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ORIGINAL ARTICLE

Erosion characteristics of ecological sludge evapotranspiration cover slopes for landfill closure

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Abstract The runoff and sediment processes under different conditions are investigated by the laboratory tests performed in ecological sludge evapotranspiration cover slopes of landfill closure. Erosion caused by rainfall is investigated in the bare slope and vegetation litter layer. Erosion easily occurs when the condition of the bare slope reaches 100 % coverage. The different matrices for sediment control are crucial for the specific condition. The ecological sludge evapotranspiration technology (EST) composite matrix has been prepared by modified sludge added with fiber and a piece of net. Under the condition of 30° slope and 80 mm/h rainfall intensity, modified sludge and clay have a similar basic runoff tendency. The modifier sludge naked slope reduces approximately 20 % the sediment value compared with that of clay naked slope. The EST composite matrix could provide the smallest sediment value in both non-vegetation and vegetation conditions. Vegetation in the modified sludge has a significantly faster growth than that for the cases of clay. The results show that EST composite matrix with grass used as the vegetation layer of the landfill cover system is very important and obviously feasible.

Keywords Landfill closure slope · Modified sludge · Ecological sludge evapotranspiration cover technology · Erosion characteristics

Introduction

In China, the closure cover system of old landfills that exist in suburban areas involves a venting layer, an impermeable layer, a drainage layer, and a vegetation layer in terms of the waste heap surface to the top surface. The layers are extensively made of compacted clay, geomembranes, geocomposites, or a combination of these materials (He et al. 2008; Benson et al. 2010; Staub et al. 2011; Kwon et al. 2011; Eid 2011; Barnswell and Dwyer 2012; Feng et al. 2012; Kim et al. 2013; Li et al. 2013). In addition, the vegetation layer has been used as forestation and protection of the drainage layer (Pusch and Kihl 2004; Schiettecatte et al. 2005; Gómez and Nearing 2005; Ran et al. 2012; Jouquet et al. 2012; Zhang et al. 2013). Nevertheless, the clay materials are inadequate in most landfills located in suburban areas. Hence, new alternative materials are urgently required. Significant practical applications may be derived from sludge as the cover materials.

Compared with rainfall splash and runoff erosion, rainfall erosion could easily cause destruction of the vegetation layer, which is primarily produced in the stage when the bare slope reaches 100 % coverage. However, it is known that when the vegetation coverage rate reaches 100 %, the effect of runoff erosion on destruction of the vegetation layer becomes dominant. Particularly, cracks and instability of the vegetation layer accelerate the rainfall erosion. Previous studies suggest that rainfall erosion could break through the vegetation layer and directly destroy the drainage layer and infiltrate into the layer, which leads to rainfall that permeates the landfill (Qian et al. 2003, 2004; Kefi et al. 2011). The rise of water level leads to the increase of leachate within the landfill, which results in a series of disasters such as cover system collapse and landslides of waste heaps. Recently, more attention has

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been drawn to the erosion characteristics of slopes (Chen et al. 2011; Srivastava et al. 2010). However, when the modified municipal sludge is applied to the vegetation layer of the landfill cover system, cracks occurred, which could result in rainfall erosion. Such erosion should be addressed to ensure the stability of the entire structure of the landfill. The relative studies are very limited.

Recently, the authors developed a new ecological sludge evapotranspiration technology (EST), which is suitable for the landfill closure cover material by employing slope ecological restoration techniques commonly used for mines and roads. The EST composite matrix has been prepared by modified sludge added with fiber and a piece of net. The sludge modifier is made from industrial residue and the fiber comprises waste straw. This study investigates the erosion characteristics of ecological sludge evapotranspiration cover slopes for landfill closure, which has important theoretical and engineering significance to verify and improve EST and solve the problem of sludge, waste straw, and industrial residue.

Materials and methods

Testing instruments

The testing instruments in this study included a rainfall tester, a moisture tester (TSC-1), and an automatic monitoring system of water-soil erosion.

The rainfall tester was mainly composed of the following components: syringe sprinkler, water supply tank with constant voltage, water supply pipes, micromotor governor, and control valve. The horizontally covered area was about 4 m^2 and 2.2 m depth above the ground surface. The baseboard had a size of 0.5 m (width) × 1.6 m (length), on which 1118 needles of $8^{\#}$ stainless medical needles were installed in a chessboard pattern at an interval of 0.03 m. The test soil box was 0.5 m (width) × 1.0 m (length) and 0.25 m in depth, with a stand to adjust the gradient.

The TSC-1 soil moisture quick tester was used to measure real-time moisture content in the edged slope soil.

The automatic monitoring system of water-soil erosion was used to measure the sediment content, rainfall capacity, and runoff. The system automatically monitors, stores, and transmits a variation of runoff and sediment for each observation point. The sampling interval of sediment concentration measurement was adjustable within 1–999 s. The measurement range of the system sensor ranged from 1 to 150 kg/m^3 with a measurement error of less than 1 %. The flow measurement of the runoff field ranged from 0.0001 to 3 L/s with a measurement error of below 1 % of the total.

Materials

Bermuda grass used in this study has an extensive root system. It is characterized by strong trampling resistance, aggressiveness, reproducibility, severe environment resistance, and extensive management resistance. The grass is widely distributed in China and is very suitable for applying in ecological slope repair. The seeding rate was about 10–12 g/m^2, and the seeding rate of grass planting by spraying seeds was approximately 15 g/m^2.

Clay was air-dried, ground, and filtered through a 2 mm sieve. The dry density of the clay was 1.58 g/cm^3.

The municipal sludge was collected from a sewage plant in Wuhan City, Hubei Province, China. After anaerobic digestion treatment, the sludge reached approximately 82.6 % water content, 1.14 kg/m^3 natural density, 7.07 pH, and 51.8 % organic matter. The sludge modifier had gelling characteristics. Six samples were evenly obtained, and their average physical characteristics were measured, respectively: 1.83 kg/m^3 density, 6.4 % surface active agent, and >360 m^2/kg BET.

The modified sludge was made from original sludge, sludge modifier (5–10 % of the original sludge weight), and slag (10–20 % of the original sludge weight), and its moisture content was controlled at 15 %.

The straw fiber had 4.85 % saturated water content and a diameter of 0.023 mm and 6 mm length.

Mark Phil's anti-erosion nets were used. The nets had >1970 basic weight (g/m^2), >12 thickness (mm), >35 tensile strength (kN/m), and >0.3 peel strength (kN/m).

Figure 1 presents the characteristics of the real modified sludge, fiber, and nets.

Methods

Sprinkler calibration and rainfall intensity measurement

The flow of the test control box was set to 1.5 L/min; the rotation speed of the sprinkler was 500 rpm; and the rainfall intensity was approximately 80 mm/h. The rainfall intensity remained stable at 80 mm/h through 16 min rainfall.

Grass planting

Macadam with a 5 cm thickness was paved at the bottom of the soil bin for rainfall drainage over time. The clay and modified sludge were filled, after that the nets were paved by the experimental design (Table 1). Seeds were sown based on the seeding rate and covered with non-woven fabric under constant watering. The layer has been sprayed with water evenly and covered with waterproof cloth in advance during rainy days, which could prevent


Modified sludge Fiber Nets

Fig. 1 Modified sludge, fiber and nets

Table 1 Erosion characteristic test factorial design and sediment

(a) 2^2 Factorial design

Sediment (g/s) [rainfall erosion stable value]	Matrix (A)	
	Clay (A_1)	Modified sludge (A_2)
Grass situation (B)		
Naked slope (B_1)	Clay naked slope ① 2.39/2.46/2.51	Modified sludge naked slope ② 0.072/0.076/0.080
Grass coverage: 100 % (B_2)	Clay with grass ④ 2.34/2.39/2.41	Modified sludge with grass ③ 0.062/0.066/0.068

(b) 2^3 Factorial design

Sediment (g/s) [rainfall erosion stable value]	Grass situation (B)	
	Naked slope (B_1)	Grass coverage: 100 % (B_2)
No fiber (C_1)		
No nets (D_1)	Modified sludge naked slope ② 2.34/2.39/2.41	Modified sludge with grass ③ 0.062/0.066/0.068
Nets (D_2)	Modified sludge nets ⑥ 2.00/2.01/2.03	Modified sludge nets with grass ⑦ 0.050/0.052/0.054
Fiber (C_2)		
No nets (D_1)	Modified sludge fiber ⑤ 2.13/2.14/2.16	Modified sludge fiber with grass ⑧ 0.053/0.055/0.057
Nets (D_2)	EST composite matrix ⑨ 1.74/1.75/1.76	EST composite matrix with grass ⑩ 0.044/0.049/0.051

water entry and runoff production. This maintenance protective method was illustrated in Fig. 2. The vegetation was regularly pruned to maintain the height at 10 cm, and the plant density was controlled at 0.25 plants/cm^2. Furthermore, the vegetation coverage rate and litter layer coverage rate, i.e., the ratio between the vegetation (litter layer) area vertical covered on the slope and the slope area, were measured.

Fig. 2 Plant breeding grass planting process

Erosion test

Ten conditions were designed and four factors were considered in this study: matrix (A), grass situation (B), fiber (C), and nets (D). Each factor was designed with two kinds of situations, such as matrix (A) containing clay (A_1) and modified sludge (A_2), as shown in Table 1. Erosion characteristics of conditions ①, ②, ⑤, ⑥, and ⑨ were monitored in different vegetation coverage rates (0, 20, 50, 80, and 100 %) and different litter coverage rates (0, 30, 70, and 100 %).

The EST composite matrix consisted of modified sludge, fiber weighing 5–10 %, and netting. The test slope angle was 30° to replicate the slope angle of over 60 % of the slopes in the landfill cover system. Each condition and every erosion test was conducted in three soil bins and the results are shown in Table 1.

The moisture content of the erosion test material in the non-vegetation conditions was controlled at 15 %. The moisture contents for various components were measured, and their filling capacities were calculated. The material was filled once and set naturally for 24 h before the erosion test. The moisture content in the soil bins with vegetation was controlled at 15 % before the erosion test. Moreover, the testing soil bins were moved to place without rainfall before the test to ensure that the moisture content of all conditions was less than 10 %. The amount of additional water was calculated by the measured moisture content. Meanwhile, the water was then evenly sprayed into the soil bins. Subsequently, the soil bins were kept under shade and fully infiltrated for 24 h. The moisture contents of all the conditions were measured using TSC-1 until the values were controlled at approximately 15 %.

Fig. 3 Erosion tests

Prior to the test, the soil bins were installed, positioned, and covered by a piece of large plastic cloth. In addition, the artificial sprinkler was adjusted to an appropriate flow and rotation frequency. The plastic cloth was turned over for testing after the rainfall stabilized. Runoff and sediment concentrations were measured and automatically recorded by the automatic water-soil erosion monitoring system. Runoff and sediments were collected every 10 min to compare and verify the data of the monitoring system on water-soil erosion. The artificially collected muddy water was precipitated and dried to determine sediment quality. Figure 3 shows the erosion test.

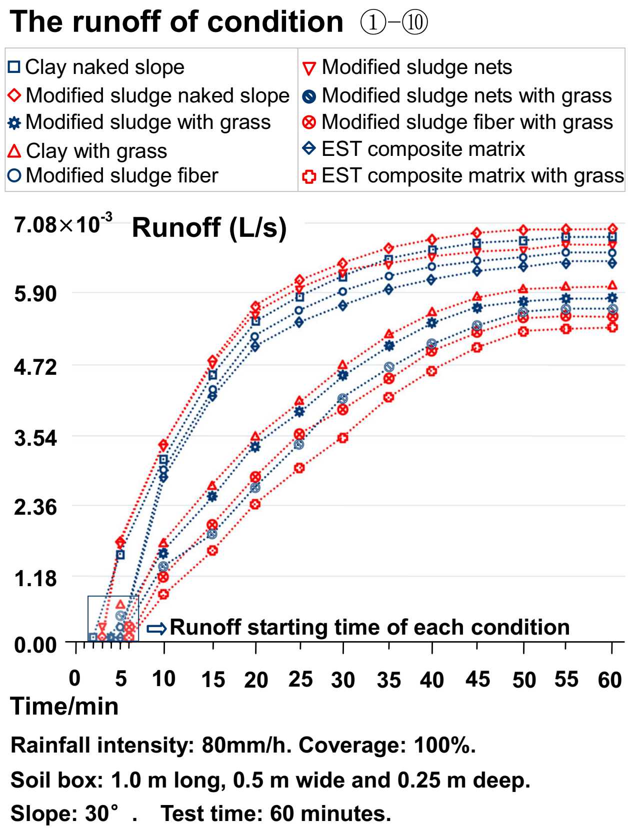
Results and discussion

Analysis of the runoff of each condition

Figure 4 shows the variation between the produced runoff and elapsed time under different conditions. It is evident that runoff increases with the elapsed time under the different condition, which has a similar development that quickly increased in the earlier stages and resulted in balanced runoff after approximately 50 min. Runoff occurs when the rainfall is higher than the matrix infiltration capacity. Runoff gradually accelerates the matrix saturation. As a result, the infiltration capacity is weakened increasingly. Finally, the substrate reaches saturation. Furthermore, the infiltration capacities decrease to a stable value, resulting in stable runoff.

The runoff in vegetation conditions is consistently less than that in non-vegetation conditions, meaning that the infiltration capacity of matrices increase with elapsed time

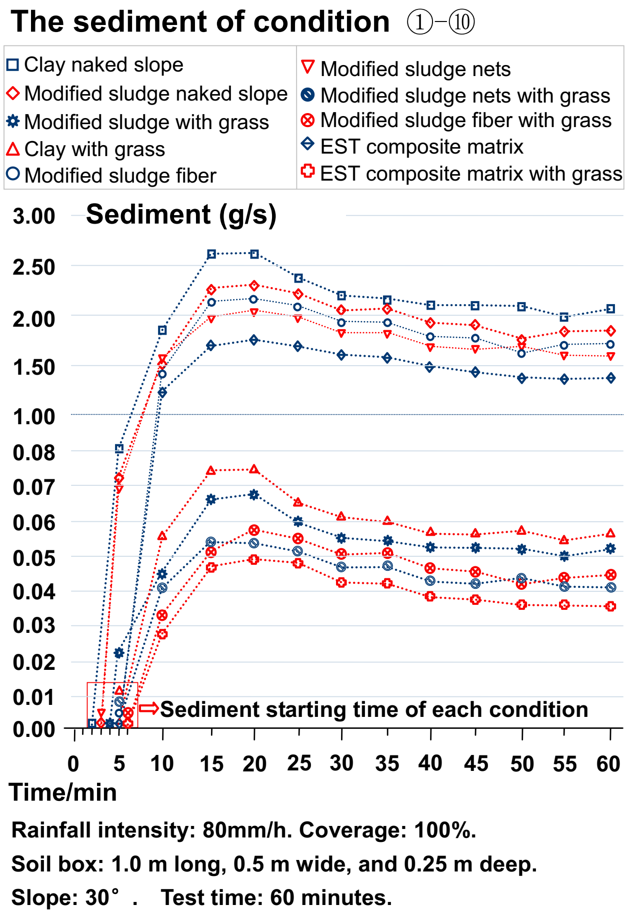
The runoff of condition ①–⑩



Rainfall intensity: 80mm/h. Coverage: 100%.
Soil box: 1.0 m long, 0.5 m wide and 0.25 m deep.
Slope: 30° . Test time: 60 minutes.

Fig. 4 The runoff of condition ①–⑩

The sediment of condition ①–⑩



Rainfall intensity: 80mm/h. Coverage: 100%.
Soil box: 1.0 m long, 0.5 m wide, and 0.25 m deep.
Slope: 30° . Test time: 60 minutes.

Fig. 5 The sediment of condition ①–⑩

and that rainwater could easily infiltrate into matrices due to the effect of the root system.

Different matrices have individual runoff stable values. Particularly, the EST composite matrix has the smallest runoff in both the non-vegetation and vegetation condition. The effect of combined fiber and nets is more beneficial for rainwater infiltration than that of their individual effect.

The runoff generation time of vegetation conditions is longer than that of non-vegetation conditions, and EST composite matrix has the longest runoff generation time in both non-vegetation and vegetation conditions. The result demonstrates that vegetation and matrix types determine runoff generation time and reflected the rainwater infiltration capacity of each condition. Due to their similar functionality, clay and modified sludge followed similar runoff rules.

Analysis of the sediment of each condition

Figure 5 shows that the sediment increases firstly and then decreases with elapsed time under all the conditions by stabilization. Table 2 shows the ANOVA of erosion characteristic test data which has been shown in Table 1. The influence of factor B is significant (Table 2a), and the sediments of vegetation conditions are far less than those of non-vegetation conditions (Fig. 5), showing that the vegetation cover has an important influence in controlling the sediment. The sediment yield of vegetation conditions is 97 % less than that of non-vegetation conditions. The influence of factor A is significant (Table 2a), showing that different matrices, such as clay and modified sludge, have little effect on the erosion characteristics. Modified sludge indicates improved anti-erosion characteristics compared with clay, because it has a denser microstructure and its pore structure has been further compressed (Fig. 6). The test data indicate that the modifier sludge naked slope decreases the sediment by approximately 20 % compared with clay naked slope (Fig. 5), which may be attributed to the high feasibility of the modified sludge as the vegetation layer. The modified sludge demonstrates good mechanical properties, with shear strength of 32.5 kPa and compressive strength of 87 kPa.

The effects of factors B, C, and D are significant (Table 2b). Factor B has the most significant influence, because the grass significantly reduces the sediment. Factor C has less significant influence than that of B, primarily due to the reduced erosion by nets, which could prevent erosion gully development. Factor D indicates the least

Table 2 ANOVA of erosion characteristic test

Sources of variation	Sum of square	*df*	Mean square	*F*	Sig.
(a) 2^2 Factorial design					
A	0.005	1	0.005	4.269	0.073
B	16.511	1	16.511	13319.022	0.000
A × B	0.003	1	0.003	2.376	0.162
Error	0.010	8	0.001		
Total	35.090	11			
(b) 2^3 ANOVA table					
B	24.400	1	24.400	102897.839	0.000
C	0.099	1	0.099	418.353	0.000
D	0.228	1	0.228	962.973	0.000
B × C	0.088	1	0.088	373.019	0.000
B × D	0.205	1	0.205	865.219	0.000
C × D	0.000	1	0.000	0.654	0.431
B × C × D	0.000	1	0.000	1.722	0.208
Error	0.004	16	0.000		
Total	52.164	23			

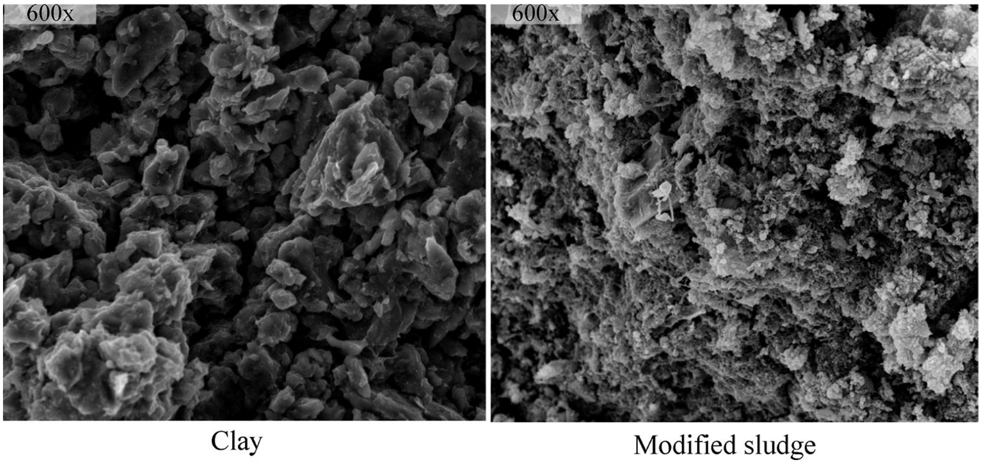


Fig. 6 Sludge scanning electron microscope (SEM) images

significant influence, because the fibers prevent modified sludge cracks (Fig. 7) and reduce shear capacity (modified sludge: 32.5 kPa, modified sludge fiber: 26.5 kPa). Interactions B × D and B × C show significant influence, whereas interactions C × D and B × C×D have no significant influence (Table 2b). Furthermore, interaction B × C×D (EST composite matrix) showed the smallest sediment value in both non-vegetation and vegetation conditions (Fig. 5). Based on the test data, the EST composite matrix indicates remarkable performance in reducing erosion than the modified sludge, modified sludge fiber, and modified sludge nets on a naked slope. Such performance occurs because EST decreases the sediment by approximately 40, 25, and 25 %, compared with modified sludge, modified sludge fiber, and modified sludge nets, respectively. The EST composite matrix combines the advantages of fiber and nets, as well as increases the anti-erosion characteristics of the modified sludge.

The differences in runoff and sediment in different conditions show a similar tendency (Figs. 4, 5). Runoff size determines the sediment size to a certain extent. The sediment decreases by increasing the rainwater infiltration capacity of matrices and reducing runoff by adding different materials or planting vegetation.

Analysis of erosion in the entire process of vegetation growth

Figure 8 shows different conditions primarily produces in the stage from bare slope reaches the 100 % coverage,

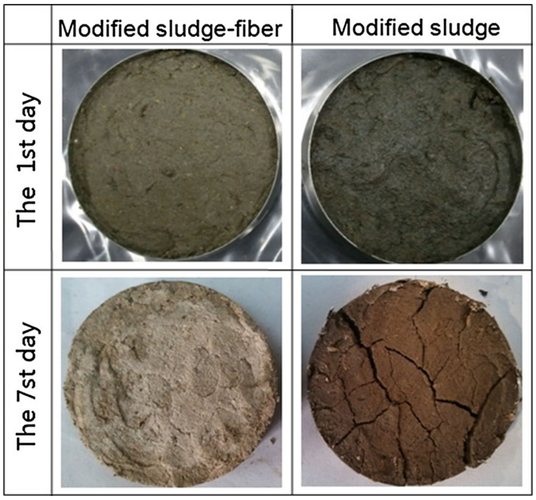


Fig. 7 Cracking of modified sludge fiber and modified sludge in the first day and seventh day

especially when the vegetation cover was less than 50 %. In addition, the litter layer is fully formed, showing that matrices of different conditions have essentially no effect on sediment in this stage. The sediment of different conditions tends to zero, especially after the litter layer has been fully formed. However, the litter layer is disadvantageous to the development of vegetation and may increase erosion quantity.

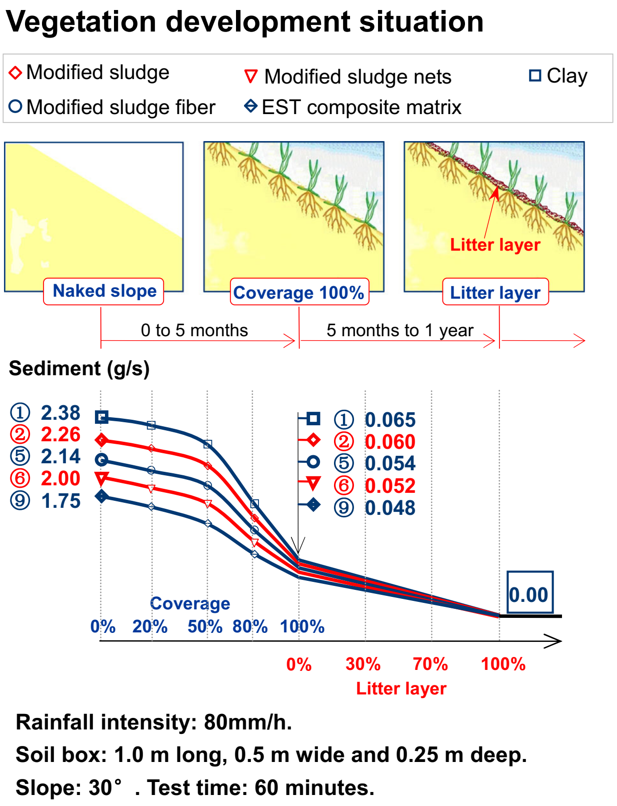


Fig. 8 The erosion of the whole process of vegetation growth

However, the matrices of different conditions are vital in reducing the sediment. This is the main stage of sediment and vegetation growth, and more than 95 % of the sediment is produced in this stage. Thus, different matrices for sediment control are crucial in this stage.

EST composite matrix reduces the sediment by 27 and 23 %, respectively, compared to the clay and modified sludge, which greatly improves erosion resistance. Such matrix is important for the security of landfill vegetation layer, which is just 20–30 mm thick, especially in rainy areas.

During planting and cultivation, grass planted on clay had been fertilized, whereas grass planted on modified sludge was not fertilized. Throughout the entire cultivation process, vegetation in modified sludge had a better growth than that in clay, particularly the modified sludge with grass achieves 100 % vegetation coverage rate 30 days earlier than clay. When the coverage rate of clay with grass reaches 100 %, the modified sludge indicates more vegetation biomass than clay. Modified sludge matrices are capable of promoting vegetation growth and form litter layer and reduce the period prone to erosion, which could improve erosion resistance and ensure the security of the landfill vegetation layer.

Conclusions

Sediments of different conditions are mainly produced in the stage from bare slope to 100 % coverage, and more than 95 % of the sediment is produced in the stage. The matrices of different conditions are vital in reducing the sediment. The different matrices for sediment control are of crucial importance in this stage. After the vegetation coverage reaches 100 %, the litter layer is formed gradually. The vegetation situations then become the absolute factors in controlling sediment. Modified sludge and clay have the same basic runoff tendency. The modifier sludge naked slope decreases the sediment by approximately 20 % compared with clay naked slope, and the vegetation in the modified sludge indicates remarkable and faster growth than that in clay. Furthermore, the EST composite matrix with grass used as the vegetation layer of a landfill cover system is significantly feasible on the basis of macroscopic perspective results.

However, the design does not consider the optimized proportion of the modified sludge. Fiber type, as well as its amount, length, and thickness are key points for subsequent experimental research, as are optimal choice of net shapes, vegetation type, and compatibility. This paper proposes an EST technology framework that improves the EST system by conducting numerous tests and theoretical studies. This framework provides additional effective guidance in the engineering application of EST in landfill cover systems.

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