Memoirs of the Faculty of Engineering, Kyushu University, Vol.67, No.4, December 2007

Erosion Rates of Soils Improved by Chemical Additives for Protection against Overland Flow

by

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(Received November 5, 2007)

Abstract

Overland flow erosion is frequently observed for the volcanic ash sandy soil named as Shirasu located in south western Japan. 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 also is shown to have a significant impact on soil erosion.

Keywords: Soil erosion, soil reinforcement, Overland flow, Soil compressive strength, Modulus of deformation, Calcium hydroxide, Calcium oxide

1. Introduction

Soil erodibility is an estimate of the ability of soils to resist erosion, based on the physical characteristics of each soil. Generally, soils with faster infiltration rates, higher levels of organic matter and improved soil structure have a greater resistance to erosion. Sand, sandy loam and loam textured soils tend to be less erodible than silt, very fine sand, and certain clay textured soils.

Japan is located in the Asia monsoon zone and has an annual precipitation reaching 1600 mm. In most of Japan, nearly half of the amount of the rain is concentrating in the summer season, enabling high potential for soil erosion. Two highly erosive soils are found in Japan. The first is weathered into granite ‘Massado”, the other is weathered into volcanic ash sandy soil “Shirasu” used in this study [1)]. Kyushu island in Japan suffers frequently from typhoon and other natural hazards which cause the erosion for riverbanks and over lands. These damages could lead to serious economical and environmental losses. Nowadays, the prevention of soil losses due to erosion is becoming an increasing serious problem. The relationship between flow erosion amounts

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or rates with the mechanical properties of soils are now under study by several researchers. This topic had been mentioned in several references. First, Consoli et al$^{2)}$ carried out triaxial compression tests to evaluate the effect of randomly distributed fiber reinforcement and cement inclusion on the response of a sandy soil to load. Cemented specimens were prepared with cement contents of 0% and 1% by weight of dry soil and cured for seven days. Fiber length was of 12.8 mm, in the contents of 0% and 3% by weight of dry-cement mixture. Test results indicated that the addition of cement to soil increases stiffness, brittleness, and peak strength. The fiber reinforcement increases both the peak and residual triaxial strength, decreases stiffness, and changes the cemented soil's brittle behavior to a more ductile one. This study concluded that the triaxial peak strength increase due to fiber inclusion is more effective for uncemented soil. However, he mentioned that the increase in residual strength is more efficacious when fiber is added to cemented soil. Peak strength envelopes indicate that the friction angle is increased from 35° to 46° as a result of fiber inclusion. The cohesion intercept is affected slightly by fiber addition, being basically a function of cementation.

In another occasion, Consoli et al $^{3)}$ examined some key parameters for the strength control for artificially cemented soils. He mentioned that the use of traditional techniques in geotechnical engineering faces obstacles of economical and environmental nature. The addition of cement becomes an attractive technique when the project requires improvement of the local soil. The treatment of soils with cement finds application, for instance, in the construction of pavement base layers, in slope protection of earth dams, and as a support layer for shallow foundations. However, there are no dosage methodologies based on rational criteria as exist in the case of the concrete technology, where the water/cement ratio plays a fundamental role in the assessment of the target strength. His study aims therefore to quantify the influence of the amount of cement, the porosity and the moisture content on the strength of a sandy soil artificially cemented, as well as to evaluate the use of a water/cement ratio and a voids/cement ratio to assess its unconfined compression strength. In his recent research, he carried out a number of unconfined compression tests, triaxial compression tests, and measurements of matric suction. The results showed that the unconfined compression strength increased linearly with the increase in the cement content and exponentially with the reduction in porosity of the compacted mixture. The change in moisture content also has a marked effect on the unconfined compression strength of mixtures compacted at the same dry density. He concluded that for the soil-cement mixture in an unsaturated state (which is usual for compacted fills), the water/cement ratio is not a good parameter for the assessment of unconfined compression strength. In contrast, the voids/cement ratio, defined as the ratio between the porosity of the compacted mixture and the volumetric cement content, is demonstrated to be the most appropriate parameter to assess the unconfined compression strength of the soil-cement mixture studied.

Rinaldi et al$^{4)}$ stated that the matric suction and cementation together have significant influence on the stress-strain behavior of many lightly cemented soils. The combined effects of suction and cementation during soil formation may stabilize the fabric of the soil at a very high void ratio. This is the case of wind-blown loess of the Pampas formation in Argentina. The scope of his work was to present some fundamental aspects related to the unsaturated stress-strain behavior of lightly cemented silty clay. Triaxial tests were performed in laboratory and strains were monitored by means of local displacement transducers. Undisturbed structured specimens as well as remolded unstructured specimens were tested both in saturated and unsaturated condition. It was observed that cementation and unsaturation cause an increase in yielding stress and shear strength, decrease in volume contraction during loading, and a higher propensity to stress localization. These effects are mainly controlled by water content and confining pressure. At low confinements, the unsaturated and cemented specimens behave more brittle as compared to the uncemented specimens due to the much lower deformation threshold required to break cementing bonds than menisci. He proposed then a bilinear model to model the fragile behavior of cemented specimens.

As an ecologic steam for the bank erosion control, Huang et al[5)] found that no-fines concrete is a pervious concrete obtained by eliminating the sand from normal concrete mix. Compared with conventional concrete, no-fines concrete has unique properties desirable for various applications. Because of the presence of large voids, no-fines concrete has lower density, thermal conductivity, smaller dying shrinkage, no segregation, larger contaminant retaining capability, and reduced capillary movement of water. No-fines concrete is used for construction of pavement, storm water control utilities and green houses. He investigated the application of no-fines concrete as an ecology preservative method for stream bank erosion control. Soil erosion is an important factor that can trigger the instability of an embankment. A sustainable revetment should provide soil erosion protection without significantly changing the existing ecologic environment. The strength of no-fines concrete provides sufficient protection against scour of embankments. Although grasses are found to be hard to survive with ordinary types of bank revetment, especially when subjected to periodic inundation from river water level fluctuations, the large pore spaces of no-fines concrete protect grass seeds and provide an environment for grasses to grow. By installing artificial access holes in the no-fines concrete revetment, the ecologic conditions can be preserved to the maximal extent. He provides an example application of a no-fines concrete revetment that achieved the desirable ecologic effects.

This current study examined an erosion control method for a compacted Shirasu soil sample imported from Aira-gun area, Kagoshima prefecture. The study was launched into two parallel ways: (i) the first way is to determine certain mechanical properties for the Shirasu soil sample, and the second way is (ii) to launch series of laboratory erosion tests on a new built physical model to measure the erosion[6)]. Those two parallel ways have an aim to determine: (i) the improvement of shirasu soil peak compressive strength (qu), (ii) the improvement of the Shirasu soil resistance against the water inflow erosion, and (iii) link the erodibility of the Shirasu soil to its compressive strength which could lead to an improvement of field measurement to predict erodibility.

Several researches were conducted to monitor the riverbanks failures. Fujisawa et al[7)] studied the failure mechanism of an embankment due to overflowing from a reservoir. Hanson et al [8)] conducted laboratory tests to model the overtopping erosion and breach formation of cohesive riverbanks. Finally, Hanson[9)] carried out a channel erosion study of two compacted soils as well as Sheikh et al[10)] measured the erosion rate of compacted Na-montmorillonite soils. For the previous studies, the following equation was proposed to describe erosion rate and its relation with the critical shear stress:

$$E_r = \alpha(\tau-\tau_c)^{\gamma} \tag{1}$$

where: E_r : erosion rate per unit time per unit area (m3/sec/m)
τ : actual shear stress
τ_c : critical shear stress
α, γ : variable measured factors from laboratory tests experimental model

Erosion rates had been often linked with the shear stress applied on the soil surface, however the current study has an objective to understand more the effect of soil mechanical properties such as the peak compressive strength (q_u) and the modulus of deformation (E_{50}) on the hydraulic erosion index such as erosion rates. In this study, the above mentioned relationship is experimentally investigated.

2. Methodology and Material Used

2.1 Experimental erosion control 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. 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.

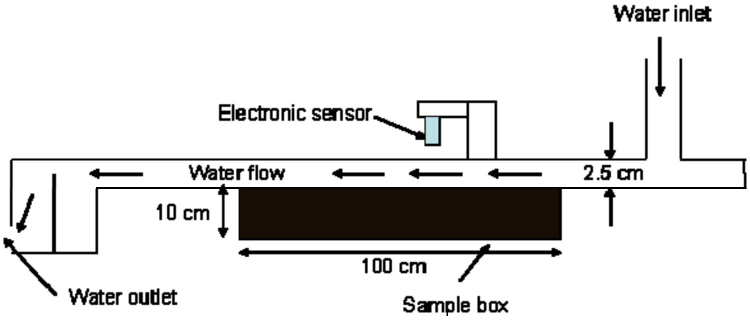


Fig. 1 Experimental apparatus profile view.

2.2 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 (**Fig. 2**). The maximum dry density was 1248 kg/cm^3. The optimum water content obtained was 20%. In most of cases, a type of chemical additive was added by variable dosage for the unit dry weight whether it was calcium oxide or calcium hydroxide.

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.

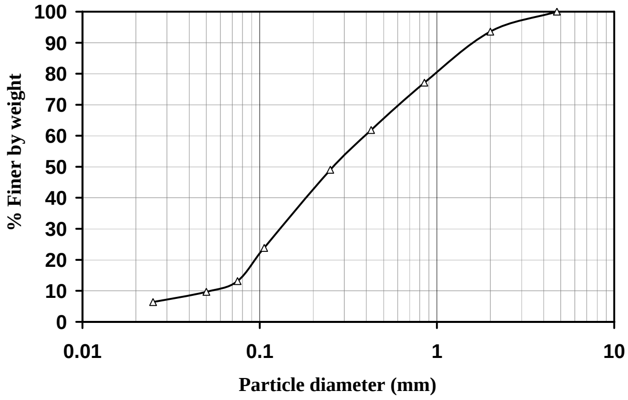


Fig. 2 Grain size distribution curve for Shirasu soil specimen.

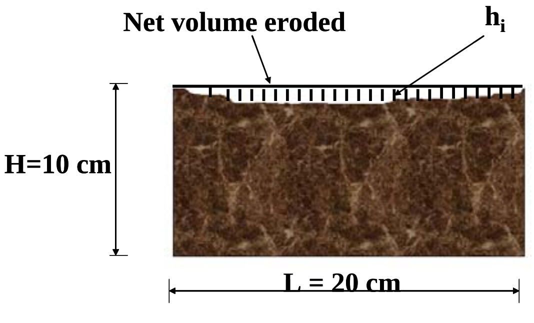
2.3 Soil specimen erosion test procedures

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 (**Fig. 3 (b)**). 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).

$$E = \Delta v / \Delta t \tag{2}$$

The net volume eroded of samples where calculated as shown in **Fig. 3 (a)** 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.

$$V\,net = \int_{A_m}^{A_1} \mathrm{L} \times \mathrm{h}_{1+2+3\ldots+n} / \mathrm{n} \times A_i \tag{3}$$



(a)

(b)

Fig. 3 (a) Soil specimen profile after erosion; **(b)** Test devices for Shirasu soil specimen

2.4 Soil specimen uniaxial compression tests procedures

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 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.

2.5 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 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 dosages 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.

3. Results and Considerations

3.1 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 (**Fig. 4.**). It is worth mentioned that higher critical velocities were obtained with the higher degree of compaction and compressive strength.

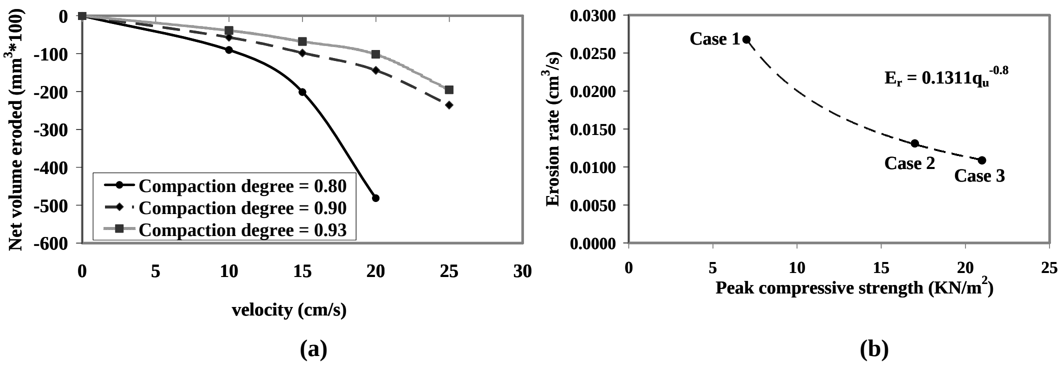


Fig. 4 (a) Net volume eroded from erosion tests results in relation with the corresponding water flow velocities.

(b) Erosion rate 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 day, 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 **Fig. 5**. 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 **Fig. 6**.

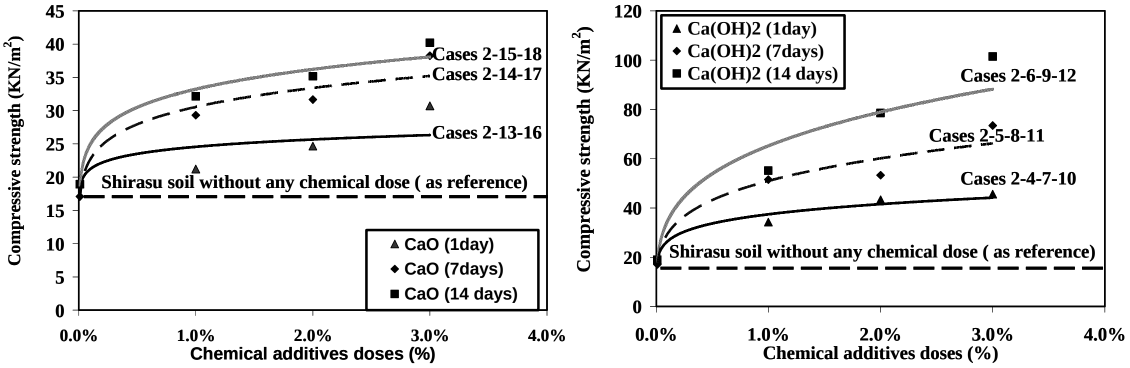


Fig. 5 Peak compressive strength improvement with chemical doses (Cases numbers referred to **Table 1**).

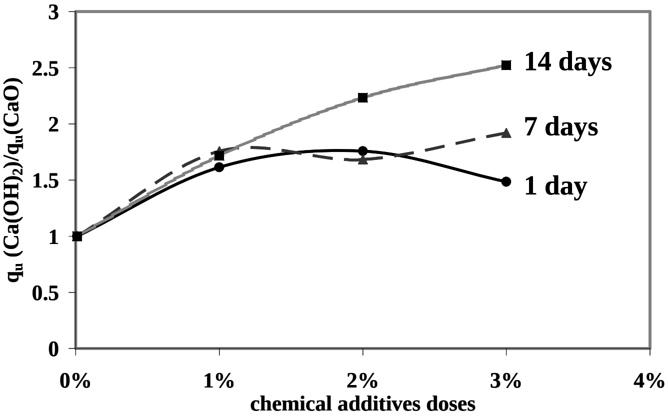


Fig. 6 Comparison between the peak compressive strength for every dose of Shirasu soil with both kinds of the chemical additives (the calcium oxide and the calcium hydroxide).

3.2 Influence of chemical additives on the Shirasu soil specimens erosion rates

The Hydraulic erosion tests were carried out to 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. It means that the uniaxial compressible strength could be a key factor to estimate the erodibility of Shirasu soils. **Table 1** summarizes the values of erosion rates, specimen properties and test conditions. **Figure 7** shows the relationship between the erosion rates and the chemical additives dosage with the water flow velocities for the cases 13 to 18 (soil improved by calcium oxide). The same results trend could be observed in **Fig. 8** also for the cases 4 to 12 (soil improved by calcium hydroxide). The data show that the erosion rates decreases for the higher dosage and the higher curing days.

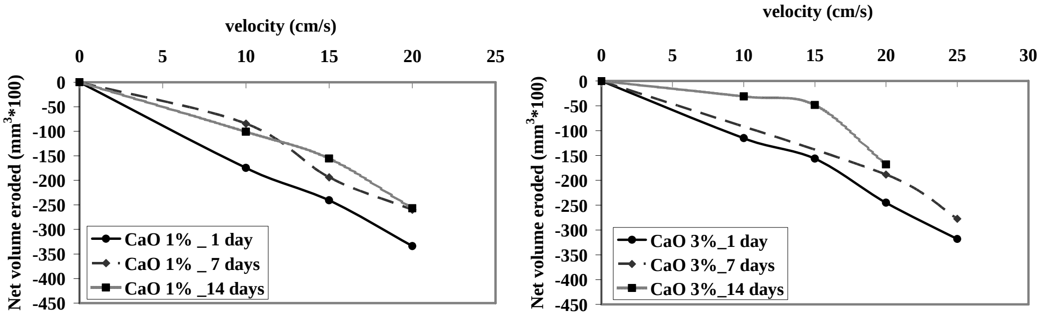


Fig. 7 Soil net volume eroded versus the water flow velocity for different cases of improved soils by calcium oxide (Cases 13- 18 shown in **Table 1**).

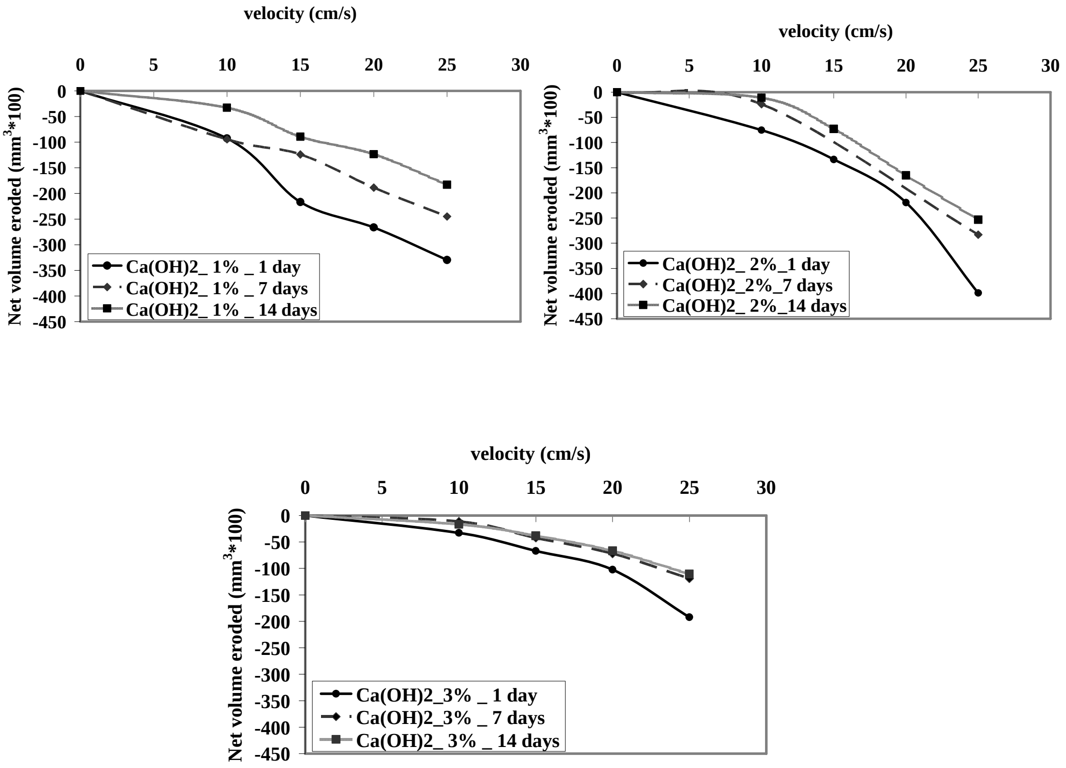


Fig. 8 Soil net volume eroded versus the water flow velocity for different cases of improved soils by calcium hydroxide (Cases 4-12 shown in **Table 1**).

Table 1 Specimen properties, tests conditions and results.

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

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. It is shown in **Fig. 9** for the case of calcium oxide, that a higher dose could lead to a better soil resistance against erosion and then less erosion rates obtained. That argument is strongly shown for the case of calcium hydroxide as less erosion rates are obtained so far (**Fig. 10**).

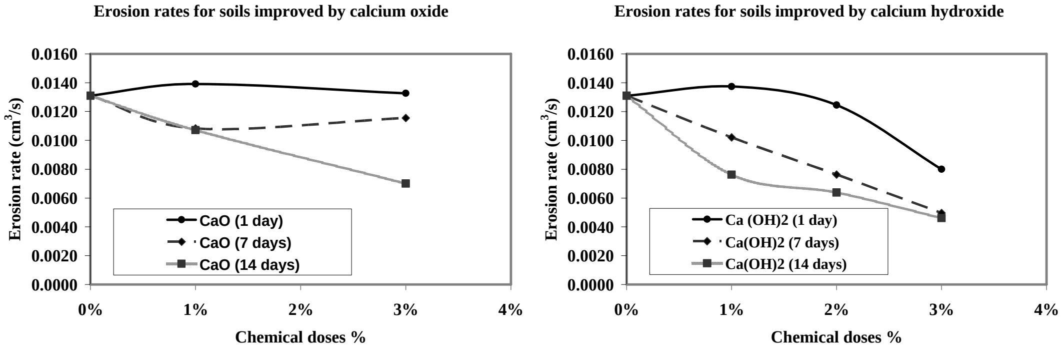


Fig. 9 Erosion rates of improved soils with different doses for calcium hydroxide and calcium oxide.

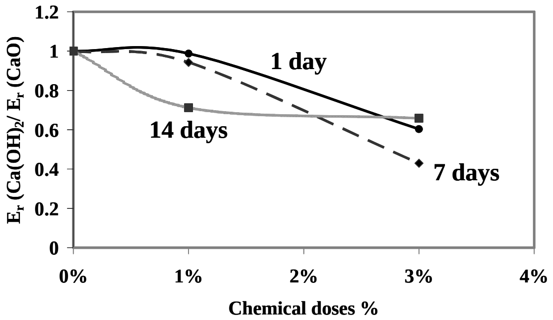


Fig. 10 Comparison between the erosion rates for every dose of the volcanic ash sandy soil with both kinds of the chemical additives (the calcium hydroxide and the calcium oxide).

3.3 Correlation of soil mechanical 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 **Fig. 11** 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 (with a correlation factor $R^2 = 0.80$):

$$E_r = 0.087\, q_u^{-0.6} \tag{4}$$

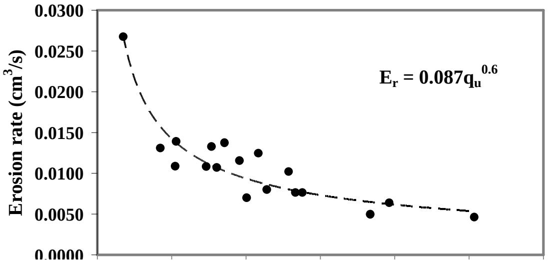


Fig. 11 Correlation of peak compressive strengths and erosion rates.

4. Conclusions

In order to understand overflow erosion, erosion tests were conducted using volcanic ash sandy soil which is commonly 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:

- The erosion rates of soil specimens improved by higher percentages of chemical doses decreased linearly when the water flow velocities exerted on the specimens are constants. This consideration is notably found for the calcium hydroxide than the calcium oxide.
- The critical flow velocities of the soil specimens are higher when exerted on high compacted soils rather than less compacted ones. The erosion rates increase with identical dry densities values when the water flow velocities increase.
- The peak compressive strengths increase linearly with higher doses of chemical additives, this behaviour could lead to a better understanding to investigate a relationship between the erodibility and the soil mechanical properties such as the peak compressive strengths.

These considerations provide important findings to analyze overflow erosion from a geotechnical point of view by measuring peak compressive strengths, and to facilitate field measurement erosion prediction, with the fact that volcanic ash sandy soils while improved by chemical additives could lead to a better resistibility against erosion.

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