Research paper

A Study of Ventilating and Watertight Resin on Mudstone Soil Erosion Control

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【Summary】

High-intensity rainfall usually causes runoff and inter-rill erosion on slopes, which are serious problems of soil and water conservation. To accelerate the re-vegetation of exposed landslide areas, hydroseeding is widely applied as an economically feasible way. However, various hydroseeding materials have different effective durations, the concentration for plant growth has some influence, and additives may be exuded. This research used a ventilating and watertight resin spray on a mudstone soil surface to investigate soil erosion, drainage water quality, and soil hardness using a rainfall simulator with various conditions of slope, rainfall intensity, and concentration. The results showed that soil erosion significantly decreased, suggesting a good erosion-resisting effect by the ventilation and watertight resin. Moreover, no significant variation in drainage water was observed, and chemical substances were not likely to be released after gelling. Nevertheless, the high resin density will result in poor workability as well as high costs; an adverse effect is that the mudstone will fracture due to raindrop impact. Therefore, realizing the benefits of the concentration of ventilating and watertight resin on erosion control improvements of mudstone soil for estimations and calculations will be conducted for future applications.

Key words: ventilating and watertight resin, mudstone, erosion, rainfall simulator.

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研究報告

透氣防水樹脂對泥岩土壤之防沖效果探討

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摘　要

台灣山坡地常因降雨之強度過大，逕流沖蝕破壞，坡地表層沖失，成為水土保持上之嚴重問題，為加速使裸露邊坡恢復植生，噴植工法為經濟可行的方法之一。惟不同噴植材料效果的延續時間差異，且不同配方濃度對植物發芽生長亦有一定的影響。本文乃以新引進之透氣防水樹脂為材料，將其應用於泥岩土樣表面作為土壤防沖保護層，並以人工降雨器模擬，在不同坡度、降雨強度與噴灑藥劑濃度之情況下，探討土壤沖蝕量、浸潤滲漏水質與土壤硬度的影響。試驗結果獲知，噴灑透氣防水樹脂的土壤沖蝕量確實明顯減少，顯示其改善防沖效果佳；又試驗採取浸潤滲漏水質檢測並無明顯變化，顯示其膠化反應後並不容易釋出化學物質。但噴灑透氣防水樹脂濃度太高時，不僅工作度變差且不經濟；濃度太低時，因泥岩土壤表面容易龜裂的特性，受到雨滴打擊會產生破裂現象。因此如何瞭解透氣防水樹脂噴灑濃度配比對泥岩土壤的抗沖蝕改善效益，並能進行推估計算，將有助於未來的應用參考。

關鍵詞：透氣防水樹脂、泥岩、沖蝕、改善估算、模擬降雨器。

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INTRODUCTION

In order to promptly restore vegetation protection for vast bare slopes, the hydroseeding method for soil and water conservation is an economically feasible method. A suitable material for the hydroseeding method should adhere to the ground and prevent soil erosion, but the various hydroseeding materials have different effective durations and different reactions to various soils, gradients, and climates. Thus, these conditions need to be quantified to compare the influences (Carr and Ballard 1980, Fohrer et al. 1999).

In southwestern Taiwan, there is a vast mudstone area, occupying an area of 1014 km^2. Mudstone usually exhibits high alkalinity, resulting in the soil having high pH values (of 8~9) and poor water retention. Owing to the low resistance to weathering and the badlands topography, and since the mudstone will swell and disintegrate, once the slope is bare, it is unlikely to spontaneously be covered by vegetation (Chen 1994, Lee et al. 1994, Tien et al. 1994, Wang and Huang 2002). Without effective soil and water conservation measures, artificial development will aggravate desertification and environment crises.

At present, ecological engineering has attracted considerable attention in Taiwan, namely the application of vegetation engineering for soil and water conservation. Vegetation engineering for soil and water conservation usually adopts grass planting, broadcast sowing, hydroseeding, and covering. Among these, hydroseeding is fast and applicable to large areas, and the engineering industry favours this method (Simanton et al. 1984, Chiu and Yin 1987, Figueiredo and Poesen 1998, Lin and Huang 2002, Kung and

Lin 2003). Among numerous hydroseeding materials, ventilation and watertight resin (KMCO-955) can control erosion and cement the surface of the soil structure; hence, it has been developed for a few years, and its characteristics and effects need to be further tested and evaluated.

This study applied KMCO-955 resin to mudstone areas to investigate its soil erosion-control by statistical comparisons, and analyses based on past erosion experimental results derived from Hsu et al. (2010). We also established an estimation formula for the soil erosion force per unit area according to different concentrations. The results can be used as a reference for future applications for the design and planning of hydroseeding.

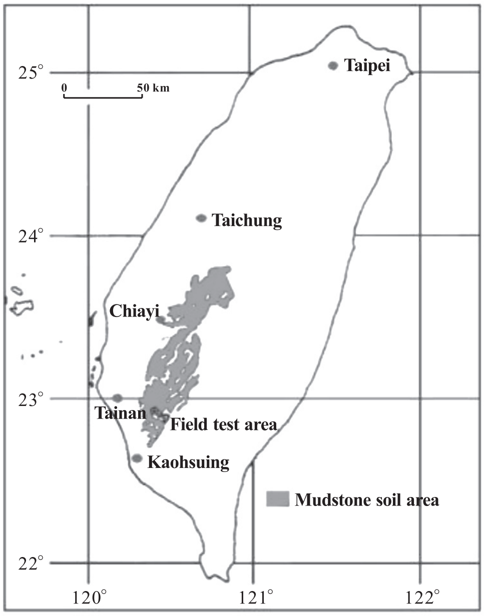

Fig. 1. Outcrops of mudstone in south western Taiwan and the location of the test area.

MATERIALS AND METHODS

Experiment materials

Test soil

Test soil was collected from weathered colluvial soil at the lower part of a bare mudstone slope at Moon World of Kaohsiung County (Fig. 1). The particular physicochemical properties of the mudstone are its pH value, percentage of silt particles, and high salt content. The material is as hard as stone when it is dry, and its surface cracks as scales. The surface layer is soft, muddy, and very unstable when it is wet. With alternations between dry and wet periods and with rain impact erosion, the mudstone surface layer is likely to fall off in flakes, drain, and form bare land with no vegetative cover. Its engineering properties are highly influenced by water, in the pronounced swelling and slaking properties, with a high erosion rate, and the strength decreases with an increase in the water content (Wang and Huang 2002). The mudstone texture is fine, the infiltration rate is very low, and runoff will likely accumulate, which contains a lot of soluble salts. These exchangeable sodium and chloride ions are likely to cause soil dispersion. Soil colloidal particles are often suspended in water, so the soil runoff consists of turbid water in the rainy season (Vincent and Bissonnais 2003, Rorke 2006), which will affects the stability of slopes, and even increases soil loss.

Properties of the ventilation and watertight resin

The ventilation and watertight resin (KMCO-955) is composed of 2 reagents (Table 1), which are polyurethane compounds, recently imported into Taiwan, and it is currently being tested for stabilizing slopes. It reacts and forms a ventilated, watertight, and reticulated foam elastomeric structure, with interfacial activity and good permeability to soil particles. It is hard to crack by vibration.

Table 1. Basic characteristic of the ventilation and watertight resin

Reagent	A Drug	B Drug
Appearance	Yellowish	Colorless
Viscocity	2000 cps	1~5 cps
Proportion	1.05	1
Gumming time	1~2 min	

In addition to covering with straw or nonwoven material to prevent erosion after filling in additional soil and sowing seeds on a slope, the KMCO-955 solution can also be sprayed due to its facile operability and performance. This study evaluated the erosion-resistance of 5 concentrations (0, 1, 5, 10, and 20%) of KMCO-955.

Artificial rainfall simulator

The erosion tests used an artificial rainfall simulator (Fig. 2), which has been extensively studied in the field and laboratory (Nolan et al. 1997, Fan and Wu 2001, Barthes and Roose 2002, Shekl et al. 2003, Tejada and Gonzalez 2006, Vahabi and Nikkami 2008). This apparatus can control most influences, such as slope, soil texture, and moisture content. Moreover, the relative effectiveness of various erosion control techniques can be assessed (Vahabi and Nikkami 2008). This study assumed 3 slopes (20°, 30°, and 40°) and intensities (20, 30, and 40 mm h^{-1}). Weathered mudstone soil was used and tamped (watered and kept outdoors for more than 2 wk) in a plastic container of 42×30×15 cm (Fig. 3).

Infiltration water quality test

To determine the effect of infiltrated matter on the soil and water quality after applying the ventilation and watertight resin solution during testing, TENCO Model 113 and pH Model 620D (Kaohsiung, Taiwan) were used to measure and compare quality changes in the infiltration water.

Fig. 2. Artificial rainfall simulator.

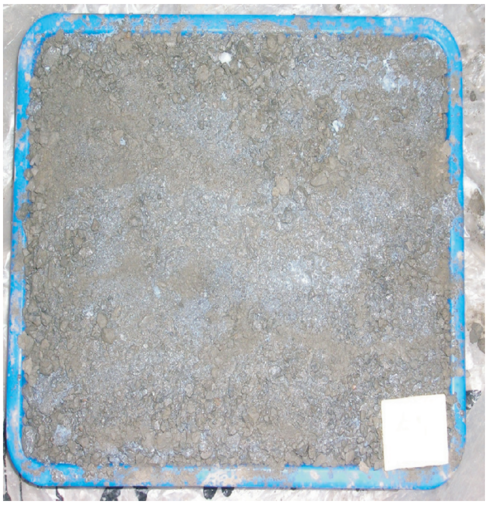

Fig. 3. Test box sprayed with a 5% concentration of KMCO-955.

Soil hardness test

In order to determine whether the KMCO-955 resin can change the soil hardness on the slope, this study compared untreated and treated plots using Yamanaka's soil hardness tester (Fujiwara Co. Ltd., Tokyo, Japan) outdoors.

Experimental analysis

The analytical method used analysis of variance (ANOVA), and a significance level of $p < 0.05$ was set throughout the study. The linear relation between a set of predictor variables and a criterion variable was obtained from the test results using a multiple-regression analysis, which is an extended application of a simple correlation. The predictive ability of each predictor variable was the important reference index of the researchers. For example, given a result of the joint examination of Y_i (criterion), and the result of a mock examination of X_i (predictor), when there is only 1 criterion variable and 1 predictor variable, this is called a simple regression, expressed as follows:

$Y = a + bX$.

When there are 1 criterion variable and more than 2 predictor variables, this is called a univariate multiple regression:

$Y = a + b_1X_1 + b_2X_2 + \ldots + b_iX_i$.

When there are more than 2 criterion variables and more than 2 predictor variables, this is called a multivariate multiple regression, and it can be expressed by a matrix mode as follows:

$Y = XB + E$;

where Y is the data matrix, X is the mode matrix, B is the parameter matrix, and E is the error matrix.

The collinearity or multicollinearity of the multiple regression analysis should be evaluated since a high relevancy between the independent variables could lead to difficulties in the regression analysis. This problem occurs when a predictor variable is a linear combination of other independent variables. Given 2 independent variables, X_1 and X_2, perfect collinearity means that X_1 is a linear function of X_2 ($X_1 = a + bX_2$). If the model contains a serious collinearity, then the parameters of the model cannot be completely estimated.

Whether there is a collinearity problem between predictor variables can be judged by the following indices.

Tolerance: The tolerance is equal to 1-R^2, and range 0~1. If the tolerance of an independent variable is too small, there may be a collinearity problem between the variable and other independent variables. If the value approaches 0, it means that this variable is almost a linear combination of other variables. In this condition, the estimated value of the regression coefficient is variable, and moreover the calculated value of the regression coefficient could be seriously in error.

Variance inflation factor (VIF): This is the reciprocal of tolerance. The larger the VIF is, the smaller the tolerance of the independent variable will be, and the greater the collinearity problems that will occur.

Condition index (CI): In the factor analysis of the independent variable-related matrix, the eigenvalue can be used as an index of dimensions between variables. If the eigenvalue approaches 0, this indicates that there is a high internal correlation between the original variables. The correlation matrix for this set of independent variables is "ill-conditioned", and a slight change in data values may result in large fluctuations of the coefficient estimates (Belsley and Oldford 1986). If the CI is > 15, it means that there may be a collinearity problem; if the CI is > 30, it means that there is a serious collinearity problem. The larger the value of CI is, the greater collinearity problem there will be.

Coefficient of correlation (R): The judgment criterion is as follows: when $R < 0.20$, there is a very low correlation; when $0.21 < R < 0.40$, there is a low correlation; when $0.41 < R < 0.70$, there is a moderate correlation; when $0.71 < R < 0.90$, there is a high correlation; and when $R > 0.91$, there is a very high correlation.

RESULTS AND DISCUSSION

Relationship between rainfall intensity and erosion

According to the relation between the soil loss (g m^{-2} h^{-1}) and the test gradient (°) under 3 different rainfall intensities, as shown in Tables 2~4, the soil loss per unit area of the mudstone soil specimen sprayed with the KMCO-955 resin was less than that of the control group (0%), and decreased with an increasing concentration of KMCO-955.

The relation between the concentration of KMCO-955 and soil loss for the 3 slopes was plotted as shown in Figs. 4~6. The relational expressions in Table 5 were derived from a simple logistic regression analysis.

According to Table 5, the mudstone soil eroded per unit area was inversely proportional to the concentration of KMCO-955 and to the test slope. As the interception of the regression relation increased with the rainfall intensity, the mudstone soil which eroded per unit area was proportional to the rainfall intensity. In addition, the coefficient of determination R^2 was between 0.7887 and 0.9653, and the R value was between 0.8881 and 0.9825. According to the judgment criterion for the statistical coefficients of the correlation, which belonged to high to a very high

Table 2. Soil loss with 20-mm h^{-1} rainfall

Slope	Experimental concentration/Soil loss (g m^{-2} h^{-1})				
	0%	1%	5%	10%	20%
20°	142.1	98.4	22.2	20.6	15.1
30°	200.8	118.3	81.0	42.1	23.8
40°	231.7	208.7	94.4	54.0	50.0

Table 3. Soil loss with 30-mm h^{-1} rainfall

Slope	Experimental concentration/Soil loss (g m^{-2} h^{-1})				
	0%	1%	5%	10%	20%
20°	547.6	377.0	95.2	27.0	20.6
30°	615.9	541.3	145.2	148.4	50.8
40°	792.1	637.3	248.4	155.6	54.8

Table 4. Soil loss with 40-mm h^{-1} rainfall

Slope	Experimental concentration/Soil loss (g m^{-2} h^{-1})				
	0%	1%	5%	10%	20%
20°	662.7	460.3	119.8	105.6	107.1
30°	750.0	532.5	299.2	232.5	113.5
40°	1220.6	1088.9	523.0	307.1	206.3

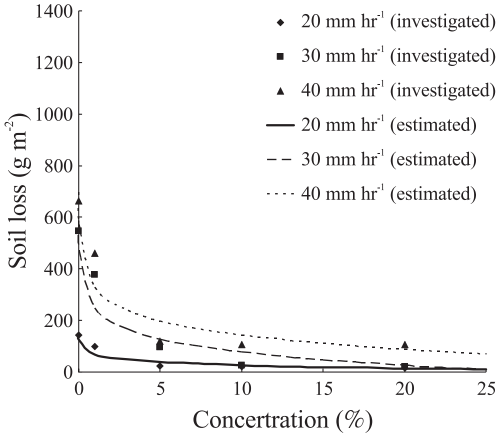

Fig. 4. Soil loss with a test slope of 20°.

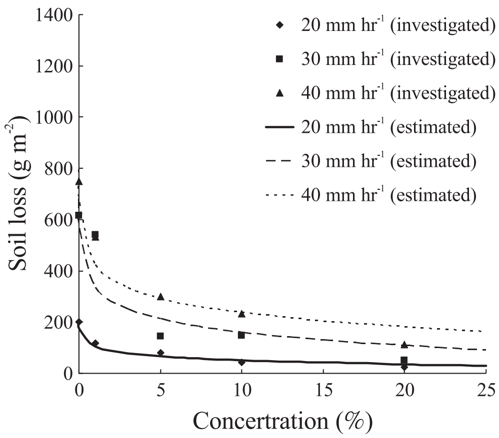

Fig. 5. Soil loss with a test slope of 30°.

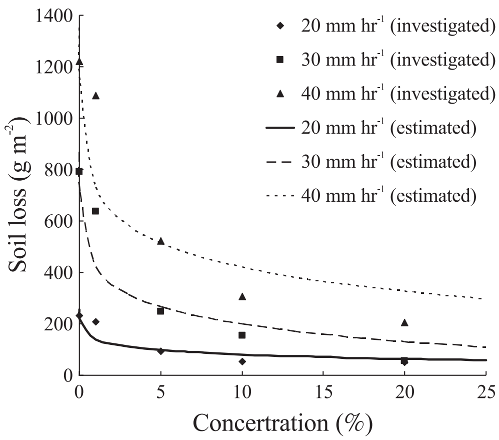

Fig. 6. Soil loss with a test slope of 40°.

correlation, the tolerance was between 0.0347 and 0.2113, and the VIF factor was between 4.7326 and 28.8184; the collinearity problem must be considered. Nevertheless, the *p* value was < 0.05 and reached a significant level.

The statistical regression equation shows, that the concentration of KMCO-955 mostly approached the 2% inflection area of the estimate line. Compared to the measured data, when the concentration of reagent was 1%, the effect of erosion-resistance began to appear; when it was 5%, there was a quite-obvious treatment effect.

Penetration water quality variation

The most sensitive pH value and electrical conductivity (EC) were measured in this study to determine whether the KMCO-955 resin could dissolve the chemical material and affect the soil or environment. pH values and the EC of soil samples of the sprayed reagents placed 30 days in the indoors were measured every day with the TENCO Model 113 and pH Model 620D. The results showed that change in the pH value and EC were not significant (Fig. 7). The variation in the pH value was 0.77, and for the EC was 0.56, both approximately 11%. Obviously, KMCO-955 applied on the grade surface for the long term would not change the properties of the soil, and material penetration from the resin decomposition or chemical matter penetration would not occur.

Soil hardness variation

Soil hardness is an indicator of soil compaction. The location of the outdoor experiment was situated on 2 adjacent steep landside slopes about 60° of moon world badlands in Tianliao Township, Kaohsing County. One was sprayed with KMCO-955, the other one was left undisturbed for comparison (Fig. 8). No rain occurred 2 wk prior to the

Table 5. Simple regression analysis results for concentration and soil loss

Slope	Rainfall intensity (mm h^{-1})	Regression equation	R^2	p
20°	20	$Y = 67.9 - 17.9 \times lnX$	0.8999	0.0139
	30	$Y = 247.5 - 73.9 \times lnX$	0.9017	0.0135
	40	$Y = 328.0 - 80.19 \times lnX$	0.8987	0.0141
30°	20	$Y = 103.6 - 22.7 \times lnX$	0.9653	0.0028
	30	$Y = 335.2 - 75.69 \times lnX$	0.7933	0.0427
	40	$Y = 422.7 - 80.64 \times lnX$	0.9281	0.0084
40°	20	$Y = 139.4 - 25.3 \times lnX$	0.7887	0.0442
	30	$Y = 422.3 - 97.1 \times lnX$	0.8528	0.0251
	40	$Y = 731.4 - 134.9 \times lnX$	0.7959	0.0418

Y, soil loss; *X*, concentration; each sample size $n = 15$.

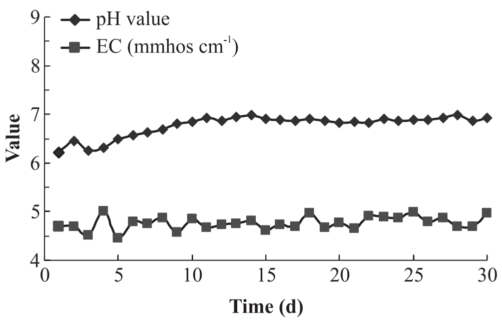

Fig. 7. Variations in the penetration water quality.

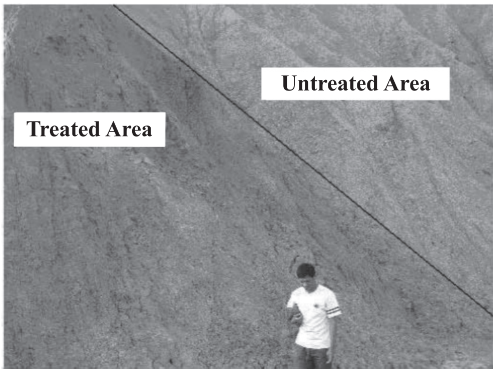

Fig. 8. The plot of the experiment area.

application, and both sites had some soil crust develop with signs of cracking. Soil hardness was measured with Yamanaka's soil hardness tester. Tests began 30 d after the KMCO-955 resin was applied.

Table 6 shows that the soil hardness of the KMCO-955 plot was 28~36 mm, the average value was 32.6 mm; and that of the untreated plot was 27~34 mm, with an average value of 31.5 mm. The statistical analysis indicated no significance; using the ventilation and watertight resin had little effect on soil hardness.

Moreover, through an on-site investigation, cracks in the on mudstone surface still existed and were easy to erode. The anti-erosion mechanism of KMCO-955 was a reaction of the foam elastomeric, which directly blocked raindrops from reacting with the soil. Therefore, during foaming, the material did not penetrate deep into the soil. This spray was only for testing, and the depth was very thin. However, since the cracks on the surface of mudstone covered a wide area, the resin was unable to penetrate deep into the soil to improve the hardness or strength.

Estimation mode of soil erosion loss

The rainfall intensity condition simulated in the test is X_1, the test slope is X_2, the concentration of KMCO-955 is X_3, and the relational expressions from the multiple-

Table 6. Measured results using Yamanaka's soil hardness tester

Project	Measured soil hardness (mm)					Average	Standard error	t-test value
Treated area	33	34	28	34	36	32.6	2.6750	0.9491
	33	35	30	34	29			
Untreated area	32	33	30	34	27	31.5	2.5055	
	34	34	28	31	32			

When α = 0.05, the critical t value is 1.7341, and at less than this test value, the null hypothesis is rejexted.

Table 7. Multiple regression analysis results for soil loss

Type	Regression equation	R^2	p
With the intercept	$Y = -0.8X_1 + 10.2X_2 - 22.8X_3$	0.6663	7.25×10^{-10}
Without the intercept	$Y = 11.6X_1 + 4.1X_2 - 24.6X_3$	0.7947	2.52×10^{-14}

Y, soil loss; X_1, rainfall intensity; X_2, slope; X_3, concentration; sample size $n = 45$.

regression analysis are shown in Table 7. The statistical analysis showed that there was high significance.

The coefficient of determinations R^2 were 0.6663 and 0.7947, R values were 0.8163 and 0.8915, which showed that the coefficients of correlation had high correlations; moreover, the tolerances were 0.3337 and 0.2053, and VIF values were 2.9967 and 4.8709, indicating that there were few collinearity problems. X_1 and X_2 were proportional, indicating that the rainfall intensity and slope were positively related to soil loss, and the concentration X_3 was negatively correlated with soil loss. Disregarding the high coefficient of the determination of the intercept regression relation, the application has physical significance. Thus, it is suggested to use this relational expression to estimate the effect of KMCO-955.

Figure 9 shows the results of mudstone soil eroded per unit area from testing and the estimation equations from the statistical regression. There may be an underestimation when the mudstone soil eroded a unit area of < 50 g m^{-2} and > 550 g m^{-2} in the 2 estimation equations. The closer the value is to both sides, the larger the deviation will be, and the intervening estimated value is slightly higher, which is still within an acceptable range.

Comprehensive analysis

For KMCO-955 sprayed on the surface of mudstone soil, the test results showed no significant variation in the drainage water quality during testing, which apparently indicated that little chemical matter was released that could affect the drainage water quality or soil properties after gelling. However, further tests and research are needed to confirm whether it will release relevant materials to change the water quality or affect soil properties.

During spraying on the outdoor plot, KMCO-955 had poor workability and may be uneconomical, because the reaction time was very short, and when the resin density was too high, the uniformity should be considered. When the resin density was too low, the mudstone still had problems of easily cracking when dry, and the protective layer could break up during high-intensity rainfall. Furthermore, KMCO-955 has low leakage and high ventilation and weather-resistant degree. Combined with hydroseeding, the effects of

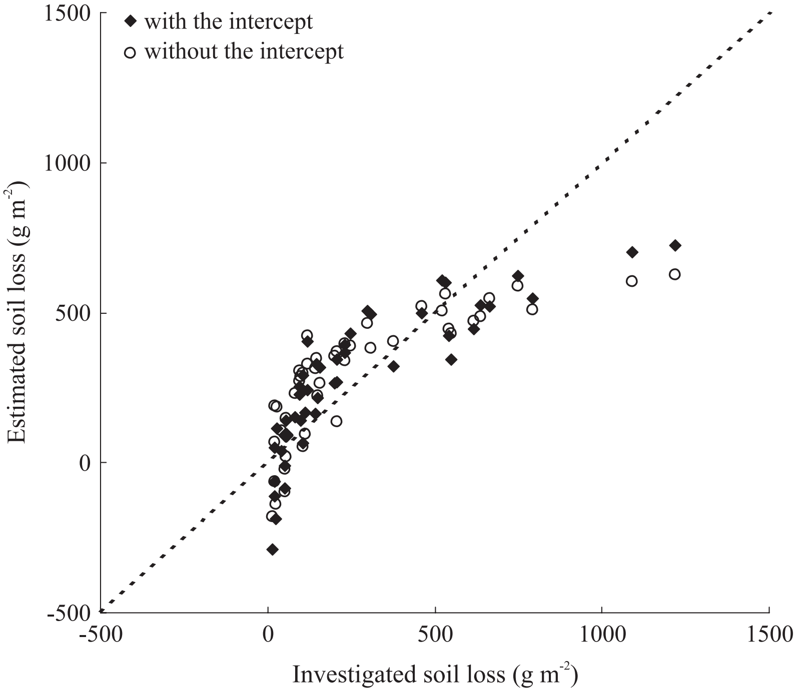

Fig. 9. Relation of investigated and estimated soil loss.

plants growth should be further examined and discussed.

The erosion control testing of KMCO-955 showed that the erosion loss of treated soil specimens could be improved. When the concentration was 5% and the rainfall intensity was 20 mm h^{-1}, the soil erosion loss of unit area was only 15.6% of the control group. However the extent of the improvement declined as the test slope and rainfall intensity increased.

According to the experiment results, using 5% KMCO-955 can achieve a preferable efficiency of soil erosion control improvement. However, the regression estimation statistics showed that the preferable improvement efficiency values mostly approached 2%, which indicated that a concentration between 1 and 5% had a preferable workability. Therefore using this estimation analysis would be helpful for engineering applications.

CONCLUSIONS

Application of KMCO-955 spraying to the surface of mudstone soil can control soil erosion, and erosion decreases as the concentration of KMCO-955 increases. In the regression relation of simulated rainfall intensity, test slope, concentration, and soil loss, the coefficient of determination disregarding the intercept was high, and the application has physical significance, suggesting that this relational equation can be used to estimate the effect of spraying. However, the concentration for different soils, the weather-resistant degree, the combination with hydroseeding, and the effects of plant growth should be further examined and discussed. In addition to understand, the effects of materials on the soil properties, scanning electron microscopy (SEM) can be used to quantitatively analyze the soil structure.

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