growth by impeding root elongation but might not hinder seedling establishment.

Table 3. Mean DBD for each berm and depth combination along with the overall means.

	---------------- Berm ---------------			
Depth (cm)	**1***	**2**	**3**	**Mean**
25.4	0.600	0.646	0.741	0.662 c[1]
50.8	0.724	0.828	0.897	0.817 b
76.2	0.900	0.854	1.051	0.935 a
Mean	0.742 b[1]	0.776ab	0.896a	

*All DBD measurements in Mg/m^3.

1. Means with similar letters are not statistically different at the 95% confidence level.

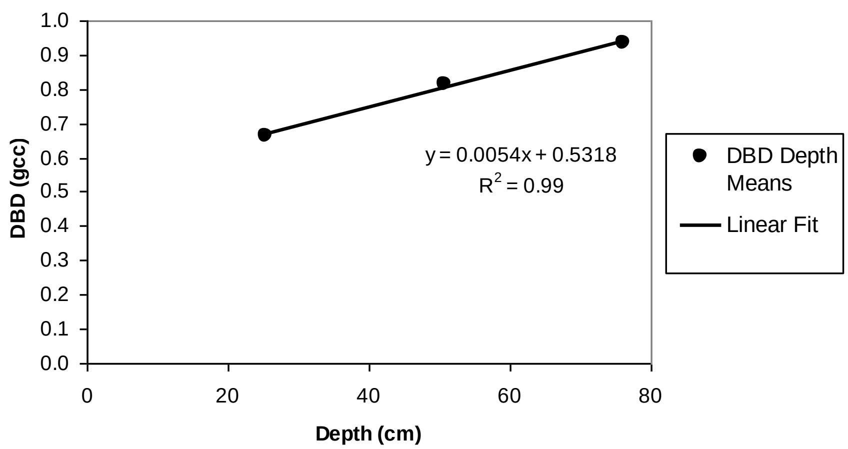

Figure 13. Mean DBD versus depth for all three berms.

Comparing berms showed that a statistical difference only exists between Berm 1 and Berm 3. The berms represented, respectively, Passes 6, 7 and 8 in Table 1. The process used to form each berm did not differ. Soil was moved from the stockpiled embankment to form a windrow, with the machine processing this soil. Differences in soil moisture content do not explain the difference since Berms 1 and 3 were formed at nearly the same moisture content (Table 2).

Including moisture content as a factor in the statistical model verified this finding, as there was no significant difference in soil bulk density due to moisture content.

The resulting analysis indicates that duplicating berm construction is difficult. Table 4 shows that significant differences between Berm 1 and 3 occur at the 51 cm depth. It is likely that the initial state of soil in the windrows used to construct these berms explains the difference in bulk density. Berm 1 was constructed from soil that had been previously processed by the soil regenerator. Berm 3 was constructed from soil excavated from the stockpile. Berm 2 was constructed using a combination of both. Therefore, it is reasonable that Berm 1 had the lowest bulk densities measured. Other natural factors such as the variability in soil type and the physical state of the stockpiled soil could contribute to the observed differences.

Table 4. Statistical comparison of DBD measured at the same depth in different berms.

	--------------------- Berm --------------------		
Depth (cm)	**1***	**2**	**3**
25.4	0.600 a[1]	0.646 a	0.741 a
50.8	0.724 b	0.828 ab	0.897 a
76.2	0.900 ab	0.854 b	1.051 a

*All DBD measurements in Mg/m^3.
1. Means with similar letters in each row are not statistically different at the 95% confidence level.

The effect of depth within each berm is presented in the columns of Table 5. The results for berms 1 and 3 indicate the same effect of depth shown for the overall means in Table 3. Although the results for 51 and 76 cm are not significantly different in Berm 2, bulk density increases with depth as in Berms 1 and 3.

Table 5. Statistical comparison of DBD measures at different depths within each berm.

	--------------------------- Berm ---------------------------		
Depth (cm)	**1***	**2**	**3**
25.4	0.600 c[1]	0.646 b	0.741 c
50.8	0.724 b	0.828 a	0.897 b
76.2	0.900 a	0.854 a	1.051 a

*All DBD measurements in Mg/m^3.

1. Means with similar letters in each column are not statistically different at the 95% confidence level.

The cone penetrometer measurements affirmed the same conclusion indicated by the DBD measurements. The analog scale on the hand penetrometer was partitioned at 0.7, 1.4, and 2.1 MPa. Anything below 0.7 MPa was considered uncompacted, 0.7 to 1.4 MPa acceptable compaction, 1.4 to 2.1 MPa possible detrimental compaction, and above 2.1 MPa probable detrimental compaction. The measured values were all less than 0.7 MPa with a high percentage being less than 0.3 MPa. Table 6 provides a summary of the mean penetrometer measurements within the three depth ranges. A few times, the needle barely moved until reaching the 31 cm depth. Again, this data revealed the looseness of the constructed soil medium. This soil state should provide a good medium for row crop growth.

Table 6. Average penetrometer measurements for the berm and mine sites.

	--------- Penetrometer Reading (MPa) ---------	
Depth (cm)	**Berm**	**Mine**
0.0 – 15.2	0.02	2.1+
15.2 – 30.5	0.08	2.1+
30.5 – 45.7	0.20	2.1+
AVG	0.10	2.1+

Average dry bulk density and moisture contents for soil reconstructed using conventional methods by Grand Eagle are presented in Table 7 along with the overall DBD and moisture content averages. All the DBD values exceeded 1.5 Mg/m^3, which was much greater than those associated with the soil regenerator. The DBD for the top 15 cm suggest that that surface layer becomes more compacted during the reclamation process due to multiple passes by bulldozers during grading. Visual observations of the reclamation process employed by Grand Eagle indicated some areas received two to three passes by a bulldozer during final grading. Occasionally additional passes were required to fill in low areas or remove excess soil from high areas. Fig. 14 illustrates the variance of DBD with reconstructed soil depth. The DBD at the lower depths tends to reach a maximum level of 1.54 to 1.58 Mg/m^3. These DBD measurements are lower than expected, but tend to approach the upper limit for acceptable values in agricultural soils. Crop yields would probably be reduced around the 1.55 Mg/m^3 level.

Table 7. Average DBD and moisture content collected from conventionally reconstructed soil at the Grand Eagle mine.

	-------------------- Mine Data --------------------	
Depth (cm)	**AVG DBD (kg/m^3)**	**AVG MC (%)**
0 - 15.2	1.71	14.7
15.2 - 30.5	1.54	16.6
30.5 - 45.7	1.58	17.2
45.7 - 61.0	1.54	17.4
AVG	1.59	16.5

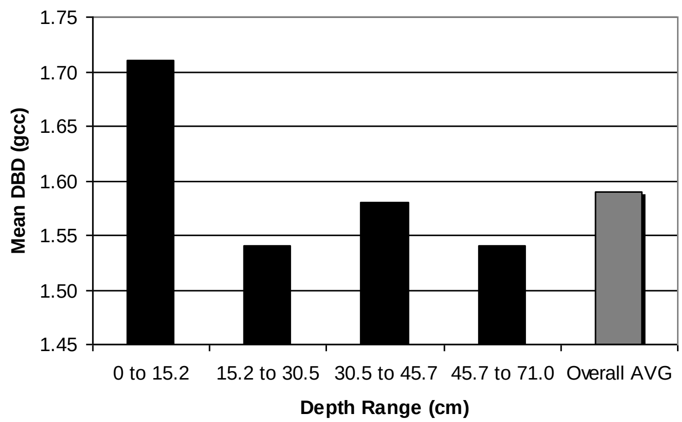

Figure 14. Mean DBD for all four-depth ranges plus overall average for conventionally reconstructed soil at the Grand Eagle mine.

Hand penetrometer measurements collected on the conventional reclaimed site exceeded 2.1 MPa at all fifteen locations; much higher than those collected on the berms formed by the prototype machine where an overall average of 0.1 MPa was computed (Table 6). Due to difficulty in reading the cone penetrometer, maximum readings were difficult to determine, except to note when the reading exceeded 2.1 MPa, the penetration resistance was associated with compaction problems. Though bulk density measured below 25 cm did not conclusively indicate excessive soil compaction, the consistently high penetrometer readings would indicate such. These data suggest that some type of physical amelioration to improve the physical condition is needed.

The soil moisture contents on the reclaimed mine area increased with depth as shown in Table 7. Although rain occurred at the site approximately a week prior to sampling, the moisture contents in Table 7 are less than field capacity. Thus, it is possible that the CI values > 2.1 MPa might not indicate root limiting soil compaction. Some of the difference between CI measured in the conventionally reconstructed soil versus that reconstructed by the ‘soil regenerator’ must be attributed to higher moisture content in the conventionally reconstructed soil. However, the CI measurements show potentially detrimental compaction at all depths within the conventionally reconstructed soil, even though measured dry bulk density appears high only in the top 15.2 cm.

SAS (SAS, 1998) was used to statistically compare DBD and soil penetrometer measurements for the two different reclamation processes. Density core samples collected from the berms reconstructed by the regenerator were taken horizontally at specified depths, whereas samples taken from the conventionally reconstructed soil were taken vertically in depth intervals of 15 cm. Thus, DBD for the 25 and 51 cm depths from the regenerator berms were compared to DBD measured for the 15 to 31 cm and 46 to 61 cm at the conventional site, respectively (Table 8). These ranges contain the 15 and 31 cm depths and should provide a good estimate for the bulk density at these depths. Data from each berm was compared to the conventional data and as expected, the overall average of all three berms along with depth comparisons was significantly different from the conventional reclaimed soil at the 0.05 level for the DBD data. Similarly, the penetrometer measurements from the three berms, at each of the three depths, were significantly different at the 0.05 level from the conventional mine data. These results supported the conclusion that the soil regenerator produced a soil that was uncompacted and should provide a better physical environment for crop growth than current surface mine reclamation processes. However, further research is required to understand how such loose soil will settle and stabilize over time and react to normal cropping practices.

In terms of operation, the soil regenerator was capable of forming an uncompacted soil profile. The machine produced soil with a nominal depth of 0.9 m with good results. Creating a 1.2 m deep berm slows production and makes the system difficult to handle due to the presence of more soil. The scraper placement used by Fulton et al. (2002) during their tests was superior to the method used in this study. The soil reconstructed with the soil regenerator was uncompacted through the entire profile with an overall average bulk density below 1.0 Mg/m^3 and a cone index well under 0.7 MPa.

Table 8. Comparison of mean DBD measured in soil reconstructed by the 'soil regenerator' versus conventionally reconstructed soil.

--------- Soil Regenerator Reconstruction --------- -------- AVG DBD (Mg/m^3) --------				- Conventional Reconstruction -	
Depth (cm)	**Berm 1**	**Berm 2**	**Berm 3**	**Depth (cm)**	**AVG DBD (Mg/m^3)**
25.4	0.60	0.65	0.74	15.2 - 30.5	1.54
50.8	0.72	0.83	0.90	45.7 - 61.0	1.54
AVG	0.66	0.74	0.82	**AVG**	1.54

Conclusion

The 'Soil Regenerator' proved to be a beneficial mechanism for reconstructing prime farmland soils. Retrofitting a bulldozer with this prototype structure showed potential for providing surface mine companies with a mechanism to reclaim the top layers of soil without adverse soil compaction. Field-testing proved the auger system functioned as intended except for lower than projected reconstruction capacity. A range in capacity from 490 m^3/hr to 804 m^3/hr, was measured for the machine which was less than the projected 2680 m^3/hr capacity. A trend was observed illustrating that the capacity of the machine decreased as soil moisture content increased primarily caused by the increased soil weight thereby reducing the amount of soil the bulldozer could push.

The inconsistency in the soil windrow being processed made it difficult to form level adjacent berms thereby generating depressions and mounds on the surface of the constructed berms. However, the machine was capable of forming a 0.9 m deep soil medium with bulk densities equal to or less than 1.0 Mg/m^3 and penetrometer measurements below 0.7 MPa. Significantly lower dry bulk densities and cone penetrometer resistance characterized soil reconstructed using the soil regenerator versus soil reconstructed using conventional methods at the same site.

Redesign of the soil regenerator could help eliminate or minimize difficulty encountered in constructing level soil surface. The overall performance of the first prototype was deemed successful in that it demonstrated the feasibility of reconstructing soil without detrimental compaction by equipment traffic. The reduction in compaction by the soil regenerator should be more suitable for crop growth allowing mining companies to reconstruct land in accordance with federal and state laws. However, future work is needed to study the resultant soil medium in terms of how its settles and develops overtime and the applicability of the regenerator to fit economically into current reclamation methods.

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