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Soil erosion is one of the major environmental problems in open-cut mines in tropical regions. It causes negative impacts including the removal of nutrient rich topsoil and subsequent reduction of agricultural productivity in the rehabilitation process. Therefore, it is important to predict soil erosion in advance and establish the proper process to minimize the phenomenon for the success of rehabilitation in the disturbed land. Field investigation to understand soil characteristics in rehabilitation areas and artificial rainfall experiment in laboratory scales were used to assess soil erosion. From a series of investigations, the soil characteristics that spread to the rehabilitation areas were uneven due to mixing overburden as contamination; moreover, it can increase the risk of soil erosion when the soil has high soil erodibility. Another study finding shows the importance of selective placement of erosion-resistant soil in an area which has a high potential for soil erosion to occur, such as slope with an establishment of rapid growing cover crop species on the surface. This paper describes soil erosion under the various soil characteristics and effective countermeasures *in situ*, and discusses the design of the self-sustainable land surface against soil erosion.

Keywords: soil erosion; open-cut mine; rehabilitation; cover crop;

1. Introduction

Mining open-cut mines causes serious impacts on the surrounding environment, such as disturbing the tropical rainforest, polluting surface and/or ground water, subsidence and erosion. Since the government and local residents have recently shown a deep interest in environmental protection, mining companies must pay more attention to the rehabilitation program in order for the ecosystem to recover after mining operations finish. Under such situations, rehabilitation is one of the important and considerable topics for a sustainable development. Adequate rehabilitation programs will improve these environmental conditions and recover the ecosystem.

Generally, post-mine surfaces show poor conditions as planting bases, and some of overburdened strata contain materials toxic to plant growth. Therefore, consideration of selective placement is needed in order to avoid an adverse effect for vegetation and for successful revegetation to occur. Basically, topsoil should be

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conserved and used for preparing a planting base in disturbed land since using fresh surface soil is the most economical and reliable way to recover the wide diversity of species which exist in native ecosystems [1]. Proper soil management is critical for land restoration. Most topsoil contains a large amount of plant growth medium, soil organic matter and seeds from native species and it has fewer adverse chemical impacts on plant growth [2]. Hence, a lot of open-cut mines keep the topsoil individually in the natural forest during the soil-stripping process and spread the topsoil to the rehabilitation area in order to prepare favorable ground conditions for plant growth.

However, specific climate events such as squall easily accelerate soil erosion in tropical regions. Soil erosion can be defined as detachment, transportation and deposition of soil particles from one place to another by natural phenomenon such as rainfall, wind or gravitational forces. The soil erosion causes soil degradation due to severe erosion phenomena such as gully erosion, surface erosion, raindrop erosion, and rill erosion [3, 4]. This situation leads to unsuccessful rehabilitation in the disturbed lands due to topsoil losses. Topsoil losses reduce soil fertility and land productivity, and give negative impacts to surrounding environments, such as sedimentation on streams and rivers, and water pollution [5]. In order to limit the negative effects on the surrounding environments, erosion control is installed and divided into two main categories: mechanical and vegetative methods. Mechanical control of erosion includes construction of terrace, erosion protection bunds, water stream dredging, and sediment ponds [6]. Vegetative control of erosion is established by implementation of cover crops. The establishment of vegetation is one of the important steps to control erosion [7, 8]. However, it can be considered that the primary importance for erosion control is to reduce soil loss from the ground surface. That is to say, it is difficult to control once severe erosion phenomena develop (Figure 1); therefore, it is important for success of rehabilitation in the disturbed land to predict and assess soil erosion adequately, and some countermeasures have to be taken in order to monitor and/or manage the rehabilitation area in the long term.

2. Site description

The Kaltim Prima Coal (KPC) Mine is the biggest open-cut coal mine in Indonesia and is located in East Kalimantan. The mine site belongs to a tropical rainforest climate and the average annual rainfall shows 2,000-4,000 mm/year and the average temperature varies from 26 to 32 °C. Currently, the demand for rehabilitation is increasing dramatically in this mine since the contract term will soon expire.

This mine is a working rehabilitation program with reference to “REHABILITATION SPECIFICATIONS” based on site and industry experience. It can be an assisted mining engineer to design a proper rehabilitation process in order to establish self-sustainable land. It is difficult to establish vegetation association in the disturbed land without the proper rehabilitation process, because post-mine surfaces usually show poor conditions as a planting base. The proper management of topsoil can provide a suitable medium for plant growth without any adverse effect. It is recommended that topsoil is stripped and placed immediately for rehabilitation in this mine. In some cases, it may be necessary to stockpile topsoil. Whenever topsoil is stockpiled, it can lose some of its qualities [9, 10]. Therefore, stockpiles should be used as soon as possible, and topsoil should be used within one year, even if the soil has to be kept in a soil stockpile. The topsoil is spread to rehabilitation area to a depth of 1 m. In soil placement procedures, only low ground-pressure bulldozers are used for spreading topsoil in order to minimize being compacted by heavy equipment. The ripping equipment works after the soil-spreading step for cultivating and loosening the ground by structural breakdown. These works give benefit for preparation of the ground to promote plant growth due to improving the water infiltration rate and relief of soil hardening [11, 12]. However, there are also possibilities to increase the risk of soil erosion because concentrated flow erosion is likely to occur by water flow on the surface due to surface roughness [13].

3. Basic characteristics of the soil spread that to the rehabilitation area

The soil that spread to the rehabilitation area has an important role for establishing a suitable plant base. In this research, the soil samples were collected from one site in a natural forest area, and four sites in the rehabilitation area which the soil spread from a similar natural forest area without a soil stockpiling process. The basic characteristics of the soil were investigated by the distribution of particle-size analysis and an Atterberg limits test, according to the ASTM D 422-63 and ASTM D 4318-00 standard. Table 1 shows the results of laboratory tests. From these results, the soil that spread to the rehabilitation area shows different soil composition despite that backfilling soil comes from a similar natural forest. This is caused by mixing overburden as contamination during the soil-stripping and soil-stockpiling process.

Furthermore, the different soil components affect soil characteristics. Figure 2 shows a plasticity chart that is convenient for comparing a variety of soils. It can be estimated that soil characteristics in the rehabilitation area are non-uniform, because the position of plots are quite different from one another in this chart [14].

The state of soil consistency, called the Atterberg limits, is one of the strongly related parameters for soil loss as erosion characteristics [15]. Soil consistency means the reaction of material at various moisture contents and corresponding changes in state; solid, semi-solid, plastic, and liquid. This parameter could have fundamental plastic properties of the stability of soil. Figure 3 shows the distributed mechanism of soil by different consistency limits. A high consistency limit means that the cohesive strength between soil particles is high because the soil has a high water-retention capacity. On the other hand, its strength decreases because of the occurrence of free water under a low consistency limit. To sum up, the risk of soil erosion increases in the low consistency limit because of low cohesive strength as the reactive force for soil erosion [16]. From the result in Figure 2, the soil in rehabilitation 3 and 4 have their plots within a low plastic range and low plastic index, hence they are less cohesive and less plastic. On the basis of the results, it can be suspected that large soil erosion may occur in some areas where soil has a low consistency limit. Therefore, the prediction of erosion under the various soil compositions is needed in order to assess the erosion hazard in the rehabilitation area.

4. Laboratory study

A laboratory study was conducted in order to predict total soil loss under various soil conditions by using an artificial rainfall simulator, which was prepared in our laboratory. The advantages of this experiment are to evaluate soil erosion for a short period and flexibility for arranging topography and soil texture [17].

4.1. Material and Methods

4.1.1. Soil sample and basic soil characteristics

In this study, six soil samples mixed by a certain ratio of decomposed granite soil and bentonite were prepared and soil composition and Atterberg limits were measured. Table 2 shows the results of the soil characteristics. It was confirmed that the liquid limit and plasticity index show a high value with increasing the clay content in the soil samples. This finding means that the cohesive strength of the soil increases with an increase in clay content since the plot on the plasticity chart, as shown Figure 4, moves to a high plastic range [18]. Therefore, it can be expected to decrease soil loss by rainfall as clay materials increases in soil sample.

4.1.2. Artificial Rainfall Experiment

An artificial rainfall experiment is useful to assess soil erosion in the field in advance because this experiment can directly measure total soil loss by rainfall. The equipment used is illustrated in Figure 5. Rainfall was simulated by drops of water free falling, starting at zero velocity, from protruding needles with an internal diameter of 0.80 mm [19]. Considering local climate conditions, a certain amount of rainfall determined by referencing the rainfall data in the KPC mine, which was arranged by changing the pressure head by adjusting the water flow into the rainfall simulator, gave the soil samples within the allotted amount of time. The duration of every experiment was 30 minutes. A rectangular-shaped bed sized 194 x 103 x 50 mm was filled with soil samples in a certain type of moisture content and soil hardness. Soil hardness is a parameter that can be measured by soil hardness equipment, which was developed in Japan, and shows the resistance force from the soil. This parameter could be used to assess the degree of soil compaction. The equipment used and the standard for evaluating the value is shown in Figure 6 and Table 3. The slope of the soil bed was changed by the pulley. The test condition is summarized in Table 4.

4.2. Result and discussion

4.2.1. Effect of soil characteristics on soil erosion

According to the results of the artificial rainfall experiment (Figure 7), soil loss decreases abruptly up to a certain liquid limit and plasticity index value, above which it decreases gradually. The amount of soil loss shows a loss of more than 5,000g/m^2 in sandy soil, which has a low liquid limit and low plasticity index, while clayey soil having a high liquid limit and plasticity index produces 1,000g/m^2 or less of soil loss. This fact indicates that the cohesive strength of soil increases with an increase in these values due to the function of clay. From these results, it is important to understand not only the distribution of natural rainfall and topography data but also the soil characteristic spread to the rehabilitation area in order to predict and assess soil erosion in the rehabilitation area. Given the backfilling of the soil with various characteristics in the rehabilitation area, the risk of soil erosion is considerably increased by mixing overburden as contamination during soil spread. In order to minimize the risk of erosion hazards in the rehabilitation area, an adequate rehabilitation process or effective countermeasures to prevent soil erosion must be considered.

4.2.2. Effective prevention for soil erosion

In this study, three control measures to prevent soil erosion are discussed as feasible methods to be applied in-situ: arrangement of the slope angle, effect of soil compaction, and application of cover crops to the surface.

The primary aim of the slope design in the rehabilitation area is to stabilize the slope in order to avoid risks of accidents involving men or machinery [20, 21]. Meanwhile, this is an integral part of most soil erosion prediction models [22]. The purpose of arranging the slope angle for soil erosion is to control the tractive force through water flow. In this study, the slope angle was arranged by a pulley to 25° and 15°.

Excessive soil compaction can occur due to the use of heavy equipment during soil placement. Soil compaction inhibits root growth of seedlings by increasing the bulk density and soil strength, and by decreasing porosity and water infiltration [23, 24]. These situations may also lead to accelerated runoff and soil erosion because low water infiltration causes high surface runoff that flows over the soil and carries soil particles [25]. On the other hand, increasing soil strength contributes to the reduction of soil loss by improving the erosion resistance of soil [26]. Therefore, it is important to understand the effects of soil compaction on soil loss caused by rainfall in order to discuss erosion control. This is discussed by arranging soil hardnesses into compacted (19~21mm) and loosened (4~6mm) based on the previous test.

Vegetation has long been identified as the most effective way to minimize soil erosion and as an important measure for soil conservation. At the beginning stage of revegetation, herbaceous cover species should be applied for maintenance and repair. Soil amelioration can be accomplished by planting grasses and legumes due to increasing soil micro-organism and nitrogen fixation [27, 28]. In addition, erosion and sediment control can also be achieved by vegetation cover [29]. Surface cover through cover crops decreases soil detachment and transport by leaf cover and root establishment. Concerning the application of cover crops to the surface, the surface cover rate was changed from 0% to 90% by an artificial plant made of waterproof 20 x 20 mm-sized paper with a toothpick (Figure 8). In this experiment, the effects of roots on infiltration and soil strength caused by plants are ignored in order to focus on the effects of the surface cover.

Figure 9 shows the results of the reduction rate of soil loss at each measurement based on the results of the previous experiment. The same pattern of prevention effects in the slope angle and soil compaction can be seen. Soil loss was obviously decreased and showed a reduction rate of 20-40% in soil No.1, No.2, and No.3 though the effect on other soils cannot be confirmed. Considering the role of each measure as mentioned above, it can be presumed that soil No.1, No.2, and No.3 are sensitive in each measure to decrease soil loss due to their low cohesive strength. In other words, these measures are not critical for reducing soil loss in soil having a high erosion resistance. From the results of the surface covered by cover crops, certain effects of reducing soil loss with surface coverage rate in all samples are as follows: 90% surface coverage gives the highest effect to decreasing soil loss (40-60% reduction) while the reduction rate of 30% and 60% surface coverage shows 15-35% and 20-45% soil loss, respectively. As this experiment was carried out under high rainfall intensity, it can be hypothesized that this reduction is attributed to the decreasing impact to the surface by raindrops. Therefore, intercepting rainfall on the surface of the rehabilitation area is the most effective way to prevent soil erosion in regions with heavy rainfall, such as tropical regions.

From a comprehensive point of view, it is important for the design of a self-sustainable land surface against soil erosion to selectively backfill the soil having a high erosion resistance, which has a high potential of soil erosion, such as slope, and it is important to cover the surface by cover crops that can be expected to grow up early and to cover a wide range of the surface. However, in some cases, the difficulty is to prepare the proper soil in-situ because topsoil characteristics used as spreading to rehabilitation area are site specific. In such a case, additional considerations such as combining each measure, application of erosion control structure, and soil amendment become necessary in order to limit the extent of soil erosion.

5. Conclusion

This paper describes soil erosion, which is considered to be one of the most significant problems of the post-mine surface in tropical regions. From the soil analysis results, the soil spread to the rehabilitation area shows various soil characteristics caused by mixing overburden as contamination during soil stripping and the soil stockpiling process, despite topsoil in the natural forest, backfills the rehabilitation area. This situation can be expected to increase the risk of erosion hazards under an abundant rainfall, such as a cloudburst in tropical regions.

Soil erosion is related to soil composition and high clay content increases the resistance against soil erosion. Considering climate conditions in tropical regions, surface coverage by cover crops in order to intercept rainfall to the ground surface is the most effective solution to limit soil loss. Therefore, soil erosion in the rehabilitation area can be effectively controlled by selective placement of resistant soil against soil erosion and rapid establishment of protective surface cover by vegetation. However, additional research, such as the effect of combining some measures, application of erosion control structure, and soil amendments, has to be conducted when sufficient amounts of erosion resistant soil are difficult to prepare.

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