Evaluation of a Mechanical System for Reconstructing Soil on Surface Mined Land

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EVALUATION OF A MECHANICAL SYSTEM FOR RECONSTRUCTING SOIL ON SURFACE MINED LAND

J. P. Fulton, L. G. Wells

ABSTRACT. The existence of excessive soil compaction has hindered the surface mining industry from returning land to pre-mining productivity after reclamation, especially on prime farmland soils. Heavy earthmoving equipment used during reclamation tends to generate root-limiting bulk densities that adversely affect plant growth thereby decreasing yields. Therefore, the purpose of this study was to evaluate a mechanism, called the ‘Soil Regenerator,’ which reconstructs soil media at minimum bulk density during surface mine reclamation. The prototype soil forming mechanism was mounted on the front of a conventional bulldozer. Soil was placed in long narrow windrows by a scraper or bulldozer. As the bulldozer pushed into the windrow, soil rose up the blade and was agitated, transported, and deposited by a helicoid auger in a 0.9−m deep berm adjacent to the bulldozer. The capacity of the prototype ranged from 490 to 804 m³/h while producing bulk densities ≤1.0 Mg/m³ and penetrometer measurements below 0.7 MPa. These measurements demonstrated the capability of the ‘Soil Regenerator’ to eliminate soil compaction on reclaimed surface mined land and to reconstruct soil more suitable for crop growth.

Keywords. Excavating equipment, Reclamation, Reclaimed land, Soil handling system, Soil profile, Bulk density.

Over the years, surface mining has been employed to extract valuable ores and minerals from the earth. In particular, surface mining disturbs and removes the topmost surface layers of the earth to expose seam(s) of minerals or ores, such as coal. Once the seam(s) are extracted, the land should then be reclaimed, or returned to its original pre-mining status, as dictated by federal and state regulations. However, the existence of soil compaction produced during soil replacement due to heavy excavation equipment hinders coal companies from restoring prime farmland to pre-mining productivity.

For Kentucky, the major regulations that govern prime farmland reclamation 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 overview the controls on the coal industry with regard to permitting and performance standards for surface coal mining and reclamation especially on land labeled as prime farmland. The purpose of the regulations was to ensure that surface mined land is reclaimed adequately by setting standard guidelines and regulatory procedures.

Several important aspects exist within these regulations pertaining to prime farmland. First, the A− and B−horizons must be segregated and stored separately upon removal. Secondly, these horizons must be replaced during reclamation to develop a uniform depth of 1.22 m of rooting zone with 0.30 m of topsoil over 0.91 m of subsoil. Thirdly, overburden material 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. Therefore, crop production studies must follow soil replacement and target yields met within a specified time frame for surety bond (required before mining as a deposit for ensuring reclamation of the mining site) release. However, the primary factor inhibiting successful reclamation is excessive compaction within the rooting zone occurring during soil reconstruction.

The impact of soil compaction on agricultural soils has been studied and documented over the years. Farmers, foresters, and others who cultivate the land have found soil compaction to be a cumbersome problem. As with many problems, it can have a wide range of influence on plants. Plants may be influenced minimally, causing a slight decrease in growth and yield, or compaction can totally impede crop growth by limiting seedling emergence resulting in little or no yield. 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 solely to heavy excavation equipment used during the reconstruction process. Earthmoving equipment applies large surface pressure, which results in increased soil density (Dollhopf and Postle, 1988). These vehicles are heavy owing to their payload capacity and final grading capability thereby
transmitting extremely high loads to the soil via their running gear.

Dunker et al. (1991) noted that the most severe and limiting factor in the reclamation of prime farmland was poor soil physical conditions retarding plant growth. These poor physical properties result from inversion and mixing of soil during transportation and replacement, which changes the texture, structure, fertility, and chemical/biological composition. The consequence is the disruption of a favorable root zone, which creates a major effect on soil productivity (Doll, 1988).

The adverse effects of soil compaction on crop growth have been recognized for years. Bulk density and soil strength are two physical properties, which quantify soil compaction. Thompson et al. (1987) concluded that both bulk density and soil strength correlated well with root length density or effective rooting depth, especially in deep soil. As bulk density and soil strength increase, porosity decreases since the soil particles move closer together, eliminating pore space. No general accepted 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) $\geq$ 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. Surface mine reclamation processes drastically change soil physical properties and cause bulk densities considerably greater than in natural soils (Bauer et al., 1976).

Soil strength can be a better predictor of detrimental 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 Gardner, 1963; Taylor and Burnett, 1964). Vance et al. (1992) showed that penetrometer data correlated well with corn and soybean yields on reconstructed soils with the lowest yields observed in reclamation treatments with the highest soil strength.

Penetrometer resistance limiting root growth depends upon the soil conditions and characteristics and the crop of interest. Ehlers et al. (1983) stated that the penetrometer resistance limiting growth of oats was 3.6 MPa in tilled Ap–horizon, but 4.6 to 5.1 MPa in untilled Ap–horizon and subsoil. Ayers and Perumpral (1982) pointed out that dry density had a considerable influence on cone index 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 penetrometer resistance 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. A maximum root growth index for citrus is 1.5 MPa (Lutz et al., 1986). Taylor et al. (1964) found that cotton roots are unable to penetrate soil strengths above 3.0 MPa in an Amarillo fine sandy loam. Murdock et al. (1995) suggested a penetrometer reading $\geq$ 2.1 MPa as indicative of severe compaction for Kentucky soils. The literature suggests that penetrometer values measured with a 13–mm, 30° 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% 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% reduction in yields on mined soils. These results illustrate the potential for compaction to depress crop yields.

Fulton et al. (2002) introduced a mechanical mechanism for reconstructing rooting media on surface mined land. The intent of this mechanism was to aid in reconstructing both the topsoil and subsoil profiles without introducing surface traffic thereby eliminating the potential for soil compaction which most frequently inhibits post mining crop productivity. In return, surface mine companies could restore land back to pre-mining levels and meet the reclamation standards set by federal and state regulations in order to collect surety bonds. Therefore, the goal of this research was to evaluate the ability of the ‘Soil Regenerator’ to reconstruct soil without introducing surface traffic and producing detrimental soil compaction for post–mining crop growth. More specifically, the objectives of this article were to 1) test and evaluate the performance of the prototype system with respect to operational capacity (m$^3$/h) and efficacy of operation, 2) experimentally evaluate the physical condition, soil density and strength, of the resultant reconstructed soil, and 3) identify potential improvements for the prototype system.

**MATERIALS AND METHODS**

**SITE OVERVIEW**

Evaluation of the Soil Regenerator occurred between October and December of 1998 at the Grand Eagle surface mine, owned by the Patriot Coal Company (Henderson County, Ky.). A 2.0–ha site was provided for testing which was classified as nonprime farmland for testing the prototype system. The area was relatively level with overburden
material already brought to desired grade. They required a minimum depth of 1.2 m for soil replacement 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 their 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 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 (Fulton et al., 2002), this procedure provided the best testing methodology. Figure 1 shows the prepared testing site.

**Performance Measurements**

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 \( \times \) 0.6 m deep (fig. 2). After placing enough material in the windrow, a final pass was made to construct a 0.9–m deep berm (fig. 3). 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.

Successive passes of the machine produced a relatively uniform reconstructed soil medium (fig. 4). Several tests were conducted over the weeks to collect power, hydraulic system pressure, and capacity measurements. The capacity of the soil regenerator was determined by collecting random width and depth measurements along the final constructed berm over a measured distance. Time to complete each berm was recorded using a stopwatch. From these measurements, the finishing capacity could be computed.

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. The auger speed was set at approximately 130 rpm before starting a pass. Minor speed adjustments were made during berm construction.

**Physical Measurements of Reconstructed Soil**

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 back dump soil on top of graded spoil and then utilize wide track bulldozers...
grade the soil to desired 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 final 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 the conventional reclaimed site. A penetration rate of 30 mm/s was maintained as outlined in ASAE Standard S313.2 (ASAE Standards, 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. Additionally, three soil cores were extracted at 15−cm vertical increments at each location of penetrometer measurements, producing four DBD ranges of 0 to 15 cm, 15 to 31 cm, 31 to 46 cm, and 46 to 70 cm. 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 numbered to coincide with the penetrometer readings. These were taken back to the lab to be weighed, dried (at 105°C), and then reweighed to calculate DBD and moisture content (MC).

For soil constructed by the soil regenerator, bulk density and hand penetrometer measurements were also made on three newly constructed 46−m berms. After completing each berm, nine random penetrometer measurements were collected using the 19.1−mm cone tip just as on the reclaimed mine area. Dry bulk density was determined from soil cores gathered at five random locations along each berm. A 1.33−cm diameter probe was fabricated to collect density cores since the smaller diameter probe did not work well in loose soil. 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. Each core was placed in an individual sealed bag and marked to represent location and depth. The same weighing and drying procedure was used to determine soil DBD and MC.

RESULTS AND DISCUSSION

POWER AND PERFORMANCE

Figure 5 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 requires 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 (table 2). At an approximate moisture content of 18%, the machine was easier to operate and steer. Therefore, a more uniform, level soil resulted with the least number of depressions and mounds. As the soil moisture content increased, soil was harder to convey and move around, not permitting timely adjustments to facilitate uniform placement. Based on these findings, the prototype should be used during the late spring, summer, and early fall months to achieve maximum output and best results.

Table 1 presents the average auger power measured over five runs. Table 2 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. Examining only 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.
Measured power never approached 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 shows the capacity measurements for seven 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 figure 6 along with measured finishing capacities. Although some scatter was observed, the data showed 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 it became heavier and more difficult to convey. Figure 7 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 (table 1).

<table>
<thead>
<tr>
<th>Pass</th>
<th>Soil Moisture (%)</th>
<th>Power (kW)</th>
<th>Finishing Capacity (m³/h)</th>
<th>Power/Capacity (kW·h/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.2</td>
<td>19.6</td>
<td>803.6</td>
<td>0.0244</td>
</tr>
<tr>
<td>2</td>
<td>18.2</td>
<td>680.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>19.6</td>
<td>674.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>19.3</td>
<td>13.4</td>
<td>582.4</td>
<td>0.0230</td>
</tr>
<tr>
<td>5</td>
<td>19.3</td>
<td>14.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>20.9</td>
<td>23.8</td>
<td>516.8</td>
<td>0.0460</td>
</tr>
<tr>
<td>7</td>
<td>20.2</td>
<td>489.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>20.5</td>
<td>21.9</td>
<td>527.5</td>
<td>0.0416</td>
</tr>
<tr>
<td>Avg.</td>
<td>18.6</td>
<td>610.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Average moisture content for each of the three berms.

<table>
<thead>
<tr>
<th>Berm</th>
<th>Avg. MC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.9</td>
</tr>
<tr>
<td>2</td>
<td>20.2</td>
</tr>
<tr>
<td>3</td>
<td>20.5</td>
</tr>
</tbody>
</table>

**RESULTANT PHYSICAL PROPERTIES**

Table 3 presents 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/m³. This is much less than typical DBD on agricultural soils, which range between 1.2 and 1.8 Mg/m³ in the rooting zone.

$$y = -91.7x + 2403.5$$  
$R^2 = 0.75$

![Figure 6](image-url)

**Figure 6.** Finishing capacity vs. moisture content with linear regression results.

$$y = 0.0088x - 0.1389$$  
$R^2 = 0.83$

![Figure 7](image-url)

**Figure 7.** Power/finishing capacity vs. moisture content with linear regression results.
Table 3. Mean DBD for each berm and depth combination along with the overall means for berms and depths.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Berm 1</th>
<th>Berm 2</th>
<th>Berm 3</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.4</td>
<td>0.600</td>
<td>0.646</td>
<td>0.741</td>
<td>0.662</td>
</tr>
<tr>
<td>50.8</td>
<td>0.724</td>
<td>0.828</td>
<td>0.897</td>
<td>0.817</td>
</tr>
<tr>
<td>76.2</td>
<td>0.900</td>
<td>0.854</td>
<td>1.051</td>
<td>0.935</td>
</tr>
<tr>
<td>Mean</td>
<td>0.742</td>
<td>0.776</td>
<td>0.896</td>
<td>0.816</td>
</tr>
</tbody>
</table>

[a] All DBD measurements in Mg/m³.
[b] Means with similar letters are not statistically different at the 95% confidence level.

The overall mean of the samples taken at the 25−cm (0.66−Mg/m³) depth was the lowest while the mean of those taken at the 76−cm (0.94−Mg/m³) depth were highest. The increase in DBD with depth was expected due to the accumulative increase in depth of the static weight of soil. Even through this compressive settling, the differences are rather small between depths with less than 0.30 Mg/m³ separating them. The same is true for the differences in the berm means with only 0.15 Mg/m³ separating the maximum and minimum. The data clearly revealed that the prototype eliminated soil compaction associated with surface mine reclamation; both at the surface and lower in the profile. Amelioration by tillage would therefore not be required.

Statistical Analysis Software (SAS, 1998) was used to assess the variance of bulk density measured in the berms reconstructed by the soil regenerator. The PROC MIXED data analysis tool within SAS was used to compare berms and depths and then divide these into berm/depth combinations for interaction comparisons. All statistical analysis was performed at the 95% confidence level.

Table 3 contains the resulting statistical analysis 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. Figure 8 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/m³ 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 soil 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 affects plant growth by impeding root elongation.

Comparing berms showed that a statistical difference only exists between Berms 1 and 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 tends to indicate that it is hard to duplicate berm construction. Table 4 showed that significant differences between Berms 1 and 3 occurred 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 have contributed to these observed differences.

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 indicating probable detrimental compaction. The measured values were all less than 0.7 MPa with a high percentage being less than 0.3 MPa. Table 5 provides a summary of the penetrometer measurements 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 4. Statistical comparison of DBD measured at the same depth in different berms.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Berm 1[a]</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.4</td>
<td>0.600 a[b]</td>
<td>0.646 a</td>
<td>0.741 a</td>
</tr>
<tr>
<td>50.8</td>
<td>0.724 b</td>
<td>0.828 ab</td>
<td>0.897 a</td>
</tr>
<tr>
<td>76.2</td>
<td>0.900 ab</td>
<td>0.854 b</td>
<td>1.051 a</td>
</tr>
</tbody>
</table>

[a] All DBD measurements in Mg/m³.
[b] Means with similar letters in each row are not statistically different at the 95% confidence level.

Table 5. Average cone index for the berm and mine sites.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Berm</th>
<th>Mine</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 – 15.2</td>
<td>0.02</td>
<td>2.1+</td>
</tr>
<tr>
<td>15.2 – 30.5</td>
<td>0.08</td>
<td>2.1+</td>
</tr>
<tr>
<td>30.5 – 45.7</td>
<td>0.20</td>
<td>2.1+</td>
</tr>
<tr>
<td>Avg.</td>
<td>0.10</td>
<td>2.1+</td>
</tr>
</tbody>
</table>

Average dry bulk density and moisture contents for soil reconstructed using conventional methods by Grand Eagle are presented in table 6 along with the overall DBD and moisture content averages. All the DBD values exceeded 1.5 Mg/m³, 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. The DBD at the lower depths tends to reach a maximum level of 1.54 to 1.58 Mg/m³. These bulk density measurements are lower than expected, but tend to approach the upper limit for acceptable values in agricultural soils. Crop yields would probably be reduced at DBD values of a maximum level of 1.54 to 1.58 Mg/m³. Visual observations of the reclamation method used at the Grand Eagle mine indicated that some areas could receive two to three passes by a bulldozer during final grading. At times, more passes were required to fill in low areas or remove excess soil from high areas.

Hand penetrometer measurements collected on the conventional reclaimed site exceeded 2.1 MPa at all 15 locations; much higher than those collected on the berms formed by the prototype machine were an overall average of 0.1 MPa was computed (table 5). 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. This would indicate that, even though bulk density measured below 25 cm, it did not conclusively indicate excessive soil compaction, the consistently high penetrometer readings would indicate such. This data suggests that some type of physical amelioration to improve the physical condition is needed.

Table 6. Average DBD and moisture content collected from reclaimed mine area.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Avg. DBD (kg/m³)</th>
<th>Avg. MC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 15.2</td>
<td>1.71</td>
<td>14.7</td>
</tr>
<tr>
<td>15.2 – 30.5</td>
<td>1.54</td>
<td>16.6</td>
</tr>
<tr>
<td>30.5 – 45.7</td>
<td>1.58</td>
<td>17.2</td>
</tr>
<tr>
<td>45.7 – 61.0</td>
<td>1.54</td>
<td>17.4</td>
</tr>
<tr>
<td>Avg.</td>
<td>1.59</td>
<td>16.5</td>
</tr>
</tbody>
</table>

The soil moisture contents on the reclaimed mine area increased with depth as shown in table 6. The increase occurred because of a previous rain within the week prior to sampling. The dry period between the rain and when the core samples were collected allowed the soil surface to dry and showed water infiltration through the profile. It should be noted that since the penetrometer data was not collected at field capacity, although highly unlikely, it is possible that values above 2.1 MPa might not be root limiting. The difference in moisture content indicated that the difference could be smaller if penetrometer measurements were taken at field capacity in both soils. Though a difference in moisture content existed, the data still showed a large difference between the two reclamation methods. Overall, the penetrometer readings and calculated DBD values for the mine’s reclaimed area indicate the need for tillage or some other type of amelioration to break up the resulting compaction.

SAS was used to compare DBD and soil penetrometer measurements for the two 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 7). 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 using the data analysis tool PROC MIXED within SAS (SAS, 1998). 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 medium that was uncompacted and should provide a better physical environment for crop growth over the current surface mine reclamation process. However, future research is required to study how such a loose soil medium will settle and stabilize over time and its ability to produce pre–mining crop performance.

Prototype Analysis

In terms of operation, the soil regenerator was capable of forming an uncompacted soil medium. The machine produced a soil medium 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 material. The scraper placement used by Fulton et al. (2002) during their tests definitely provided the best method for constructing windrows as long as the scraper does not compact the windrow too much due to multiple passes during soil placement. The resultant soil medium could definitely be described as loose through its total profile with an overall average bulk density below 1.0 Mg/m³ and a cone index well under 0.7 MPa.

The largest drawback of the machine was producing a uniform, level berm. Depressions or mounds develop at the end of the auger as the volume of soil being processed fluctuates. The operator can make adjustments in the bulldozer’s heading and speed along with varying the auger speed, but many times it was difficult to foresee a required change. If the operator could steer in and out of the berm while maintaining a constant forward speed, a fairly uniform berm was created with very few depressions and mounds. Most of the time, however, the dozer could not be steered when pushing a full volume of soil in front of the blade. Therefore, forward progress and momentum were stopped and the bulldozer was repositioned by backing up. Several times difficulty was encountered to continue forming a uniform berm since the bulldozer heading was changed.

Occasionally, one side of the blade tended to cut deeper, creating a tilted situation for the auger. Once this occurred, there was no adjustment to counter this circumstance. A tilt cylinder usually allows an operator to maintain a level cut, but this cylinder was removed during fabrication. Therefore, the operator must back up and reposition the bulldozer to compensate for blade angling. Such an adjustment can cause the auger to burrow into the previously constructed berm and create mounds. Raising the auger helped, but this also increased the fill zone causing depressions to develop if the auger was conveying insufficient soil at the time of height change. Reinstallation of the tilt cylinder would help during these situations.

CONCLUSIONS

The soil regenerator proved to be a beneficial mechanism for reconstructing prime farmland soils after the completion of surface mining. The concept of using an auger mounted on the front of a bulldozer showed potential for providing surface mine companies with a machine to reclaim the top layers of soil without generating compaction problems. The designed and fabricated auger system functioned as intended during field-testing except that the measured capacity of the prototype was lower than the projected 2680–m³/h capacity for the machine. The capacity of the machine ranged from 490 up to 803.6 m³/h when placed by dozers at a mine site. Data also showed that capacity of the soil regenerator decreased as soil moisture content increased because as soil weight increased the dozer was able to push less soil.

Forming a level berm was also difficult because depressions and mounds developed as the volume of soil pushed by the machine varied. 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/m³ and penetrometer measurements below 0.7 MPa. Significantly lower dry bulk densities and cone penetrometer resistance characterized soil reconstructed using the soil regenerator than land reconstructed using conventional methods at the same site.

A couple of major drawbacks to the current configuration were identified. First, maintaining a level auger during soil reconstruction was cumbersome at times. Another problem was mounding or depressions occurring at the end of the auger in the newly constructed soil medium. Redesign and refinements of the soil regenerator could help eliminate or minimize these issues and allow such a mechanism to fit into current surface mine reclamation processes and produce acceptable results. The overall performance of the first prototype was judged to be 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.

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