CHEMICAL COMPOUNDS EFFECTS ON CRITICAL SHEAR STRESS AND ERODIBILITY OF VOLCANIC ASH SOILS

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Runoff flow erosion is frequently observed for the volcanic ash sandy soil located in Kagoshima area, south western Japan. Worldwide, it is becoming more important to predict the hydraulic erosion amounts depending on the soil mechanical properties to facilitate the method to detect the areas more vulnerable and subjected to erosion. This research presented the peak compressive strength as a main soil property to predict the soil critical shear stress and thus to calculate the erosion rates. However, only a few studies have documented the relationship between soil mechanical properties and critical shear stress, and the results obtained have sometimes seemed contradictory. That is why this research had an aim to overcome these difficulties by using a new laboratory sophisticated erosion model. A series of physical model tests were performed with a wide range of variability of parameters such as chemical compounds conditions, degree of compaction, flow rates and soil mechanical properties, to allow predicting a reliable trend for the critical shear stresses and erosion rates with the peak compressive strengths with a limited tolerance margin. The results show a significant correlation between these parameters. On the other hand, the results proved a remarkable improvement for soil ultimate strength with the common use of chemical compounds doses. The results show that the calcium hydroxide offers a better soil improvement rather than the calcium oxide with a trend of 40%~60% limitation of soil erosion rates, 4~5 times improvement in soil peak compressive strength, and a risen critical shear stress from 5Pa to 8.8 Pa. These results could then provide important findings to predict runoff flow erosion from a geotechnical point of view and thus facilitate field measurement erosion prediction for the volcanic soils

Key Words : *Shirasu soil, shear strength, critical shear stress, soil improvement, hydraulic erosion*

1. INTRODUCTION

Runoff flow erosion is frequently observed for the volcanic ash sandy soil named as Shirasu located in south western Japan[1) 2)]. This paper presents a primary study to predict the rate of soil loss by overflow erosion (E_r) and its relation with the peak compressive strength (q_u). Series of physical models tests were performed on different samples of Shirasu soils reinforced by chemical additives such as calcium hydroxide and calcium oxide. The primary results reinforced the need to account for spatial variability of parameters such as the degree of compaction, water content and particles grading to make realistic predictions of soil loss through erosion by overland flow. The influence of spatial trend in the mean behavior of the critical flow velocities and soil erodibility is also shown to have a significant impact on soil erosion. Several researches were conducted to monitor the riverbanks failures [3)]. Hanson[4)] carried out a channel erosion study of two compacted soils as well as Sheikh et al[5)] measured the erosion rate of compacted Na-montmorillonite soils:

$$E_r = \alpha(\tau - \tau_o)\gamma \qquad (1)$$

Where E_r is the erosion rate per unit time per unit area (m^3/sec/m), τ is the actual shear stress, τc is the critical shear stress and (α, γ) are the variable measured factors from laboratory tests experimental model.

Erosion rates had been often linked with the shear stress applied on the soil surface. The current study has an objective to understand more the effect of soil mechanical properties such as the peak compressive strength (q_u) on the hydraulic erosion index such as erosion rates. In this study, the above mentioned relationship is experimentally investigated.

2. PHYSICAL MODEL EROSION APPARATUS

The erosion experimental apparatus flume was using acrylic plates materials. Figure 1 shows a schematic view of the channel. A sample box hole with the dimensions (100 cm x 10 cm x 20 cm) was created at 147 cm upstream from the outlet, where a compacted soil sample was set.

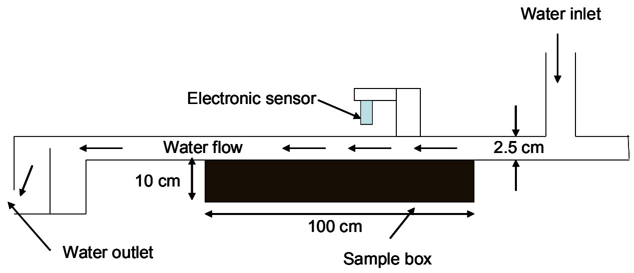

Fig. 1 Experimental apparatus profile view.

A water tank with 1.2 m^3 volume was then set on a frame above the inlet of the flume to maintain a constant head and regulate the flow velocity during the test. On the other hand, a barrel to receive the water passing the apparatus outlet was set at the end to collect the water and by using a pump; the water was driven back to the upper water tank. A mobile electronic sensor was installed above the soil sample box to measure the surface level variations before and after the flow. The results were then transmitted to a data logger to transfer the level surveys in installments.

3. SOIL SPECIMEN

The material used in the erosion tests was the volcanic ash sandy soil (Shirasu soil) taken from Kagoshima prefecture. It is expected that around 27 kg of soil is required for each erosion test, depending on the targeted degree of compaction. The maximum grain size distribution for the soil sample placed in the sample box of the apparatus was 4 mm. The uniformity of this sample was 5 (Figure 2). The maximum dry density was 1248 kg/cm^3. The optimum water content obtained was 20%. In most of cases, a chemical compound (calcium oxide or calcium hydroxide) was added by variable doses for the unit dry weight. To make soil specimen, the sample was compacted using a wooden compactor cylinder of 19 cm in length and 4 cm in diameter until reaching the required compaction degree. The compaction was done layer by layer to ensure particles logging, prevent segregation and then to have a final 10 cm thick homogenous compacted layer. The compaction was carried out in order to respect the maximum dry density at the water optimum value in predetermined calibrated manner.

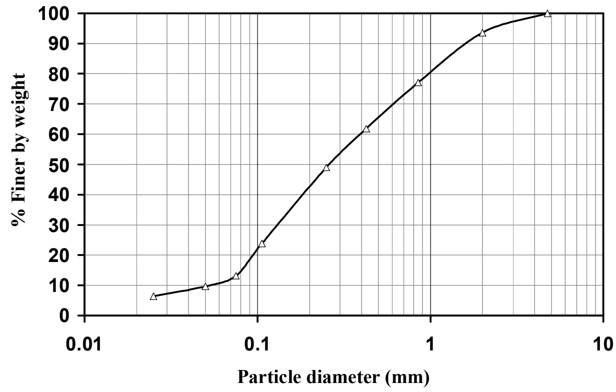

Fig. 2 Grain size distribution curve for Shirasu soil specimen.

4. SOIL SPECIMEN EROSION TEST PROCEDURE

To prepare the soil specimen, the wooden roller was first used to compact soil. The specimen surface area was then adjusted to be horizontal by leveling the soil sample with its box edge. The soil surface survey was then to be measured by the electronic sensor in order to get the initial soil surface area. The sample is then covered by plastic cover until the erosion test start. Water was supplied to the upper tank by a pump till reaching a required head to maintain the variable flow velocities during the test. The flow rate is then regulated by the velocity regulator at the inlet and kept constant during the test. After the primary flow velocity elapsed time, the test is then stopped, and pre-test survey was carried out. The increment of erosion volume (Δv) with the elapsed time (Δt) donate the increment of the loss of the specimen with the elapsed time which could be defined as an erosion rate (E_r).

$$E = \frac{\Delta V}{\Delta t} \tag{2}$$

The net volumes eroded of samples where calculated as shown in Figure 3 and Figure 4 where several lateral profiles were taken into calculations. The average height ($h_m = h_{(1+2+3\ldots+n)/n}$) was obtained for each profile and was multiplied with the width of the sample (L) (which equals 20 cm), then the calculated profiles were integrated together to form the total volume from the erosion test.

$$V_{net} = \int_{A_m}^{A_1} \frac{L \times h_{(1+1+3...+n)}}{n} dA \quad (3)$$

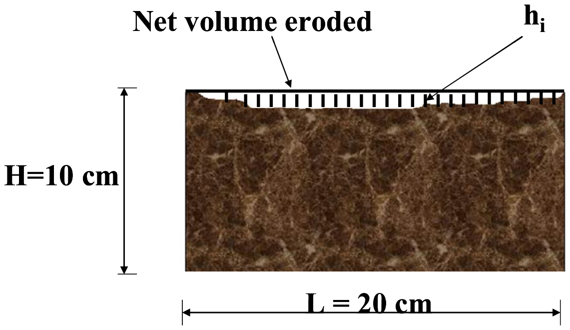

Fig. 3 Soil specimen profile after erosion.

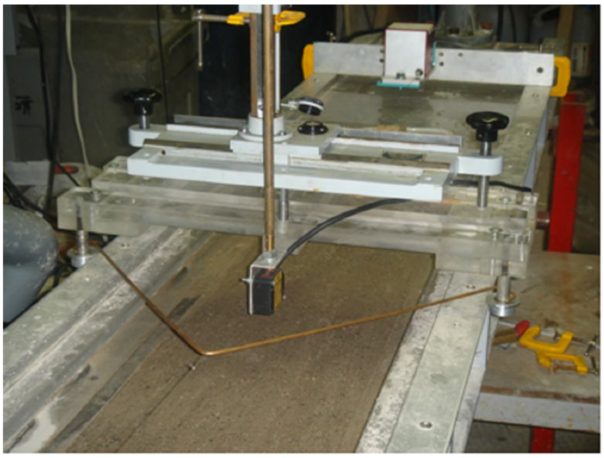

Fig.4 Photograph of the erosion control apparatus of Kyushu University.

5. SOIL SPECIMEN UNIAXIAL COMPRESSION TESTS

The material used for the uniaxial compression tests was at the same condition for that used in the erosion tests in order to maintain the constant conditions of soil properties for both tests. The same dosage of chemical compounds additives and types were applied. Cylindrical specimen of an initial diameter 50 mm and height of 100 mm height were used. The specimens were also compacted in a predetermined manner until reaching around the targeted compaction degree. For each material tested, a separate stress vs. strain curve was plotted.

6. EXPERIMENTAL CASES

Two types of erosion experimental tests were conducted in this study. First, a type of experiments was carried out to investigate the effect of erosion on different degrees of compaction which correspond to cases 1 to 3. On the other hand, another type of experiments was to investigate the influence of the different dosages and types of chemical compounds additives on the erosion rate which is corresponding to cases 4 to 18. The tests conditions and results are summarized in Table 1.

The specimens for cases 1 to 3 were compacted in the apparatus with different compaction layers for each case, in order to obtain different compaction degrees of 0.8, 0.9 and 0.93 of the maximum dry density at the optimum water content mentioned before. The calcium hydroxide doses of 1%, 2% and 3% were added to the Shirasu soils specimens and cured for 1, 7, 14 days respectively which represent cases 4 to 12. The calcium oxide dosages of 1% and 3% were added to the Shirasu soils specimens and cured for 1, 7, 14 days which represent cases 13 to 18.

7. EXPRESSIONS AND METHODS TO ESTIMATE THE CRITICAL SHEAR STRESS

The estimation of the critical shear stress of a soil is usually achieved by subjecting a sample of this soil to a range of hydraulic shear stresses6). The shear stress at a given location at the soil surface can be estimated from the logarithmic vertical velocity profile:

$$u(z) = \frac{u_*}{K} \ln(\frac{Z}{Z_0}) \quad (4)$$

Where u is the velocity at elevation z above the bed, u* is the shear velocity, K is von Karman's constant (generally set to 0.4) and Zo is the roughness height. The shear stress is then estimated from the shear velocity:

$$\tau = \rho u_*^2 \quad (5)$$

However it is difficult to measure $u(z)$ near the bed, so shear stress is thus more conveniently estimated at:

$$\tau = \rho g h S_f \quad (6)$$

Where ρ is water mass density, g is the gravity constant, h is the water depth and Sf is the friction slope[7].

The best way to obtain τ was by using the Moody Chart (Moody, 1944)8) for pipe flows.

$$\tau = \frac{1}{8} f \rho v^2 \quad (7)$$

Table 1. Specimen properties, test conditions and results

	Case No.	Compaction degree (%)	Water content (%)	Dry density (g/cm³)	Critical velocity (cm/s)	Eroded volume (cm³)	Erosion rate (cm³/s)	Chemical additive	Dose percentage	Curing days	Peak compressive strength (qu) (KN/m²)	Critical Shear stresses (Pa)
Series I	1	0.8	18.9	1.02	18	48.1700	0.0268	…….	…….	1	7	3.17844
	2	0.9	18.9	1.11	23	23.5700	0.0131	…….	…….	1	17	5.18949
	3	0.93	18.8	1.14	25	19.5600	0.0109	…….	…….	1	21	6.13125
Series II	4	0.89	20.3	1.1	25	32.9800	0.0137	$Ca(OH)_2$	1%	1	34.24	6.13125
	5	0.91	19.6	1.12	25	24.4980	0.0102	$Ca(OH)_2$	1%	7	51.50	6.13125
	6	0.9	20	1.11	26	18.3012	0.0076	$Ca(OH)_2$	1%	14	55.17	6.63156
Series III	7	0.9	20.1	1.11	27	29.8870	0.0125	$Ca(OH)_2$	2%	1	43.37	7.15149
	8	0.9	19.2	1.11	28	18.3135	0.0076	$Ca(OH)_2$	2%	7	53.29	7.69104
	9	0.91	20.6	1.12	28	15.3237	0.0064	$Ca(OH)_2$	2%	14	78.55	7.69104
Series IV	10	0.9	19.8	1.11	29	19.2080	0.0080	$Ca(OH)_2$	3%	1	45.61	8.25021
	11	0.89	19.9	1.1	30	11.9140	0.0050	$Ca(OH)_2$	3%	7	73.46	8.829
	12	0.9	19.7	1.11	30	11.0680	0.0046	$Ca(OH)_2$	3%	14	101.44	8.829
Series V	13	0.88	20.3	1.09	22	33.3863	0.0139	CaO	1%	1	21.22	4.74804
	14	0.9	19.8	1.11	23	25.9892	0.0108	CaO	1%	7	29.31	5.18949
	15	0.92	20.1	1.13	23	25.7078	0.0107	CaO	1%	14	32.14	5.18949
Series VI	16	0.91	20	1.12	25	31.8348	0.0133	CaO	3%	1	30.72	6.13125
	17	0.9	19.2	1.11	25	27.7356	0.0116	CaO	3%	7	38.26	6.13125
	18	0.9	20.2	1.11	26	16.8097	0.0070	CaO	3%	14	40.2	6.63156

8. RESULTS AND CONSIDERATIONS

(1) Erosion rates and chemical additives versus the compaction degree

The influence of compaction degree on erosion of soils was investigated. For these primary tests, uniaxial compression tests were carried for the mentioned three degree of compaction to understand the variation of the compressive strength of these samples. Comparing cases 1 to 3, the results obtained show that higher compressive strengths and less erosion rates were found with the higher compaction degree (Figure 5.). It is worth mentioned that higher critical velocities were obtained with the higher degree of compaction and compressive strength.

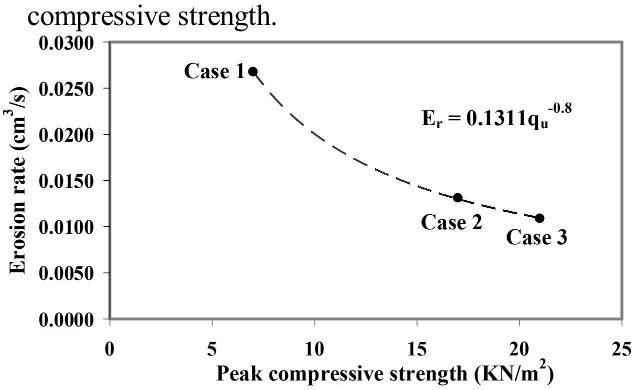

Fig. 5 Erosion rates in relation with peak compressive strengths values for different degrees of compaction.

Uniaxial compression tests were carried out for samples of Shirasu soils (for compaction degree of 0.9) with 1, 7, 14 days and 1%, 2%, 3% of soil dry weight with chemical dosage of CaO and Ca $(OH)_2$. The mechanical analysis for the specimens (Shirasu with CaO or Ca $(OH)_2$) shows a higher compressive strength after any case of curing days (1, 7, 14 days) for Ca $(OH)_2$ than CaO for different dosages. The relationship between the peak compressive strength (KN/m^2) and the different chemical additives doses is shown in Figure 6(a). The compressive strength increases with the higher dose of chemical component whether it is CaO or Ca $(OH)_2$ but relatively the calcium hydroxide gave higher values as shown in Figure 6(b).

(2) Erosion rates, Peak compressive strengths and critical shear stresses

The influence of comp The hydraulic erosion tests were carried out for the cemented soil to provide a better understanding of the effect of cementation to reduce the erosion and to detect the effect of curing days of soil on its strength. Table 1 summarizes the values of erosion rates, specimen properties and test conditions. For the cases 13 to 18 (soil improved by calcium oxide), the results pointed out that higher erosion rates were found for less dose percentage and less curing days. The same results trend could be observed also for the cases 4 to 12 (soil improved by calcium hydroxide).

The erosion rates obtained from Table 1 were defined by monitoring the final survey after the test completion for every case, and then by dividing the volume eroded by the elapsed time, the erosion rates could be then obtained as mentioned in equation (2).

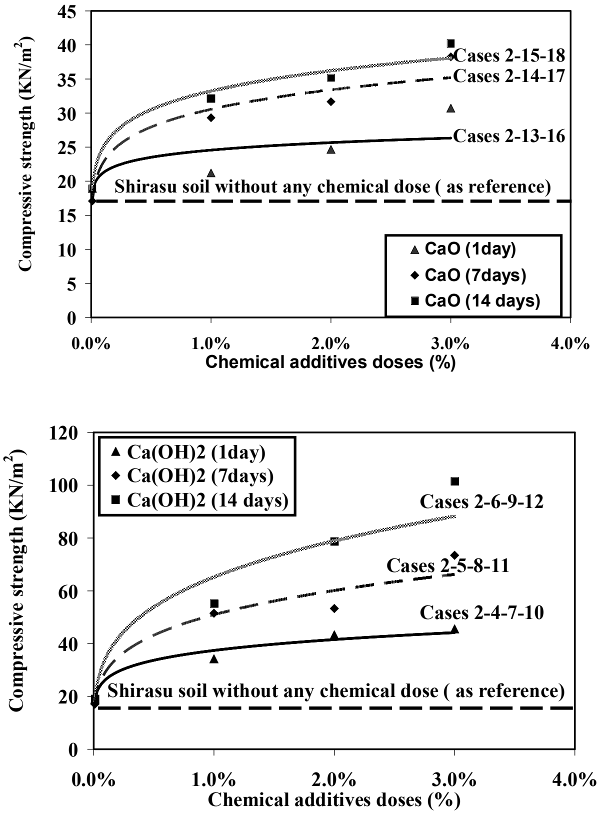

Fig. 6 Peak compressive strengths improvements with chemical doses.

It is shown in Figure 7 for the case of the use of chemical compounds doses that a higher dose could lead to a better soil resistance against erosion and then less erosion rates are obtained. That argument is strongly shown for the case of calcium hydroxide as less erosion rates are obtained so far.

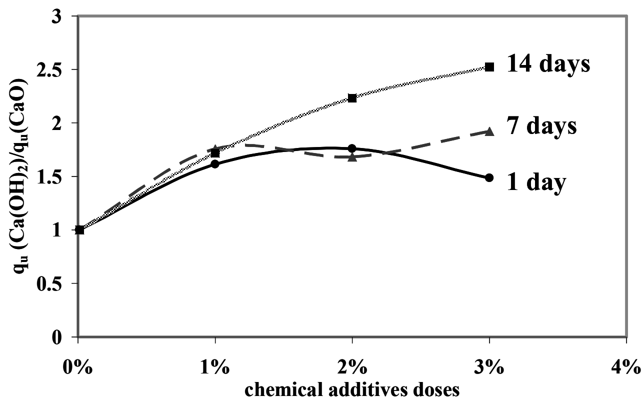

Fig. 7 Normalisation of peak compressive strengths of Ca(OH)2 and CaO in relation with the doses percentages

It was shown that a peak compressive strength improvement of 2.5 times are found for calcium hydroxide rather than calcium oxide (for 14 days curing days case and 3% dose), at the same time half erosion rate are found for the calcium hydroxide are found than the calcium oxide (for 7 days curing days and 3% dose).

For the cases 6 and 15 (1% dose and 14 days curing), it was found out that 30% less erosion rate was obtained for the calcium hydroxide (0.076 cm3/s) than the calcium oxide (0.107 cm3/s). This ratio was found increased for the cases 10, 11,12,16,17 and 18 where 40 to 50% less erosion rate was obtained for the calcium hydroxide rather than the calcium oxide. It worth mentioned that for the case 11, the erosion rate for the calcium hydroxide was 0.050 cm3/s more than 50% less than the case 17 where the erosion rate for the calcium oxide was found at 0.116 cm3/s. It was found out also that higher values are obtained by the use of the calcium hydroxide compounds than the use of the calcium oxide. These higher values could be doubled if the dose is 3% and the curing days will be sustained for 14 days.

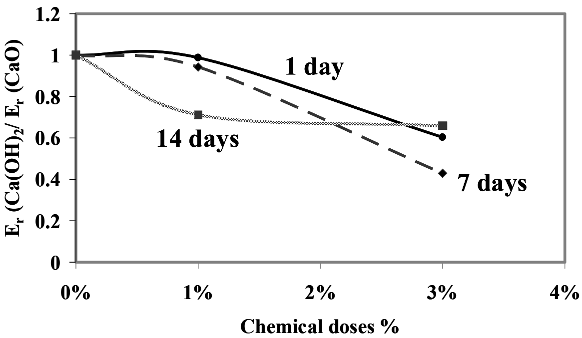

Fig.8 Normalisation of Erosion rates of Ca(OH)2 and CaO in relation with the doses percentages

(3) Correlation of soil mechanics properties and erosion rates

The purpose of the study is to conduct a certain judgment of the dependability between the soil erosion rates and soil mechanical properties. It is found out that for highly compressive strengths soils, less erosion rates were occurred. A correlated relationship between the erosion rates and the peak compressive strength was drawn in Figure 9 to show the possibility to prove that hypothesis. From the experimental results shown at that figure, the erosion rates can be described by the following empirical equation.

$$E_r = 0.09 q_u^{-0.6} \qquad (7)$$

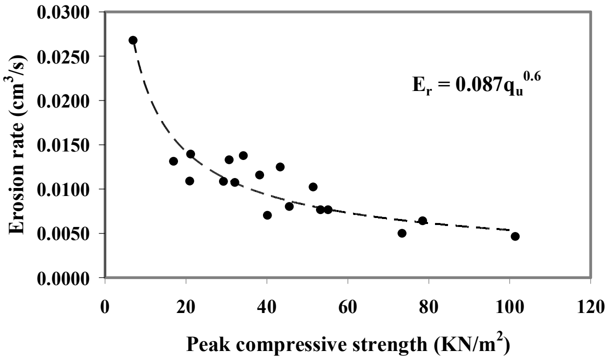

Fig. 9 Correlation of erosion rates with peak compressive strengths

Figure 10 shows the possibility to describe a correlation between the critical shear stresses obtained from the experimental tests in relation with the erosion rates exerted on the specimens by the following empirical equation (with a correlation factor R^2= 0.84).

$$E_r = 0.15 \tau_c^{-1.5} \qquad (8)$$

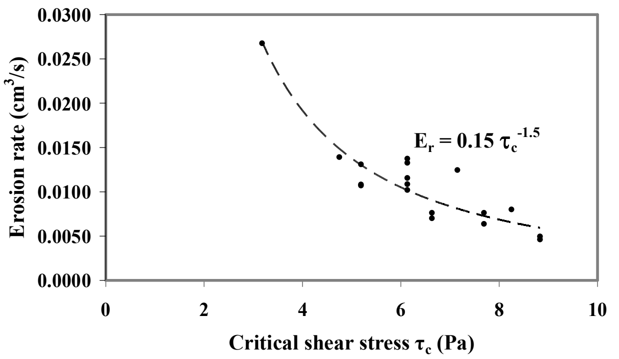

Fig. 10 Correlation of erosion rates with critical shear stresses

It is important to mention that the equation (8) do not contradict the equation (1) as the trend of results in that research is located between specific values and do not represent general range of results.

9. CONCLUSIONS

In order to understand an overflow erosion, a series of erosion tests were conducted using volcanic ash sandy soil which is found at the south western part of Kyushu Island. The experiments investigated the erosion characteristics on the soil improved by chemicals additives and the dependency of erosion rates on the peak compressive strengths. The following are the clarified considerations:

1. The erosion rates of specimens improved by higher percentages of chemical doses are decreased linearly when the flow velocities exerted on the specimens are constants. This consideration is notably found more for the calcium hydroxide.
2. The critical flow velocities of the soil specimens are higher when they are exerted on high compacted soils rather than less compacted ones.
3. The peak compressive strengths increase with higher doses of chemical additives. This important finding could lead to better understand the relationship between the erodibility and the soil mechanical properties. It was found out also that higher values are obtained by the use of calcium hydroxide compounds than using the calcium oxide. Therfore, the peak compressive strength might be an important index to evaluate the degree of erodibility for volcanic sandy soils.

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REFERENCES

1) S. Nakao and T. Tomosho; Analysis of soil erosion and sediment transport along a rill channel using a sediment transport model, *Transactions of the Japanese Society of Irrigation, Drainage and Reclamation Engineering* 64(1); pp. 11-21 (1996), [in Japanese].
2) K. Fujisawa, S. Momoki, K. Yamamoto, A. Kobayashi and S. Aoyama; Failure mechanism of an embankment due to overflowing from a reservoir, *Journal of Applied Mechanics, JSCE,* Vol.9, pp. 385-394, (2006), [in Japanese]
3) I.Awad, N.Yasufuku and H.Ochiai; Erodibility of Unsaturated Volcanic Ash sandy soils related to degree of compaction, *Proceedings of the 3rd Asian conference on unsaturated soils*, Nanjing, China, April 21-23, pp. 169-174, (2007).
4) G. J. Hanson; channel erosion study of two compacted soils, *Transactions of the ASAE*, Vol.32, No.3, pp296-305, (1988).
5) A. Shaikh, Ruff J. F. and S. R. Abt; Erosion rate of compacted Na-montmorillonite soils, *Journal of geotechnical Engineering*, Vol. 114, No.3, pp.127-131, (1990).
6) J. Leonard and G.Richard; Estimation of Runoff critical shear stress for soil erosion from soil shear strength, *CATENA*, Volume 57, Issue 3, 22 August 2004, Pages 233-249 (2003).
7) V. Chow, D. Maidment and L. Mays; *Applied hydrology. Water Resources and Environmental Engineering*. McGraw-Hill, New York, p. 33.
8) J.L. Briaud, F.C.K Ting, H.C Chen, Y. Cao, S. W. Han, K. W. Kwak; Erosion function apparatus for scour rate predictions, *Journal of geotechnical and geoenvironmental engineering*, Vol. 127, n 2, pp 105-113, (2001)