A New Approach to Reducing Soil Thickness in Re-Vegetation Projects of Coal Waste Piles with Spontaneous Combustion: Soil Compaction

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***Abstract*-A huge amount of soil has been used in re-vegetation projects of coal waste piles with spontaneous combustion in China. This paper focused on a new approach to reducing soil thickness in re-vegetation projects based on soil compaction. The effect of soil compaction on soil saving and Festuca arundinacea's growth was researched. The results showed that both soil compaction and reducing soil thickness could reduce the depth of the Festuca arundinacea roots' distribution in the soil, and Festuca arundinacea could significantly increase the total activity of SOD and POD to reduce the damage caused by soil compaction and reduction in soil thickness. At least 55% of the soil will be saved, which meant about 53.2 billion tons of soil and 162 billion dollars would be saved by using this new approach.**

Keywords-Re-vegetation; Soil Compaction; Soil Thickness; Soil Bulk Density; Festuca Arundinacea; Coal Waste Piles; Spontaneous Combustion

I. INTRODUCTION

There are a huge number of coal waste piles with spontaneous combustion which need to be re-vegetated in China. There are more than 1 500 coal waste piles in China [1]. The accumulated stock of coal waste is up to 7 billion tons. More than 30% of coal waste piles are spontaneously combusting [2], which bring a lot of pollution [3]. Because the stock of coal waste will increase by more than 100 million tons per year [1] and utilization of coal waste is less than 30% [4], so the only way to solve the problems brought by coal waste piles with spontaneous combustion is re-vegetation.

However, re-vegetation on coal waste piles with spontaneous combustion is quite different from the other re-vegetation projects. Firstly, there is an alkalinity layer (Fig. 1) in re-vegetation project of the coal waste pile with spontaneous combustion. This alkalinity layer is compacted to inhibit oxygen infiltrating into coal waste piles [3, 5, 6]. This layer should be well protected and roots are not allowed to grow through it. Secondly, this alkalinity layer contains strong alkaline material such as fly ash [5]. The PH is too high for plants to grow in this layer. Thus, soil thickness should be greater than the roots' distribution. As a result, re-vegetation needs great quantities of soil covered on coal waste piles with spontaneous combustion. 23 940 000m^3 new soil will be needed for re-vegetating all the coal waste piles with spontaneous combustion in China. This amount of soil is equivalent to a tow meter deep hollow with an area of 1197 hm^2 [3, 7-9]. It will destroy large areas of land and ecological balance by excavating soil. According to the survey [10], reclamation of coal waste piles with spontaneous combustion costs $69 000 to $115 000 per hm^2, two thirds of which have been used to purchase new soil, transportation and cover. The total investment for the treatment of coal waste piles with spontaneous combustion in China will be from $ 276 000 000 to $460 000 000. Thus, it is important to find a new approach to save soil in the re-vegetation projects.

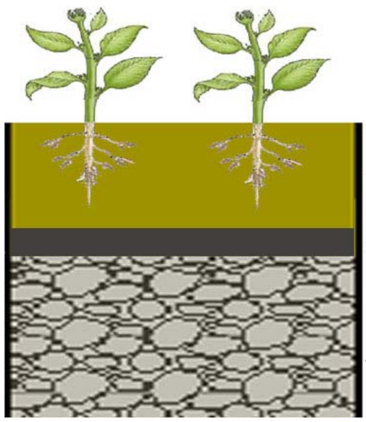

Fig. 1 Sectional view of re-vegetation projects on the coal waste piles

Soil compaction can reduce plant roots' length [11, 12], so the thickness of soil needed for re-vegetation can be reduced. Soil compaction also directs closer contact between root and soil [11]. Furthermore, soil compaction promotes more water and nutrients into the root growth zone, which can improve the absorptive capacity of a single root [11]. Thus, it is possible to use soil compaction to save soil in the projects. But all the researches about soil compaction focused on reducing the impact of soil compaction on plant growth [11, 12].

However, this research focused on reducing soil thickness by proper soil compaction in the projects of coal waste piles with spontaneous combustion. Festuca arundinacea was selected as the test plant. Different levels of soil bulk density and soil thickness were set in the experiment. The effect of soil compaction and reducing soil thickness on Festuca arundinacea was tested to evaluate the most efficient soil bulk density and soil thickness in the re-vegetation projects by soil compaction. 3990000 m^3 of soil will be saved if 10cm of soil thickness is saved. This approach has a huge ecological and economic value, as well as a considerable application prospect in re-vegetation projects of coal waste piles with spontaneous combustion.

II. MATERIALS AND METHODS

A. Materials

Festuca arundinacea was purchased from the Tong-lin gardening company. Soil sample was taken from the Beijing suburbs, which was loam soil. By standard light compaction test [13], the optimum moisture content of the soil was 15% and the maximum dry density was 1.8g/cm^3. The soil particle size was shown in Table 1[13].

TABLE 1 SOIL PARTICLE SIZE (MM)

Soil sieve aperture (mm)	Percentage %
>2	18.71
1--2	16.30
0.5--1	16.38
0.25--0.5	15.34
0.075--0.25	17.07
<0.075	16.20

The major nutrient content of the soil sample was tested by Beijing Forestry University. The soil sample contains 1.47% organic, 8.85mg/kg available phosphorus, 102mg/kg potassium and 0.0402% total nitrogen [14].

B. Methods

Orthogonal experimental design was used in this research. 10cm diameter PVC pipes were used as planting containers. The PVC pipes were filled with soil as a plant growth medium. Soil was compacted by a hammer into 4 soil bulk densities: 1.2g/cm^3, 1.4 g/cm^3, 1.6 g/cm^3 and 1.8 g/cm^3. Each soil bulk density had 3 soil thicknesses: 10cm, 20cm and 30cm. Every treatment had 3 repeats. 200ml water was given to each PVC pipe. Root length, plant height, relative conductivity, total activity of SOD and total activity of POD were tested for 3 months after seed germination [15].

C. Statistics and Analysis Software

Factorial analysis of variance and analysis of variance were used in this paper to analyze difference in relative conductivity, total SOD and POD in different treatments. The level of significance was set at 0.05 ($p<0.05$). Excel2007 and SAS9.0 were used for data statistics and analysis.

III. RESULTS AND ANALYSIS

A. Festuca Arundinacea Roots' Distribution after Soil Compaction

Soil compaction could effectively control the maximum depth distribution of roots. Based on the maximum depth of

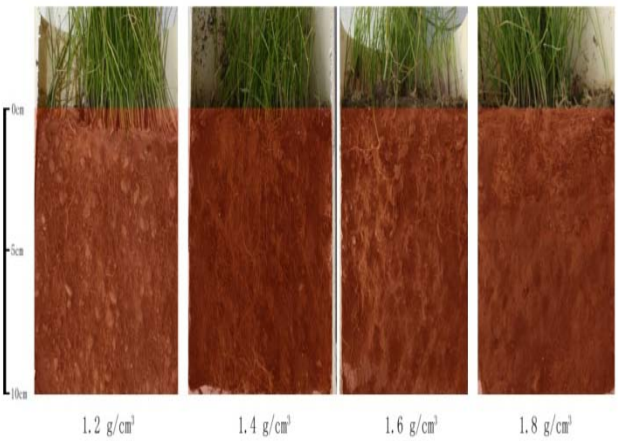

Fig. 2-1 Different soil bulk density on the impact of the max root length (Soil thickness of 10cm)

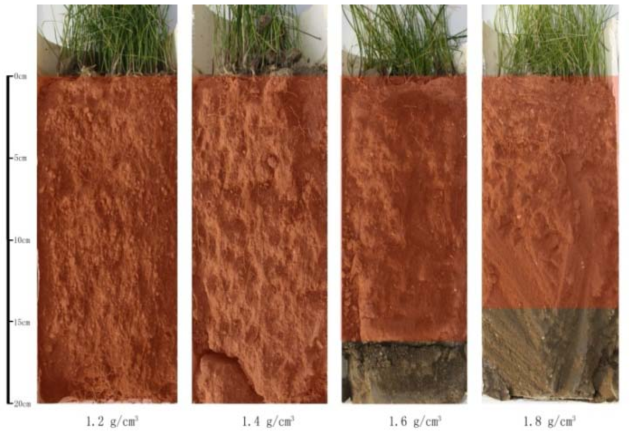

Fig. 2-2 Different soil bulk density on the impact of the max root length (Soil thickness of 20cm)

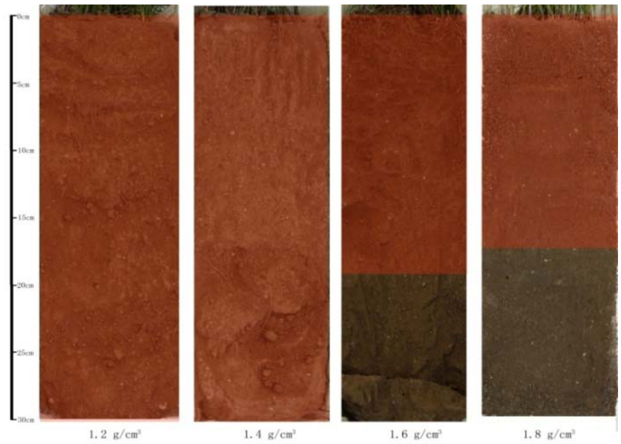

Fig. 2-3 Different soil bulk density on the impact of the max root length (Soil thickness of 30cm)

Note: max roots' distribution was marked in red

roots distribution (Table 2), Festuca arundinacea's roots could reach the bottom of the container in the low soil bulk density (1.2g/cm^3 and 1.4g/cm^3). However, the roots could not reach the bottom of the container in the high soil bulk density (1.6g/cm^3 and 1.8g/cm^3) when the thicknesses of soil were 20cm and 30cm. This indicated that compaction could effectively control the maximum depth of roots and the most efficient use of soil thickness was under 19cm.

Reducing soil thickness also had an effect on the maximum depth distribution of roots. The maximum depth distribution of roots decreased with a decrease in reducing soil thickness (Table 2).

It showed that the average height of Festuca arundinacea decreased with an increase in soil bulk density ($P= 0.0043$) and increased with an increase thickness of soil ($P <0.0001$).

TABLE 2 MAXIMUM DEPTH OF ROOTS DISTRIBUTION

Soil thickness (H)	Soil bulk density (C)			
	1.2g/cm^3	1.4g/cm^3	1.6g/cm^3	1.8g/cm^3
10cm	10	10	10	10
20cm	20	20	16	14
30cm	30	30	19	17

TABLE 3 AVERAGE HEIGHT (CM)

Soil thickness (H)	Soil bulk density (C)			
	$1.2g/cm^3$	$1.4g/cm^3$	$1.6g/cm^3$	$1.8g/cm^3$
10cm	20.89	20.24	19.21	15.41
20cm	31.91	26.28	24.99	19.92
30cm	42.29	38.91	35.21	27.94

B. Festuca Arundinacea'S Adaption to Soil Compaction

1) Roots' Adaption to Soil Compaction

The roots of Festuca arundinacea were very adaptable to soil compaction. There was no significant difference when increasing/ decreasing soil bulk density or soil thickness.

As shown in Figure 3, the relative conductivity of the roots increased with an increase in soil bulk density and decreased with an increase in thickness of soil. Factorial analysis of variance showed that there was no overall significant difference between soil bulk density treatments (P=0.9246, DF=3), and there was no overall significant difference between soil thicknesses (P=0.4927，DF=2).

The analysis of variance of the impact of compaction on roots' relative conductivity showed that there was no significant difference between different soil bulk density for each soil thickness (H=10cm, P=0.2025; H=20cm, P=0.1407; H=30cm, P=0.0537), and there was also no significant difference between different soil thicknesses for each soil bulk density ($C=1.2g/cm^3$, P=0.8842;$C=1.4g/cm^3$,P= 0.5337;$C=1.6g/cm^3$,P= 0.9612;$C=1.8g/cm^3$,P= 0.5288).

TABLE 4 ROOT AVERAGE RELATIVE CONDUCTIVITY

Soil thickness (H)	Soil bulk density (C)			
	$1.2g/cm^3$	$1.4g/cm^3$	$1.6g/cm^3$	$1.8g/cm^3$
10cm	0.6205	0.6522	0.6659	0.6954
20cm	0.6110	0.6413	0.6634	0.6770
30cm	0.6036	0.6260	0.6580	0.6694

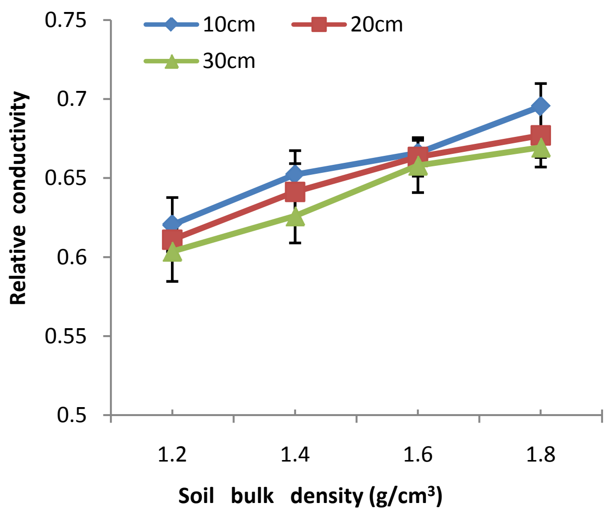

Fig. 3 Roots average relative conductivity

TABLE 5 ROOTS AVERAGE TOTAL SOD ACTIVITY

Soil thickness (H)	Soil bulk density (C)			
	$1.2g/cm^3$	$1.4g/cm^3$	$1.6g/cm^3$	$1.8g/cm^3$
10cm	163.64	231.82	281.82	331.82
20cm	130.15	200.00	240.91	300.00
30cm	86.36	163.64	218.18	295.45

Festuca arundinacea reduced damage to roots that soil compaction and reducing soil thickness brought by increasing total activity SOD. It showed that root total SOD activity of Festuca arundinacea significantly increased with an increase in soil bulk density (P<0.0001), which suggested that Festuca arundinacea reduced damage of soil compaction brought by increasing total activity SOD. Roots' total SOD activity of Festuca arundinacea significantly increased with a decrease in soil thickness (P=0.0004) which suggested that Festuca arundinacea reduced damage in reducing soil thickness brought by increasing total activity SOD.

TABLE 6 ROOTS AVERAGE TOTAL POD ACTIVITY

Soil thickness (H)	Soil bulk density (C)			
	$1.2g/cm^3$	$1.4g/cm^3$	$1.6g/cm^3$	$1.8g/cm^3$
10cm	12.86	11.36	15.63	43.72
20cm	6.14	12.86	23.06	37.76
30cm	6.92	19.97	32.78	114.39

Festuca arundinacea reduced damage to roots that soil compaction brought by increasing total activity POD. It showed that root total POD activity of Festuca arundinacea significantly increased with an increase in soil bulk density (P=0.0482). But root total POD activity didn't significantly increase with a decrease in soil thickness (P=0.2504).

2) Leaves' Adaption to Soil Compaction

Leaves of Festuca arundinacea were very adaptable to growth medium. There was no significant difference when increasing/ decreasing soil thickness or soil bulk density.

As shown in Figure 4, relative conductivity of leaves increased with an increase in soil bulk density, decreased with an increase in thickness of soil. Factorial analysis of variance showed that there was no overall significant difference between soil bulk density treatments (P=0.9246, DF=3), and there was no overall significant difference between soil thicknesses（P= 0.7527，DF=2）.

TABLE 7 LEAVES' AVERAGE RELATIVE CONDUCTIVITY

Soil thickness (H)	Soil bulk density (C)			
	$1.2g/cm^3$	$1.4g/cm^3$	$1.6g/cm^3$	$1.8g/cm^3$
10cm	0.2309	0.2534	0.2869	0.3856
20cm	0.2198	0.2374	0.2714	0.3084
30cm	0.2117	0.2266	0.2574	0.3087

Analysis of variance of the impact of compaction on leaves' relative conductivity showed that there was no significant difference between different soil bulk density for each soil thickness (H=10cm，P= 0.0751；H=20cm，P= 0.377;H=30cm，P= 0.1051) and there was also no significant difference between different soil thickness for each soil bulk density (C=1.2g/cm^3，P= 0.6347；C=1.4g/cm^3，P= 0.8416；C=1.6g/cm^3，P= 0.8124；C=1.8g/cm^3，P= 0.4473).

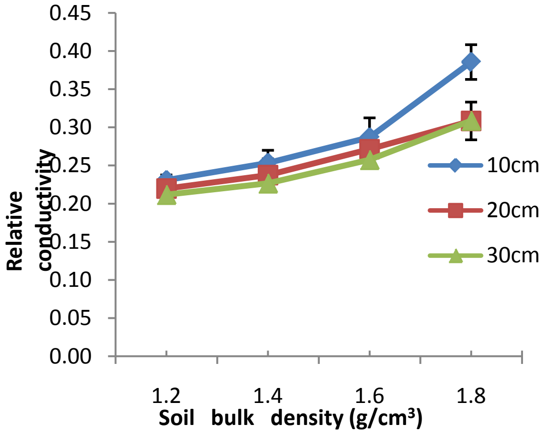

Fig. 4 Leaves average relative conductivity

TABLE 8 LEAVES' AVERAGE TOTAL SOD ACTIVITY

Soil thickness (H)	Soil bulk density (C)			
	1.2g/cm^3	1.4g/cm^3	1.6g/cm^3	1.8g/cm^3
10cm	310.06	315.21	334.63	342.39
20cm	300.97	323.62	334.30	338.83
30cm	300.00	324.60	330.10	334.63

Festuca arundinacea reduced damage to leaves that soil compaction brought by increasing total activity SOD. It showed that leaves total SOD activity significantly increased with an increase in soil bulk density (P=0.0005). However, leaves total SOD activity of Festuca arundinacea didn't significantly increase with the decrease in soil thickness (P=0.6423).

TABLE 9 LEAVES' AVERAGE TOTAL POD ACTIVITY

Soil thickness (H)	Soil bulk density (C)			
	1.2g/cm^3	1.4g/cm^3	1.6g/cm^3	1.8g/cm^3
10cm	88.85	104.37	142.43	154.63
20cm	79.95	108.55	131.62	149.88
30cm	78.66	90.48	126.97	148.71

Festuca arundinacea reduced damage that soil compaction and reducing soil thickness brought by increasing total activity POD. It showed that leaves' total POD activity significantly increased with an increase in soil bulk density (P<0.0001), and leaves' total POD activity of Festuca arundinacea significantly increased with a decrease in soil thickness (P=0.0354).

C. The Possibility Analysis of Reducing Soil Thickness in Re-Vegetation Projects by Soil Compaction

It was possible to reduce the soil thickness in re-vegetation projects of coal waste piles with spontaneous combustion by proper soil compaction.

Soil compaction could effectively reduce the maximum depth distribution of roots (Fig.2-1, Fig.2-2 and Fig.2-3). Based on maximum depth of roots distribution (Table 2), Festuca arundinacea's roots couldn't reach the bottom of the container in the high soil bulk density (1.6g/cm^3 and 1.8g/cm^3) when thickness of soil were 20cm and 30cm.The most efficient use of soil thickness was under 19cm.

Festuca arundinacea showed a very good adaption to soil compaction. Soil compaction stressed the growth of Festuca arundinacea resulting in shorter roots length and plant height. However, soil compaction had no significant effect on cell membrane permeability of Festuca arundinacea. It was due to the fact that Festuca arundinacea significantly increased the total activity of SOD and POD to reduce the damage to roots and leaves caused by soil compaction and reducing soil thickness. Festuca arundinacea reduced damage to roots that soil compaction brought by increasing total activity of SOD and POD, and reduced damage to roots that reducing soil thickness brought by increasing total activity of SOD. Festuca arundinacea reduced damage to leaves that soil compaction brought by increasing total activity of SOD and POD, and reduced damage of reducing soil thickness brought by increasing total activity of POD.

D. The Most Efficient Soil Bulk Density and Soil Thickness for Festuca Arundinacea Re-Vegetation

There is an alkalinity layer (Fig. 1) in re-vegetation project of the coal waste pile with spontaneous combustion. This alkalinity layer is compacted to inhibit oxygen infiltrating into coal waste piles. This layer should be well protected and roots are not allowed to grow through it. This alkalinity layer contains strong alkaline material such as fly ash. The PH is too high for plants to grow in this layer. Thus, soil thickness should be greater than the roots' distribution.

In this research, the most efficient use of soil thickness was under 19cm in high soil bulk density (1.6 g/cm^3 and 1.8 g/cm^3) (Table. 2). Therefore the soil thickness should be greater than maximum growth of root length, in order to prevent roots from contacting and destroying the alkaline layer. As a result, the thickness of soil should be greater than 19cm.

20cm should be the most suitable soil thickness for re-vegetation, because utilization efficiency of soil was higher in soil thickness of 20cm than in soil thickness of 30cm (Table 2, Fig2-1, Fig 2-1and Fig 2-3), and there was no significant difference of relative conductivity between soil thickness of 20cm and 30cm for both roots (Table 4) and leaves (Table 7). When soil thickness was 20cm, the max roots distribution was 16cm. So there was still 4cm beyond alkalinity layer.

When soil thickness was 20cm and soil bulk density was 1.6 g/cm^3, soil had the highest utilization efficiency. Firstly, it was showed that when soil thickness was 20cm, roots and leaves' relative conductivity were lower in soil bulk density of 1.6 g/cm^3 than in soil bulk density of 1.8 g/cm^3 (Table. 4 and Table.7), which meant roots and leaves had lower stress by soil compaction in soil bulk density of 1.6 g/cm^3. Furthermore, roots' distribution was deeper in the 1.6 g/cm^3 soil than in the 1.8 g/cm^3 soil (Table. 2, Fig2-1, Fig 2-1and Fig 2-3), which showed that roots had a higher utilization efficiency of soil in the soil of 1.6 g/cm^3 when soil thickness was 20cm. Last but not the least it needed less energy to achieve soil bulk density of 1.6 g/cm^3 compared to soil bulk density of 1.8 g/cm^3.

E. Construction Method Deducing

The soil sample used in this research has the same compaction test parameters as Chen's [6], whose data has been referenced for deducing construction. The main parameters of the compaction roller were as following [6]: cross-section diameter was 1.58m; width was 1.1m; weight was about 4.5t. The compaction roller was towed by an excavator.

Construction method was deduced in this research. The following equation showed the relationship between soil bulk density and thickness of loose soil under the condition of rolling back and forth once by a compaction roller.

Thickness of loose soil (cm) = 32/Soil bulk density (g/cm^3) (20cm< soil thickness <40cm)

IV. DISCUSSION

A. The Effect of Soil Compaction on Re-Vegetation

Soil compaction may affect the normal growth of plants: first, the soil compaction can increase soil bulk density and mechanical resistance; second, it also can decrease soil porosity and water permeability; third, chemical element absorption can be restricted in soil by compaction. However, soil microbial, such as arbuscular mycorrhiza, can increase plant growth, and reduce the stressful effects of soil compaction on plant growth, though its effectiveness may decrease with increasing compaction [16].

B. A New Approach to Reducing Soil Thickness in Re-Vegetation Projects of Coal Waste Piles with Spontaneous Combustion

Soil compaction could be a new approach to the reduction of soil thickness in re-vegetation projects of coal waste piles with spontaneous combustion: first, soil compaction could effectively reduce the maximum depth distribution of roots; second, it was found that reducing soil thickness could also impact on Festuca arundinacea's growth, which could also reduce the maximum depth distribution of roots; third, Festuca arundinacea showed a very good adaption to soil compaction and reducing soil thickness. Cell physiology of both roots and leaves had no significant difference when increasing/ decreasing soil bulk density or soil thickness.

When soil thickness was 20cm and soil bulk density was 1.6 g/cm^3, soil had the highest utilization efficiency and could avoid roots growing through the alkaline layer. The construction method was also deduced: Thickness of loose soil (cm) = 32/Soil bulk density (g/cm^3) (20cm< soil thickness <40cm, under the condition of rolling back and forth once by compaction roller)

C. Mechanism of Using Soil Compaction to Reduce Soil Thickness

Roots grow fast in loose soil, but the roots' ability to absorb water and nutrients was limited due to the lack of contact between the soil liquid phase and roots [17]. Proper soil compaction could increase the contact between the roots and the soil and improve the utilization of fertilizer and water. Compaction impacts roots' ability to absorb water and nutrients in two ways [17-20]: First, soil compaction increases contact between roots and soil, which forces more water and nutrients to enter the root growth zone, thereby soil compaction increases the absorptive capacity of a single root; second, soil compaction reduces the total amount of the root, so that the total absorption decreases. However, above ground biomass is also reduced, so the relative absorption of water and fertilizer can still meet the needs of plant growth. Therefore, proper compaction can improve the utilization efficiency of soil, and reduce the thickness of the soil covering on coal waste piles with spontaneous combustion, ultimately reducing treatment costs. Thus it is possible to reduce soil thickness of reclamation of coal waste piles with spontaneous combustion by soil compaction.

D. Ecological Value and Economic Value

At least 53.2 billion tons of soil will be saved by proper soil compaction if this approach is used for all the coal waste piles with spontaneous combustion. A large amount of energy used for excavating and transporting soil will also be saved. The alkaline layer for oxidation inhibition [3] will be well protected, and less air will infiltrate into coal waste piles, which would be beneficial for long term ecological restoration [6].

55% of the re-vegetation cost, which is about 162 billion dollars, will be saved by using this new approach.

V. CONCLUSION

Soil compaction could be a new approach of the reduction of soil thickness in re-vegetation projects of coal waste piles with spontaneous combustion.

Not only soil compaction but also reducing soil thickness could reduce Festuca arundinacea's roots' distribution depth.

Festuca arundinacea showed a very good adaption to soil compaction and reducing soil thickness. It was due to the fact that Festuca arundinacea significantly increased the total activity of SOD and POD to reduce the damage caused by soil compaction and reduction in soil thickness.

When soil thickness was 20cm and soil bulk density was 1.6 g/cm^3, soil had the highest utilization efficiency and could avoid roots growing through the alkaline layer.

The construction method was deduced: Thickness of loose soil (cm) = 32/Soil bulk density (g/cm^3) (20cm< soil thickness <40cm, under the condition of rolling back and forth once by a compaction roller)

Further research should focus on Festuca arundinacea's dynamic adaptation mechanism of soil compaction. Re-vegetation requires the formation of a stable plant community on the coal waste piles. Consequently, other plants' species adaptation, especially bushes, to soil compaction should also be well researched.

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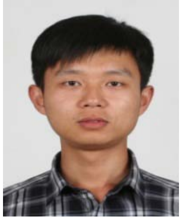

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