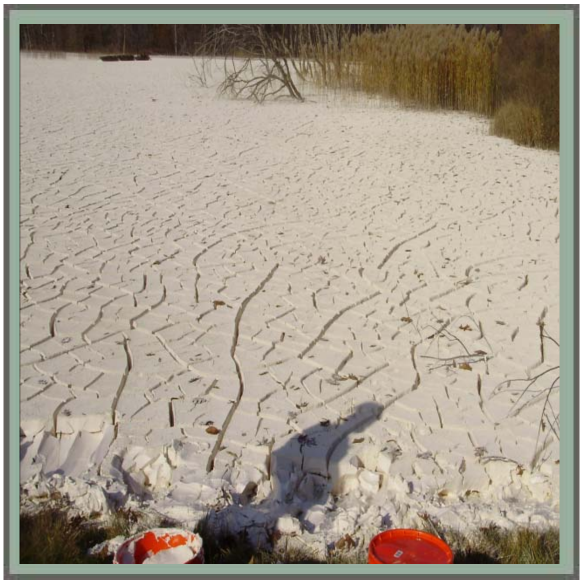
Beneficial Utilization of Lime Sludge for Subgrade Stabilization: A Pilot Investigation



Xiong (Bill) Yu, Bin Zhang
and Donald Cartweight

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16. Abstract

Water plants annually produce thousands of tons of lime sludge from the water treatment procedures. The lime sludge is then discharged into a retention pond. When the storage limit is reached, lime sludge is usually disposed into landfills, where they are treated as solid wastes. The large amount of lime sludge available (the quantity of lime sludge is estimated to be millions of tons for Ohio alone), the inexpensive (essentially free) material is very attractive if it can be used for soil stabilization in transportation constructions.

In order to use efficiently lime sludge as subgrade stabilization, proper design procedures for lime sludge introduction need to be followed to achieve the optimal performance. Besides, the long term performance of lime sludge modified soils needs to be verified. The purpose of this study was to determine the feasibility of using lime sludge as subgrade stabilization. The study focused on the feasibility of using lime sludge as a substitute of regular lime used in road construction, design issues such as, method of lime sludge introduction, the optimum content of lime sludge and the long term performance etc. Experimental study was conducted on five typical types of subgrade soils in Ohio as well as a high plastic clay soil in Cleveland area.

Common procedures for determining the optimal lime content for soil stabilization based on pH values are found not applicable for lime sludge. Instead, performance criteria based on unconfined compression tests need to be utilized. Lime sludge was found to increase the soil deformation modulus and reduce the plastic behaviors. Wet mix and dry mix methods do not appear to significantly affect the strength of lime sludge modified soil. Considering of the economic factors associated with drying lime sludge, lime sludge can be introduced in the slurry format via the wet mix procedure. The existing testing data indicated that lime sludge does not significantly improve the unconfined soil strength. Lime sludge however demonstrated the positive effects in reducing the plasticity of soils and improve the freeze/thaw durability. The long term performance evaluation could provide data to quantify the effectiveness of lime sludge as an economic and sustainable material.

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Final Report

Beneficial Utilization of Lime Sludge for Subgrade Stabilization: A Pilot Investigation

By

Xiong (Bill) Yu
Ph.D., P.E., Assistant Professor, Department of Civil Engineering
Case Western Reserve University

Bin Zhang
Visiting Associate Professor, Department of Civil Engineering
Case Western Reserve University

Donald Cartweight
Department of Civil Engineering
Case Western Reserve University

Ohio Department of Transportation
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The project team would like to acknowledge the contributions, guidance and assistance of the following ODOT engineers during the course of this project.

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Beneficial Utilization of Lime Sludge for Subgrade Stabilization: A Pilot Investigation

INTRODUCTION

Soil stabilization has performance and economic benefits in providing pavement with a rugged base supporting. A global chemical stabilization design is adopted by the Ohio Department of Transportation (ODOT), which is believed to produce the following benefits: 1) Improve the budget accuracy; 2) Facilitate scheduling by identifying all subgrade work at time of bidding; 3) Reduce or eliminate construction arguments, issues, and claims related to subgrade; 4) Increase productivity by providing a stable platform for the contractor; 5) Allow work on subgrade immediately after precipitation and reduce weather delays; 6) Provide a uniform and superior subgrade for pavements, and improve performance and durability; 7) Allow for an improved subgrade CBR and reduce the overall pavement thickness. Global soil stabilization was found to provide superior product with no additional cost. For a single project in I-71 lane expansion, the use of global subgrade stabilization was estimated to lead to better subgrade strength, 1.5" reduction in asphalt thickness that would have saved $12.0 million.

Given the large quantities of lime required for implementing a global soil stabilization, it is the interest of transportation agencies if inexpensive sources of soil stabilizer can be utilized for subgrade stabilization. The resultant savings will be significant. One potential resource can be utilized is the lime sludge produced from drinking water plants.

Water plants annually produce thousands of tons of lime sludge from the water treatment procedures. The lime sludge is then discharged into a retention pond. When the storage limit is reached, lime sludge is usually disposed into landfills, where they are treated as solid wastes. The large amount of lime sludge available (the quantity of lime sludge is estimated to be millions of tons for Ohio alone), the inexpensive (essentially free) material is very attractive if it can be used for soil stabilization in transportation constructions.

Lime is commonly used in water treatment process to reduce the hardness of water. The residual lime settles on a retention pond. This residual, a mixture of calcium, magnesium, and other minerals and water is called lime sludge. Lime sludge is typically sent to a surface lagoon for storage (1). Huge quantity of lime sludge is generated each year from the normal operations of water plants. For example, Massillon water plant in Lake county, Ohio, a private utility owned by Aqua America, Inc., discharges ten thousand tons of lime sludge (dry weight basis) annually. Over the past 40 years, it contains over 400,000 tons of lime sludge (dry weight) (Figure 1).

Storage of lime sludge in a lagoon is not a permanent solution as the storage capacity will be exceeded. The possibility of increasing storage capacity is limited by the government policy and environmental considerations. Disposal of lime sludge in municipal solid waste landfills poses financial burden because the water plant needs to pay the cost of drying, loading and transporting the sludge plus tipping fees. The Massillon plant, for example, pays over $1M each year to dispose part of its lime sludge in solid waste facilities.

Figure 1 Photo lime sludge storage lagoon at Massillon, OH

Possible ways of reusing lime sludge has been studied (2, 3 and 4). One promising application is to adjust the pH value of farm soils. The application in this area is limited due to the high transportation cost and the time and energy required to dry lime sludge. Other applications include using lime sludge in cement production, power plant SOx treatment, dust control on gravel roads, wastewater neutralization, and in-fill materials for road construction (2). Most of these have technical and economic hurdles. As investigated by several researchers, use of lime sludge as soil stabilizer holds promises from both performance and economic considerations (2).

PURPOSE AND SCOPE

In order to efficiently use lime sludge for subgrade stabilization, proper design procedures for lime sludge introduction need to be followed. Besides, the long term performance of such materials needs to be verified. The purpose of this study was to determine the feasibility of using lime sludge for subgrade stabilization. The study focused on the feasibility of using lime sludge as a substitute of regular lime used in road construction, design issues such as method of lime sludge introduction, the optimum content of lime sludge and the long term performance, etc.

Experimental study were conducted on five types of soils, including low plastic clay soil and high plastic clay soil. The experimental testing include the measurement of soil index properties, characteristics of lime sludge, testing for pH values of lime sludge and stabilized soil, testing for unconfined compressive strength of soil and stabilized soil, microstructure testing, and so on.

CHARACTERISTICS OF LIME SLUDGE

Lime sludge samples were collected from the lagoon of Massillon water plant in Ohio. It appears to be paste with a high natural water content over 90%. The physical description of the lime sludge samples is shown in Table 1.

TABLE 1 Visual Description of Lime Sludge Sample

Physical Properties	Description
Color	White to light grey
Odor	None
Hardness	Soft, greasy
Wetness	Wet, natural moisture content 98.4%
Flowability	Non-flowable at natural status
Density	Light
Dry status	Fine powder
Vegetation	No vegetation in lime pond

Both chemical and mineral analyses were conducted on the collected lime sludge sample using an Energy-Dispersive X-ray spectroscopy (EDX) equipped with Scanning Electron Microscopy (SEM) probe. Prior to the test, lime sludge was first dried in an oven. EDX measures the existence and concentration of different elements in a sample (Figure 2, Table 2). The chemical content of each constituent (e.g. CaO, MgO, …) is derived from the measured percentage of each element. The exact values of chemical content of CaO and $CaCO_3$ need further tests to be specified clearly. The results are shown in Table 2. Also shown in this table are the chemical components of a commercial hydrated lime. The proportions of lime sludge resemble those of the commercial hydrated lime. One major difference is that there seems to be significant amount of $CaCO_3$ in lime sludge compared with the hydrated lime. This might be due to the carbonization of Calcium hydrate under long term exposure to the atmosphere.

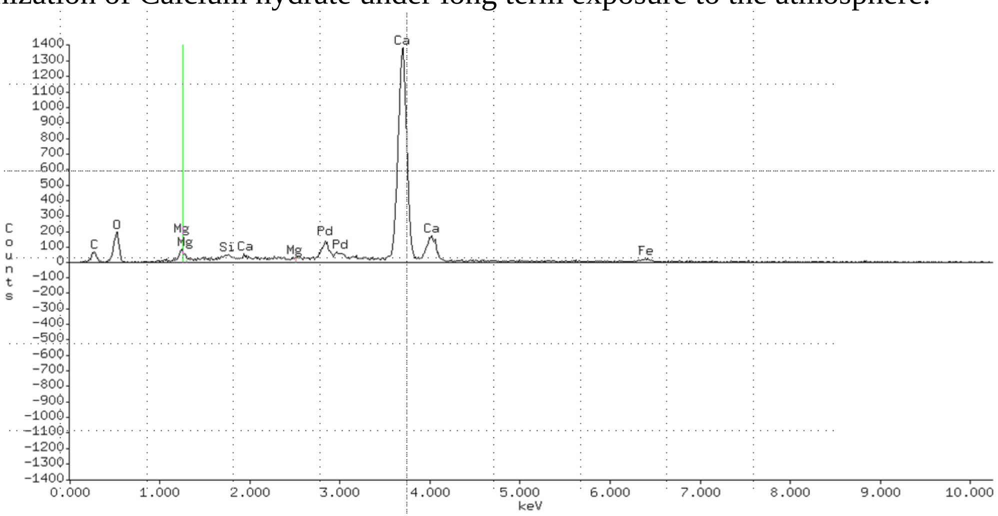


FIGURE 2 EDX Spectral of Measured Dry Lime Sludge Sample

TABLE 2 Concentrations of Major Chemical Components of Lime Sludge versus Commercial Hydrated Lime

	Lime Sludge		Chemical Content of Commercial Hydrated Lime
	Element Content by EXD	Chemical Content	
CaO	43.93% (Ca)	3.50%	72.4%
MgO	1.78% (Mg)	2.97%	1.9%
$CaCO_3$		58.00%	1.94%
SiO_3	0.52% (Si)	0.24%	1.5%
Fe_2O_3	1.91% (Fe)	2.73%	0.2%
Al_2O_3	0.23% (Al)	0.65%	0.8%
CO_2	6.96% (C)		0.85%
As	0.19% (As)	0.19%	

Figure 3 shows SEM images of lime sludge sample, from which its surface and structural characteristics can be observed (Figure 3). From the SEM image, the dry lime sludge appears to be uniform fine particles resembling those of silts. The size of particles is in micron.

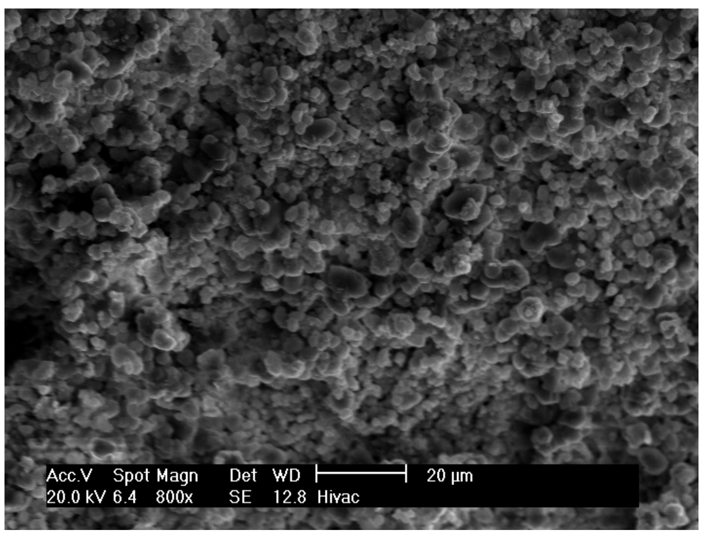


FIGURE 3 SEM Image of Lime Sludge Sample

EXPERIMENTAL PROGRAM AND PROCEDURES

From design considerations, a few issues need to be resolved to use lime sludge as a soil stabilizer. These include, for example, procedures to determine the optimal lime content and the procedures for mixing lime sludge with soil. Six types of cohesive subgrade soils were collected with assistance of Bill Christensen. In addition, one type of local clay was collected from a construction site in Cleveland. The soil is a glacial till and classified as CL and CH by Unified Soil Classification System (USCS), the detail physical parameters of different soil are given in Table 3 and Fig. 4. As lime stabilization is not effective for soils with low plasticity, soil 4 was not included in the testing program considering lime sludge has much lower reactivity than commercial quick lime. Therefore, altogether five types of soils were tested in this study.

Table 3 Physical Parameters of Five Soils

Sample ID	% Gravel	% Coarse Sand	% Fine Sand	% Silt	% Clay	Liquid Limit	Plastic Limit	Plasticity Index	ODOT Classification
1A	7	4	9	26	54	30	15	15	A-6a
1B	6	4	9	26	55	29	16	13	A-6a
2	7	5	10	28	50	25	14	11	A-6a
3	10	7	10	14	59	40	18	22	A-6b
4	2	1	2	38	57	25	17	8	A-4a
5	7	0	4	23	66	43	25	18	A-7-6

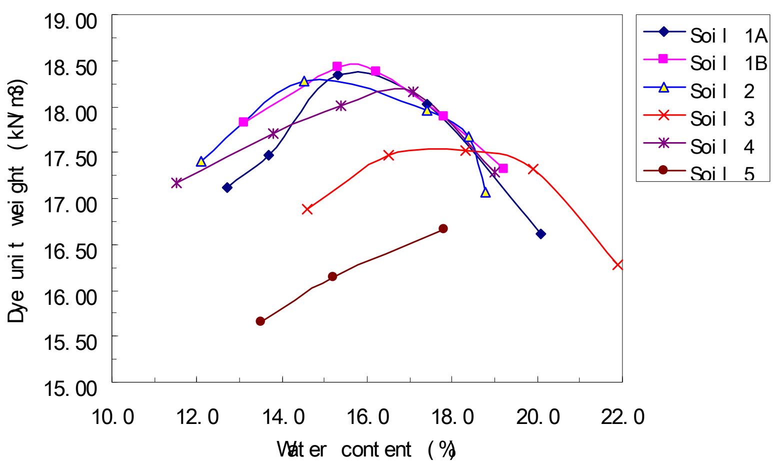


FIGURE 4 Compaction Curves of Five Soils

Soil specimens for unconfined compressive strength tests were prepared using Harvard Miniature Compactor. Equipment for Harvard Miniature Compactor are shown in Fig. 5. Soil samples with specified water content were first prepared and compacted into a standard mold at three layers. Each layer was compacted with 25 blows. Uniform specimen was obtained by controlling the soil mass of each layer. It was then extruded with assistance of an manual extruder. Duplicate numbers of specimens were prepared. The soil specimen is in cylinder shape with a height of 71mm and a diameter of 33mm (Fig. 6). All specimens were wrapped in plastic wrap and sealed in an airtight and moisture proof sealing bag and were cured in a standard moisture curing room for 0, 7, 14 and 28 days before tests were performed, as shown in Fig 7.

FIGURE 5 PICTURE of the Harvard Miniature Compactor

FIGURE 6 Picture of the Soil Specimens

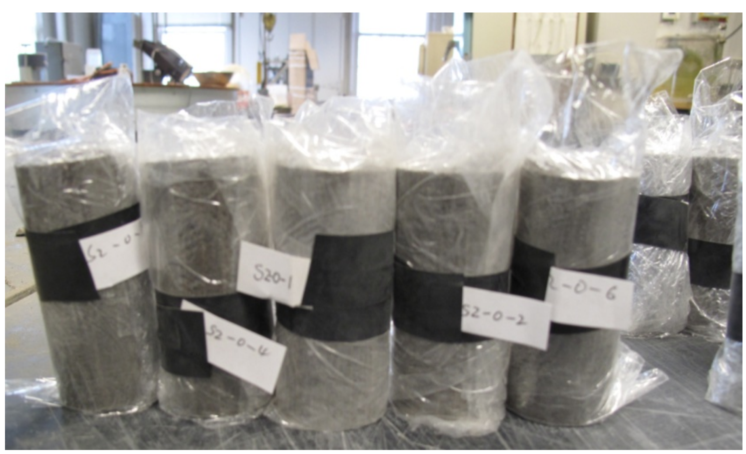


FIGURE 7 Picture of the Soil Specimens Sealed with Sling Film

A MTS loading machine is used for the unconfined compression strength (i.e., Fig. 8 and Fig. 9).

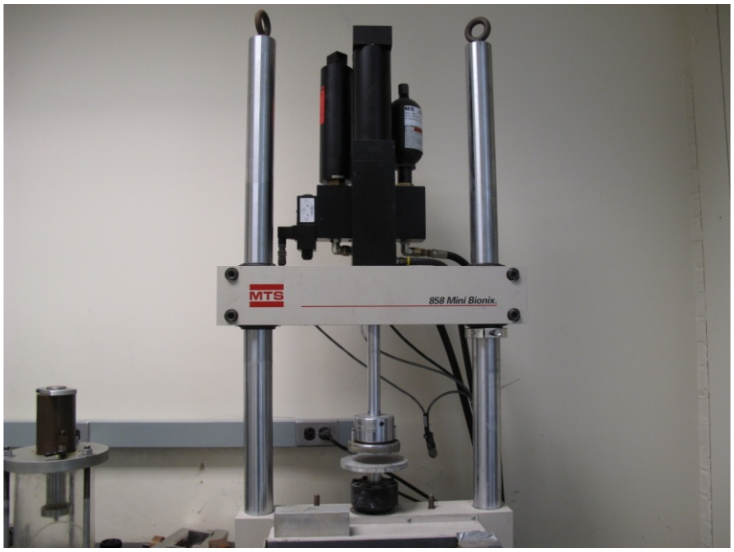


FIGURE 8 Picture of the 858 Mini MTS Apparatus

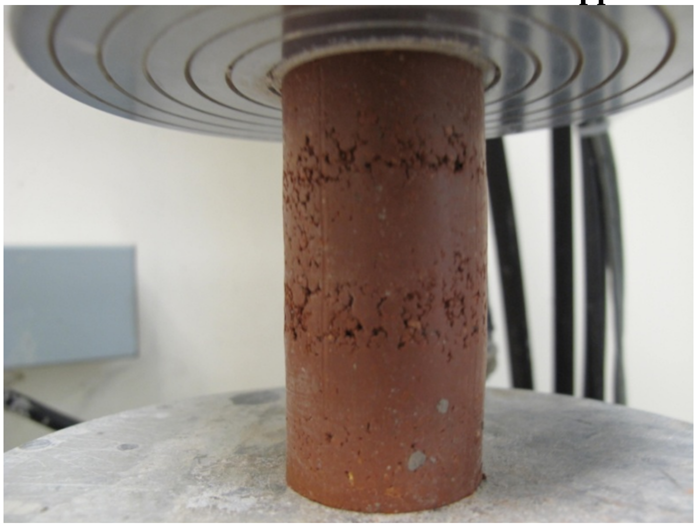


FIGURE 9 PICTURE of the Soil Specimen on the Apparatus

In order to investigate the effect of cyclic freeze-thaw durability of lime sludge stabilized soils, a system was developed to automate the freezing-thawing process. It include temperature sensor and controller, as well as a TDR unit. A photo of the refrigerating cabinet is shown in Figure 10. Figure 11 shows example of generated freezing-thawing cycles.

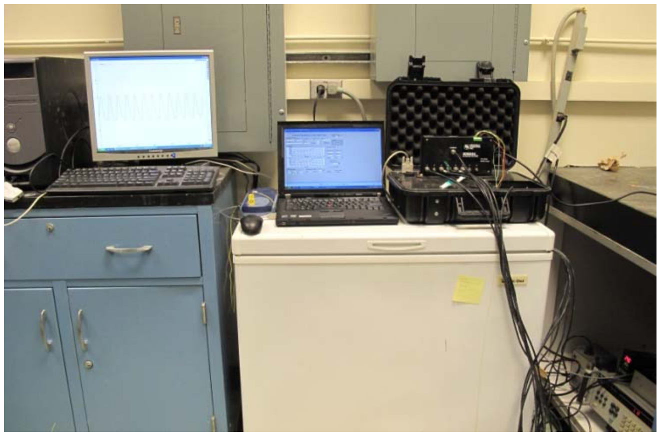


Figure 10 Picture of Freeze-Thaw Testing Apparatus System

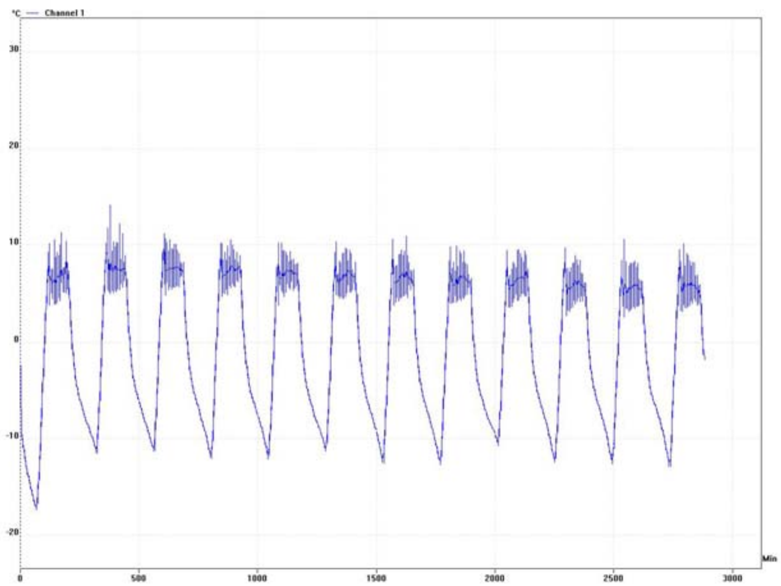


Figure 11 Temperature Curve Showing the Freezing-Thawing Cycles

SUMMARY OF EXPERIMENTAL DATA

Altogether 193 specimens were prepared during the testing program using the five typical types of Ohio subgrade soils.

Factorial experimental design is used in designing the experiments. Factors considered in the experimental program include:

1) Lime sludge content: The lime sludge content varies from (0%, 5%, 10%, 15% and 20%).
2) Freeze-thaw durability
3) Strength development with time

Tables 4-9 summarize the results of testing programs on the 6 types of soils (1A, 1B, 2, 3, 4, 5, Cleveland Soil).

TABLE 4 Laboratory testing program for different proportion and result (Soil 1A)

Sample ID	Lime sludge percentage (%)	Water content (%)	Dry density		Water content (after testing) (%)	Unconfined compressive strength		Curing condition
			kN/m^3	pcf		kPa	Psi	
S1A(0)W15-1	0	13.76	17.78	113.2	13.89	531	77.01	7 Days
S1A(0)W15-2	0	13.76	17.82	113.5	13.85	520	75.42	7 Days
S1A(0)W15-3	0	13.76	17.72	112.8	13.74	555	80.50	7 Days
S1A(0)W15-4	0	13.76	17.71	112.8	13.45	435	63.09	Freezing-thawing
S1A(0)W15-5	0	13.76	17.69	112.6	13.39	365	52.94	Freezing-thawing
S1A(0)W15-6	0	13.76	17.61	112.1	13.52	374	54.24	Freezing-thawing
S1A(5)W15-1	5	13.66	18.22	116.0	13.59	510	73.97	0 Days
S1A(5)W15-2	5	13.66	18.30	116.5	13.48	508	73.68	0 Days
S1A(5)W15-3	5	-	-		-	-		-
S1A(5)W15-4	5	13.66	18.02	114.7	13.58	582	84.41	7 Days
S1A(5)W15-5	5	13.66	18.00	114.6	13.37	637	92.39	7 Days
S1A(5)W15-6	5	13.66	17.94	114.2	13.58	578	83.83	14 Days
S1A(5)W15-7	5	13.66	18.16	115.6	13.70	624	90.50	14 Days
S1A(5)W15-8	5	13.66	18.03	114.8	13.43	693	100.5	28 Days
S1A(5)W15-9	5	13.66	17.91	114.0	13.51	578	83.83	28 Days
S1A(5)W15-10	5	13.66	17.82	113.5	13.45	462	67.01	Freezing-thawing
S1A(5)W15-11	5	13.66	18.02	114.7	13.70	475	68.89	Freezing-thawing
S1A(10)W15-1	10	14.70	17.69	112.6	14.15	484	70.20	0 Days
S1A(10)W15-2	10	14.70	17.73	112.9	14.06	510	73.97	0 Days
S1A(10)W15-3	10	14.70	17.69	112.6	14.00	-		7 Days
S1A(10)W15-4	10	14.70	17.77	113.1	13.94	509	73.82	7 Days
S1A(10)W15-5	10	14.70	17.70	112.7	13.85	510	73.97	7 Days
S1A(10)W15-6	10	14.70	17.67	112.5	13.63	511	74.11	14 Days
S1A(10)W15-7	10	14.70	17.60	112.1	13.62	485	70.34	14 Days
S1A(10)W15-8	10	14.70	17.68	112.6	-	531	77.01	28 Days
S1A(10)W15-9	10	14.70	17.64	112.3	13.97	530	76.87	28 Days
S1A(10)W15-10	10	14.70	17.65	112.4	13.70	455	65.99	Freezing-thawing
S1A(10)W15-11	10	14.70	17.62	112.2	-	463	67.15	Freezing-thawing
S1A(15)W15-1	15	14.73	17.74	113.0	14.65	384	55.69	0 Days
S1A(15)W15-2	15	14.73	17.78	113.2	14.48	377	54.68	0 Days
S1A(15)W15-3	15	14.73	17.90	114.0	14.85	593	86.01	7 Days
S1A(15)W15-4	15	14.73	17.77	113.1	14.60	503	72.95	7 Days
S1A(15)W15-5	15	14.73	17.97	114.4	14.51	658	95.43	7 Days
S1A(15)W15-6	15	14.73	17.86	113.7	14.17	589	85.43	14 Days
S1A(15)W15-7	15	14.73	17.88	113.8	14.40	596	86.44	14 Days
S1A(15)W15-8	15	14.73	17.83	113.5	14.60	601	87.17	28 Days
S1A(15)W15-9	15	14.73	17.82	113.5	14.41	642	93.11	28 Days
S1A(15)W15-10	15	14.73	17.85	113.7	14.34	567	82.24	Freezing-thawing
S1A(15)W15-11	15	14.73	17.83	113.5	-	470	68.17	Freezing-thawing
S1A(20)W15-1	20	13.95	17.91	114.0	13.90	445	64.54	0 Days
S1A(20)W15-2	20	13.95	17.89	113.9	-	404	58.59	0 Days
S1A(20)W15-3	20	13.95	17.65	112.4	-	433	62.80	28 Days
S1A(20)W15-4	20	13.95	17.71	112.8	14.13	465	67.44	7 Days
S1A(20)W15-5	20	13.95	17.72	112.8	13.94	456	66.14	7 Days
S1A(20)W15-6	20	13.95	17.65	112.4	-	444	64.40	14 Days
S1A(20)W15-7	20	13.95	17.75	113.0	14.13	442	64.11	14 Days

S1A(20)W15-8	20	13.95	17.54	111.7	14.02	430	62.37	28 Days
S1A(20)W15-9	20	13.95	17.67	112.5	14.22	441	63.96	28 Days
S1A(20)W15-10	20	13.95	17.71	112.8	13.97	318	46.12	Freezing-thawing
S1A(20)W15-11	20	13.95	17.68	112.6	13.68	321	46.56	Freezing-thawing

TABLE 5 Laboratory testing program for different proportion and result (Soil 1B)

Sample ID	Lime sludge percentage (%)	Water content (%)	Dry density		Water content (after testing) (%)	Unconfined compressive strength		Curing condition
			g/cm^3	pcf		kPa	psi	
S1B(0)W14-1	0	13.16	17.22	109.6	12.90	430	62.37	7 Days
S1B(0)W14-2	0	13.16	17.30	110.2	12.61	460	66.72	7 Days
S1B(0)W14-3	0	13.16	17.22	109.6	12.42	410	59.47	7 Days
S1B(0)W14-4	0	13.16	17.20	109.5	12.37	366	53.08	Freezing-thawing
S1B(0)W14-5	0	13.16	17.08	108.8	12.31	323	46.85	Freezing-thawing
S1B(0)W14-6	-	-	-		-	-		-
S1B(5)W14-1	5	11.62	16.83	107.2	11.67	345	50.04	7 Days
S1B(5)W14-2	5	11.62	16.70	106.3	12.04	300	43.51	7 Days
S1B(5)W14-3	5	11.62	16.70	106.3	11.71	328	47.57	7 Days
S1B(10)W14-1	10	13.21	16.87	107.4	13.25	400	58.01	7 Days
S1B(10)W14-2	10	13.21	16.73	106.5	12.95	390	56.56	7 Days
S1B(10)W14-3	10	13.21	16.83	107.2	12.88	342	49.60	7 Days
S1B(15)W14-1	15	13.50	16.79	106.9	13.56	396	57.43	7 Days
S1B(15)W14-2	15	13.50	16.87	107.4	13.26	424	61.50	7 Days
S1B(15)W14-3	15	13.50	16.77	106.8	-	445	64.54	7 Days
S1B(20)W14-1	20	14.60	14.01	89.2	17.18	501	72.66	7 Days
S1B(20)W14-2	20	14.60	14.69	93.5	17.06	482	69.91	7 Days
S1B(20)W14-3	20	14.60	14.38	91.6	17.04	431	62.51	7 Days
S1B(10)W14-4	10							Freezing-thawing
S1B(10)W14-5	10							Freezing-thawing
S1B(10)W14-6	10							Freezing-thawing

TABLE 6 Laboratory testing program for different proportion and result (Soil 2)

Sample ID	Lime sludge percentage (%)	Water content (%)	Dry density		Water content (after testing) (%)	Unconfined compressive strength		Curing condition
			g/cm^3	pcf		kPa	psi	
S2(0)W15-1	0	13.72	17.24	109.8	13.40	460	66.72	7 Days
S2(0)W15-2	0	13.72	17.26	109.9	13.32	496	71.94	7 Days
S2(0)W15-3	0	13.72	17.37	110.6	13.35	464	67.30	7 Days
S2(0)W15-4	0	13.72	17.32	110.3	12.98	392	56.85	Freezing-thawing
S2(0)W15-5	0	13.72	17.23	109.7	-	394	57.14	Freezing-thawing
S2(0)W15-6	0	13.72	17.22	109.6	12.49	323	46.85	Freezing-thawing
S2(5)W15-1	5	13.73	17.23	109.7	13.23	436	63.24	7 Days
S2(5)W15-2	5	13.73	17.20	109.5	13.20	477	69.18	7 Days
S2(5)W15-3	5	13.73	17.25	109.8	12.89	394	57.14	7 Days
S2(10)W15-1	10	14.00	17.28	110.0	13.82	463	67.15	7 Days
S2(10)W15-2	10	14.00	17.29	110.1	14.00	425	61.64	7 Days
S2(10)W15-3	10	14.00	17.42	110.9	13.50	430	62.37	7 Days
S2(15)W15-1	15	13.29	17.07	108.7	13.00	401	58.16	7 Days
S2(15)W15-2	15	13.29	16.92	107.7	12.65	399	57.87	7 Days
S2(15)W15-3	15	13.29	17.02	108.4	12.57	408	59.18	7 Days
S2(20)W15-1	20	13.56	17.02	108.4	13.73	363	52.65	7 Days
S2(20)W15-2	20	13.56	17.03	108.4	13.16	403	58.45	7 Days
S2(20)W15-3	20	13.56	16.90	107.6	13.17	363	52.65	7 Days
S2(10)W15-4	10	14.00	17.32	110.3	13.63	364	52.79	Freezing-thawing
S2(10)W15-5	10	14.00	17.39	110.7	14.11	396	57.43	Freezing-thawing
S2(10)W15-6	10	14.00	17.32	110.3	13.69	377	54.68	Freezing-thawing

TABLE 7 Laboratory testing program for different proportion and result (Soil 3)

Sample ID	Lime sludge percentage (%)	Water content (%)	Dry density		Water content (after testing) (%)	Unconfined compressive strength		Curing condition
			g/cm^3	pcf		kPa	psi	
S3(0)W15-1	0	16.15	17.04	108.5	15.33	601	87.17	7 Days
S3(0)W15-2	0	16.15	17.09	108.8	14.90	605	87.75	7 Days
S3(0)W15-3	0	16.15	17.09	108.8	14.89	590	85.57	7 Days
S3(0)W15-4	0	16.15	17.11	108.9	16.47	387	56.13	Freezing-thawing
S3(0)W15-5	0	16.15	17.12	109.0	16.31	401	58.16	Freezing-thawing
S3(0)W15-6	0	16.15	17.10	108.9	16.32	393	57.00	Freezing-thawing
S3(5)W15-1	5	15.49	17.20	109.5	15.42	474	68.75	0 Days
S3(5)W15-2	5	15.49	17.12	109.0	15.38	478	69.33	0 Days
S3(5)W15-3	5	15.49	17.16	109.1	15.37	586	84.99	7 Days
S3(5)W15-4	5	15.49	17.16	109.3	15.63	645	93.55	7 Days
S3(5)W15-5	5	15.49	17.28	110.0	14.90	668	96.88	7 Days
S3(5)W15-6	5	15.49	17.20	109.5	15.53	568	82.38	14 Days
S3(5)W15-7	5	15.49	17.16	109.3	15.75	565	81.95	14 Days
S3(5)W15-8	5	15.49	17.18	109.4	15.23	588	85.28	28 Days
S3(5)W15-9	5	15.49	17.03	108.4	15.12	562	81.51	28 Days
S3(5)W15-10	5	15.49	17.15	109.2	15.87	400	58.01	Freezing-thawing
S3(5)W15-11	5	15.49	17.17	109.3	15.96	420	60.92	Freezing-thawing
S3(10)W15-1	10	16.43	17.46	111.2	16.13	475	68.89	0 Days
S3(10)W15-2	10	16.43	17.32	110.3	16.21	466	67.59	0 Days
S3(10)W15-3	10	16.43	17.34	110.4	16.12	630	91.37	7 Days
S3(10)W15-4	10	16.43	17.41	110.9	15.98	647	93.84	7 Days
S3(10)W15-5	10	16.43	17.42	110.9	16.01	624	90.50	7 Days
S3(10)W15-6	10	16.43	17.38	110.7	16.42	626	90.79	14 Days
S3(10)W15-7	10	16.43	17.38	110.7	16.37	602	87.31	14 Days
S3(10)W15-8	10	16.43	17.28	110.0	16.31	647	93.84	28 Days
S3(10)W15-9	10	16.43	17.40	110.8	16.45	595	86.30	28 Days
S3(10)W15-10	10	16.43	17.28	110.0	16.49	380	55.11	Freezing-thawing
S3(10)W15-11	10	16.43	17.38	110.7	16.65	460	66.72	Freezing-thawing
S3(15)W15-1	15	16.23	17.25	109.8	16.07	450	65.27	0 Days
S3(15)W15-2	15	16.23	17.28	110.0	16.07	445	64.54	0 Days
S3(15)W15-3	15	16.23	17.20	109.5	15.79	534	77.45	7 Days
S3(15)W15-4	15	16.23	17.31	110.2	16.20	535	77.59	7 Days
S3(15)W15-5	15	16.23	17.29	110.1	16.18	575	83.40	7 Days
S3(15)W15-6	15	16.23	17.21	109.6	16.35	560	81.22	14 Days
S3(15)W15-7	15	16.23	17.19	109.5	16.36	523	75.85	14 Days
S3(15)W15-8	15	16.23	17.21	109.6	15.68	526	76.29	28 Days
S3(15)W15-9	15	16.23	17.18	109.4	15.67	578	83.83	28 Days
S3(15)W15-10	15	16.23	17.13	109.1	16.70	415	60.19	Freezing-thawing
S3(15)W15-11	15	16.23	17.22	109.6	15.82	455	65.99	Freezing-thawing
S3(20)W15-1	20	16.40	17.31	110.2	16.25	461	66.86	0 Days
S3(20)W15-2	20	16.40	17.22	109.6	16.25	472	68.46	0 Days
S3(20)W15-3	20	16.40	17.20	109.5	16.48	516	74.84	7 Days
S3(20)W15-4	20	16.40	17.30	110.2	16.28	542	78.61	7 Days
S3(20)W15-5	20	16.40	17.19	109.5	16.22	550	79.77	7 Days
S3(20)W15-6	20	16.40	17.21	109.6	16.39	545	79.05	14 Days
S3(20)W15-7	20	16.40	17.24	109.8	16.34	553	80.21	14 Days
S3(20)W15-8	20	16.40	17.21	109.6	15.71	552	80.06	28 Days
S3(20)W15-9	20	16.40	17.23	109.7	15.86	554	80.35	28 Days
S3(20)W15-10	20	16.40	17.17	109.3	17.30	410	59.47	Freezing-thawing
S3(20)W15-11	20	16.40	17.09	108.8	15.44	371	53.81	Freezing-thawing

TABLE 8 Laboratory testing program for different proportion and result (Soil 5)

Sample ID	Lime sludge percentage (%)	Water content (%)	Dry density		Water content (after testing) (%)	Unconfined compressive strength		Curing condition
			g/cm^3	Pcf		kPa	psi	
S5(0)W19-1	0	17.8	16.41	104.5	15.15	592.3	85.91	7 Days
S5(0)W19-2	0	17.8	16.46	104.8	15.63	603.3	87.50	7 Days
S5(0)W19-3	0	17.8	16.39	104.4	15.52	591.1	85.73	7 Days
S5(0)W19-4	0	17.8	16.43	104.6	-	-		Freezing-thawing
S5(0)W19-5	0	17.8	16.36	104.2		428.3	62.12	Freezing-thawing
S5(0)W19-6	0	17.8	16.27	103.6		453.5	65.77	Freezing-thawing
S5(5)W19-3	5	18.23	16.63	105.9	16.85	552.3	80.10	7 Days
S5(5)W19-4	5	18.23	17.14	109.1	17.49	554.6	80.44	7 Days
S5(5)W19-5	5	18.23	16.97	108.1	17.25	552.7	80.16	7 Days
S5(5)W19-6	5	18.23	16.99	108.2		502.5	72.88	Freezing-thawing
S5(5)W19-7	5	18.23	17.02	108.4		521.0	75.56	Freezing-thawing
S5(5)W19-8	5	18.23	17.01	108.3		508.7	73.78	Freezing-thawing
S5(10)W19-3	10	18.32	16.73	106.5	16.26	570.0	82.67	7 Days
S5(10)W19-4	10	18.32	16.95	107.9	16.69	573.0	83.11	7 Days
S5(10)W19-5	10	18.32	16.86	107.4	17.17	580.0	84.12	7 Days
S5(10)W19-6	10	18.32	16.98	108.1		462.5	67.08	Freezing-thawing
S5(10)W19-7	10	18.32	16.75	106.7		500.0	72.52	Freezing-thawing
S5(10)W19-8	10	18.32	16.91	107.7		495.0	71.79	Freezing-thawing
S5(15)W19-3	15	17.91	17.06	108.6	16.60	563.0	81.66	7 Days
S5(15)W19-4	15	17.91	17.11	108.9	16.54	586.5	85.06	7 Days
S5(15)W19-5	15	17.91	17.17	109.3	16.41	559.0	81.08	7 Days
S5(15)W19-6	15	17.91	17.05	108.6		530.0*	76.87	Freezing-thawing
S5(15)W19-7	15	17.91	16.95	107.9		465.0	67.44	Freezing-thawing
S5(15)W19-8	15	17.91	16.84	107.2	17.71	460.0	66.72	Freezing-thawing
S5(20)W19-3	20	18.79	16.81	107.0	16.59	560.0	81.22	7 Days
S5(20)W19-4	20	18.79	16.86	107.4	16.30	571.0	82.82	7 Days
S5(20)W19-5	20	18.79	16.81	107.0	16.68	589.0	85.43	7 Days
S5(20)W19-6	20	18.79	16.85	107.3	17.16	519.0	75.27	Freezing-thawing
S5(20)W19-7	20	18.79	16.89	107.5	17.04	556.0*	80.64	Freezing-thawing
S5(20)W19-8	20	18.79	16.74	106.6	17.24	564.0*	81.80	Freezing-thawing

TABLE 9 Laboratory testing program for different proportion and result (Cleveland Clay Soil)

Sample ID	Lime sludge percentage (%)	Water content (%)	Dry density		Water content (after testing) (%)	Unconfined compressive strength		Curing condition
			g/cm^3	pcf		kPa	psi	
SC(0)W15-1	0	13.60	17.35	110.5	-			7 Days
SC(0)W15-2	0	13.61	17.05	108.6	-	98.2	14.24	7 Days
SC(0)W15-3	0	13.02	18.13	115.4	-			7 Days
SC(0)W15-4	0	-	-		-			Freezing-thawing
SC(0)W15-5	0	-	-		-	65.2	9.46	Freezing-thawing
SC(0)W15-6	0	-	-		-			Freezing-thawing
SC(5)W15-1	5	12.7	17.64	112.3	-			7 Days
SC(5)W15-2	5	12.69	17.25	109.8	-	280	40.61	7 Days
SC(5)W15-3	5	12.48	16.96		-			7 Days
SC(10)W15-1	10	12.61	17.25	109.8	-			7 Days
SC(10)W15-2	10	12.41	17.25	109.8	-	363	52.65	7 Days
SC(10)W15-3	10	12.24	16.86	107.4	-			7 Days
SC(10)W15-4	10	-		0.0	-			Freezing-thawing
SC(10)W15-5	10	-		0.0	-	196.2	28.46	Freezing-thawing
SC(10)W15-6	10	-		0.0	-			Freezing-thawing
SC(15)W15-1	15	11.78	16.27	103.6	-			7 Days
SC(15)W15-2	15	11.68	16.46	104.8	-	310	44.96	7 Days
SC(15)W15-3	15	11.57	16.56	105.4	-			7 Days
SC(20)W15-4	20	11.65	17.05	108.6	-			7 Days
SC(20)W15-5	20	11.36	16.86	107.4	-	300	43.51	7 Days
SC(20)W15-6	20	11.46	17.05	108.6	-			7 Days

EXPERIMENTAL RESULTS AND ANALYSES

1. Method for the Determination of the Optimal Lime Sludge Content

Determine the Optimal Content of Lime Sludge by pH Method

The optimal lime content for soil stabilization is generally determined the method specified by ASTM D6276 (5). This standard specifies the optimal lime content as the minimal lime content that produces a pH value of 12.4. The pulverized air-dried soil was first passed through the No. 10 sieve. The lime sludge was oven-dried for several days. 2.0g of dried lime sludge was dissolved into 100ml deionized water. For the remaining specimens with lime sludge/soil ratios (dry weight base) of 2%, 5%, 8%, 11% and 14% were prepared according to ASTM D6276 (*5*). The pH values of the slurry were measured. Figure 10 shows the results of pH value versus the lime-soil mass ratio. The data on 100% scale is the result of pure lime sludge solution. Test results in Figure 10 indicate that all the pH values are smaller than 12, which is specified by ASTM D6276 for determining the optimal lime content for soil stabilization. This is also the case even for the pure lime sludge slurry. The optimum lime content can not be determined using ASTM D6276. The low pH value corroborated the results from the EDX analyses, as Table 2. Carbonization of lime sludge reduces the active base components that can be created in the solution.

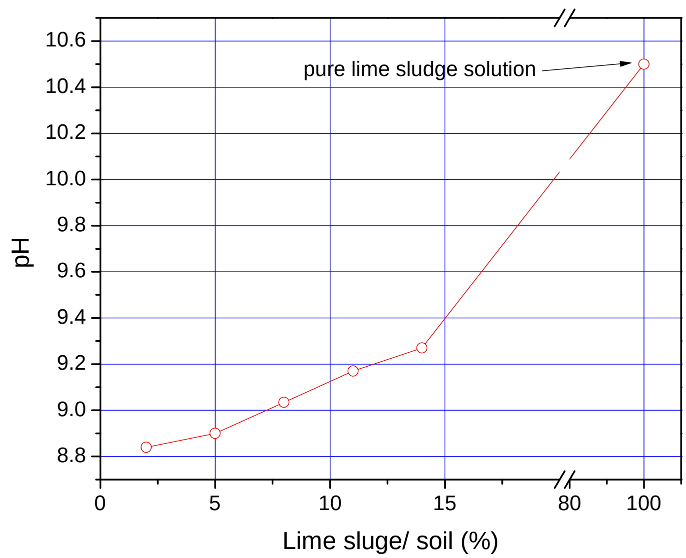


FIGURE 10 pH Test for estimating Soil-Lime Sludge Proportion.

Determine the Optimal Content of Lime Sludge by Unconfined Compressive Strength test

As an alternative method to determine the optimal lime sludge content, unconfined compressive strength tests were conducted on soil mixed with different concentrations of dried lime sludge. Unconfined compressive strength is a control parameter for road fill design. With a compressive strength greater than 345kPa, the potential for settlement in deep fills can be significantly reduced (*6*). Unconfined compressive strength tests of lime sludge treated soil specimens were conducted to study the effect of dry/wet mix method on soil strength and find the optimum soil-lime sludge ratio.

According to ASTM D5102 (*7*), a loading rate (strain controlled) of 0.02mm/s was applied during the compression test. The unconfined compressive strength is determined either by the maximum axial stress or by the axial stress at 5% axial strain, whichever occurs first during a performance of a test.

Five types of soil, about 193 specimens were prepared using Harvard miniature compactor at different lime sludge contents (dry weight base) of 0%, 5%, 10%, 15% and 20%. Soil and lime sludge powder were first mixed before water was introduced. Three specimens were prepared at each lime sludge content. The physical properties and results of unconfined compression tests are shown in Table 4 to Table 9. This table indicates that the specimens were prepared with high quality control, as indicated by the mass and water content. Finished specimens were wrapped by plastic wrap and sealed in a zip bag. Specimens were cured for different days in a curing room before the unconfined compression test were conducted.

Soil 1A

Figure 11 show the stress versus strain curves for soil specimens 1A treated with different percentage of lime sludge. Figure 12 shows the stress strain curves of lime sludge treated soils subjected to different curing ages. Soil specimens subjected to freezing-thawing processes were also plotted in this figure to show the freeze-thaw susceptibility.

The Figure 11 shows the introduction of lime sludge slightly increases the strength, modulus and brittleness of treated soil; such effects, however, are insignificant.

Figure 13 summarizes the influence of lime sludge treatment on the soil strength. An optimal lime sludge content of around 15% could be estimated from this figure.

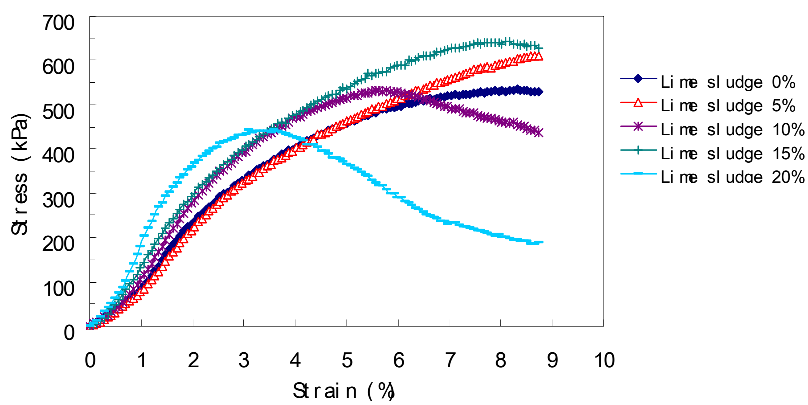
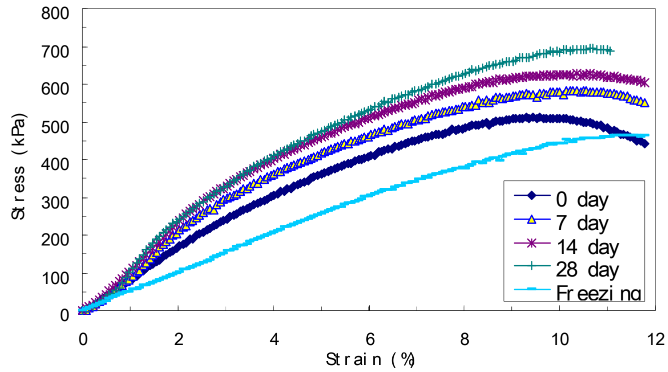
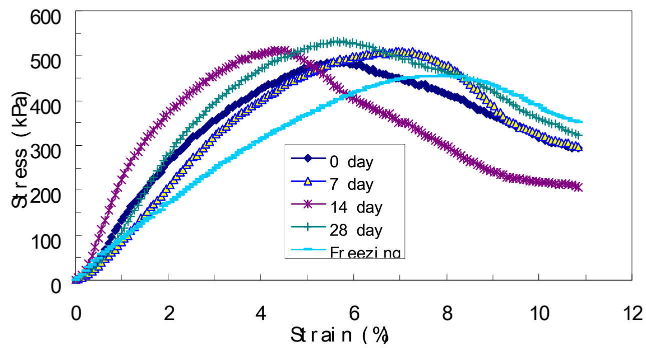


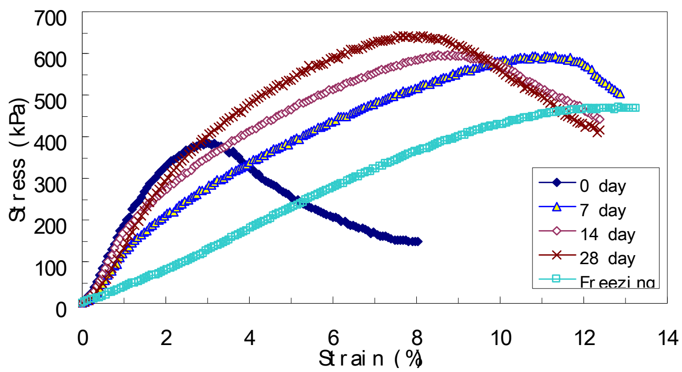
Figure 11 Stress-Strain Relationships of Soil Specimens with Different Lime Sludge Incorporating Ratio



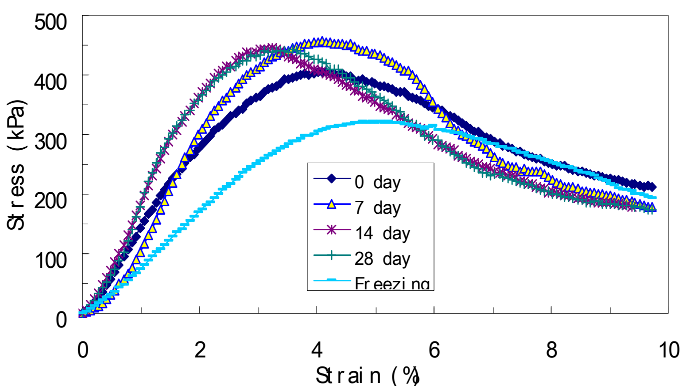
a. Lime sludge percentage 5%



b. Lime sludge percentage 10%

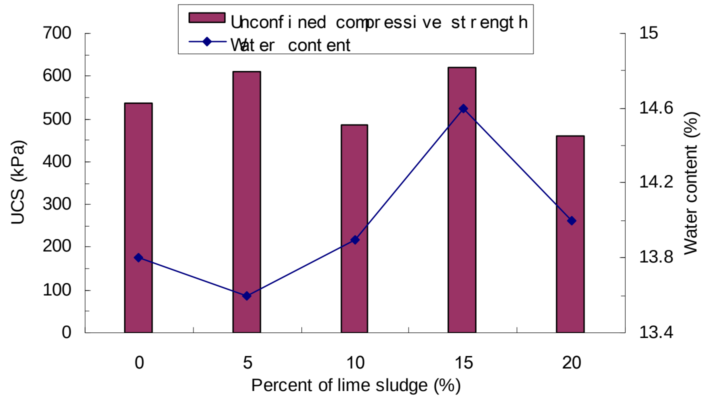


c. Lime sludge percentage 15%

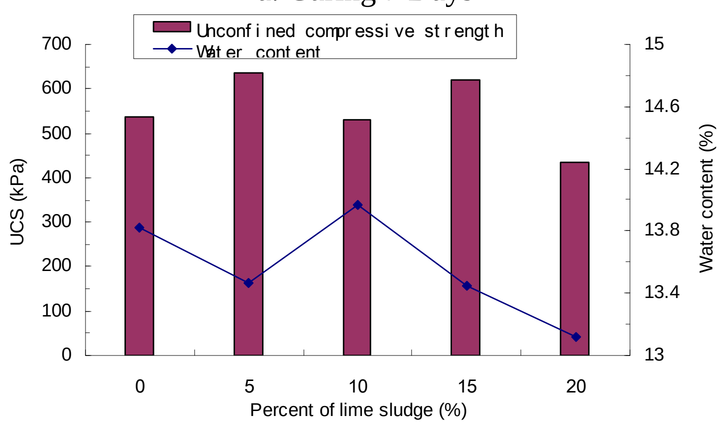


d. Lime sludge percentage 20%

Figure 12 The Effect of Changing Curing Time and Condition on the Stress-Strain Behaviors



a. Curing 7 Days



b. Curing 28 Days

FIGURE 13 Summary of Lime sludge Content versus Unconfined Compressive Strength for Soil 1A

Figure 14 plots the development of unconfined compressive strength with time. The strength development was faster in the early age (within 7days) and gradually become stable at around 28 days.

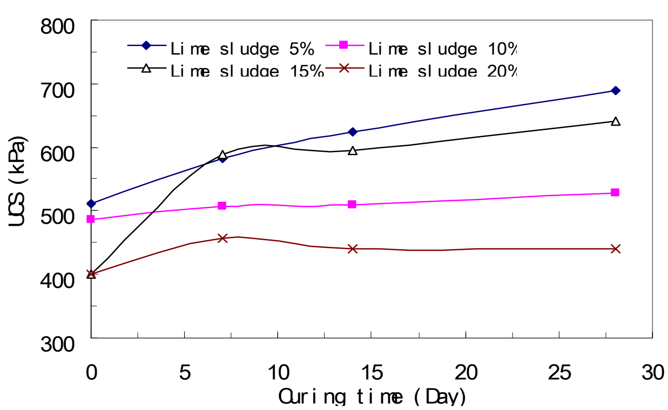


Figure 14 The Relationship of Curing Time to the Unconfined Compressive Strength with Different Lime Sludge Percentage

Soil 1B

Figure 15 shows the stress strain curves of Soil 1B specimens treated with different percentage of lime sludge. The lime sludge slightly increased the strength, modulus and brittleness of treated soil. Figure 16 shows the variations of the unconfined compression strength of treated soil versus lime sludge content. Optimal lime sludge content can't be confidently determined from the trend of change in the strength of lime sludge treated soils.

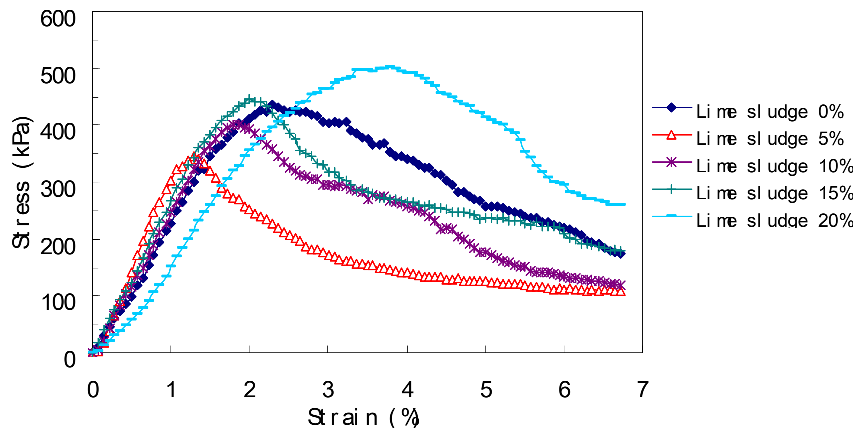


Figure 15 Stress-Strain Relationship of Soil Specimens with Different Lime Sludge Incorporating Ratio

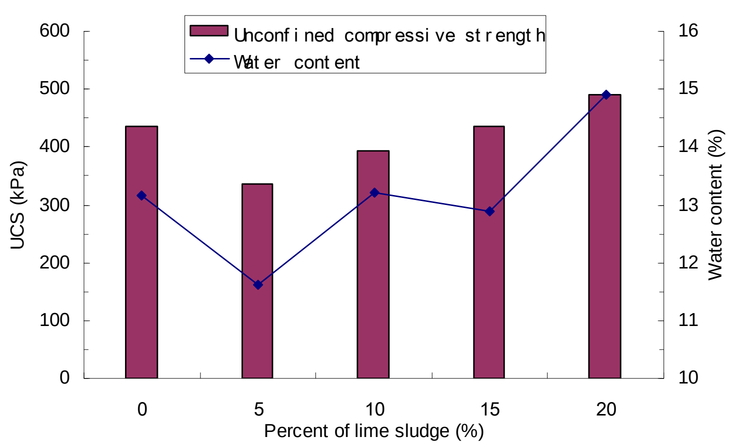


FIGURE 16 Lime sludge Content versus Unconfined Compressive Strength

Soil 2

Figure 17 shows the stress strain curves of Soil 2 specimens treated with different percentage of lime sludge. The lime sludge slightly increased the strength, modulus and brittleness of treated soil. Figure 18 shows the variations of the unconfined compression strength of treated soil versus lime sludge content. However, the improvement effect is not so obvious. An optimal lime sludge content is estimated to be around 10% based on the trend of strength variation in Fig. 18.

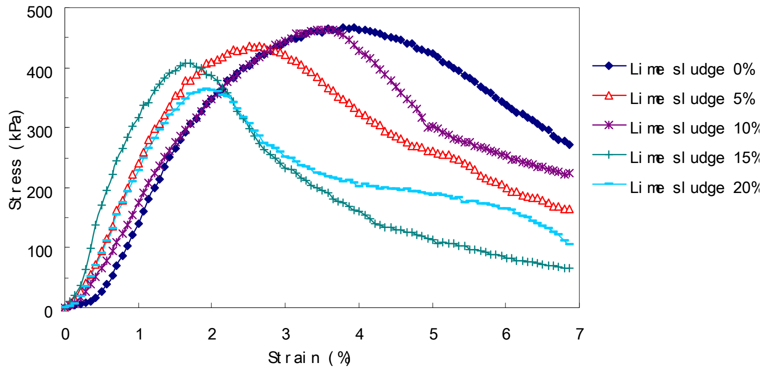


Figure 17 Stress-Strain Relationship of Soil Specimens with Different Lime Sludge Incorporating Ratio

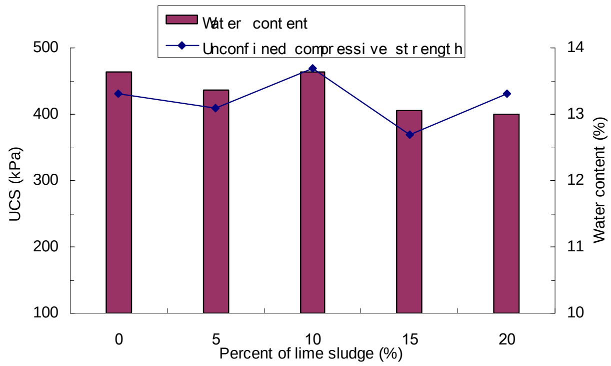


FIGURE 18 Lime sludge Content versus Unconfined Compressive Strength

Soil 3

Figure 19 show the stress versus strain curves for soil specimens 3 treated with different percentage of lime sludge. Figure 20 shows the stress strain curves of lime sludge treated soils subjected to different curing ages. Soil specimens subjected to freezing-thawing processes were also plotted in this figure to show the freeze-thaw susceptibility.

The Figure 19 shows the introduction of lime sludge slightly increases the strength, modulus and brittleness of treated soil; such effects, however, are insignificant.

Figure 21 summarizes the influence of lime sludge treatment on the soil strength. An optimal lime sludge content of around 19% could be estimated from this figure.

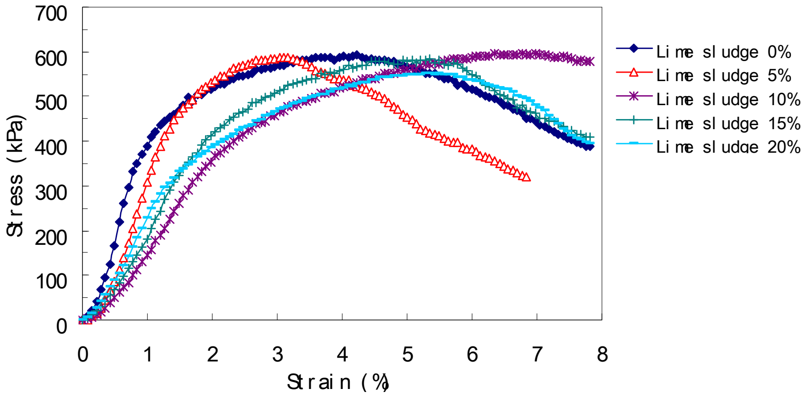
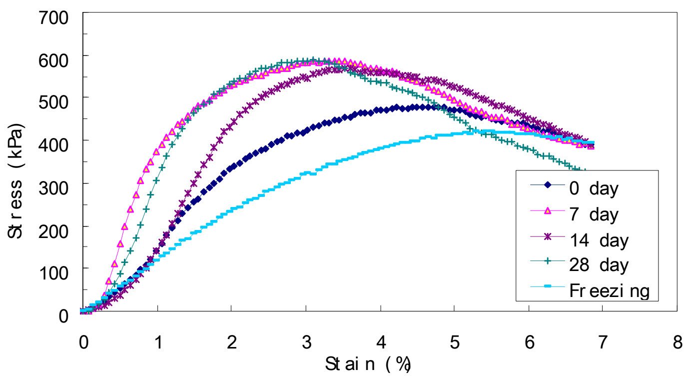
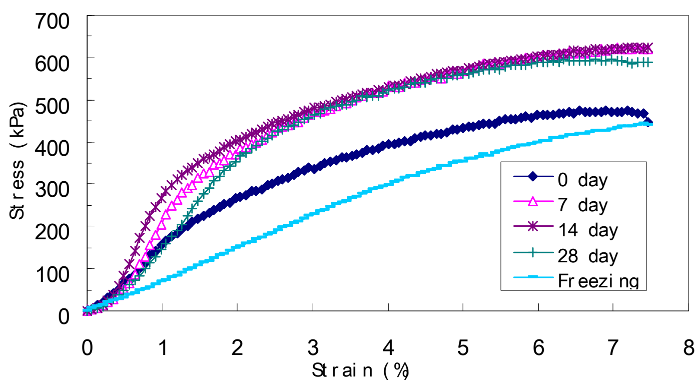


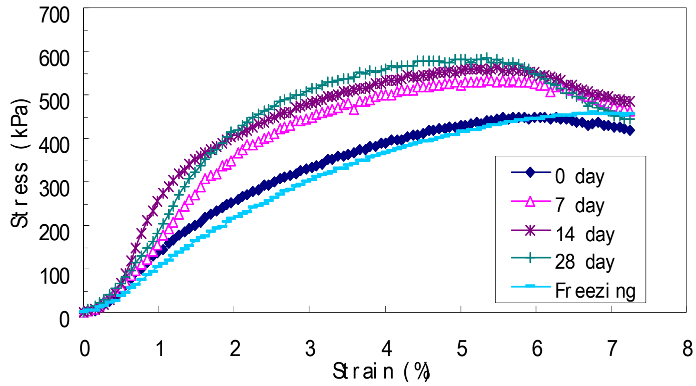
Figure 19 Stress-Strain Relationship of Soil Specimens with Different Lime Sludge Incorporating Ratio



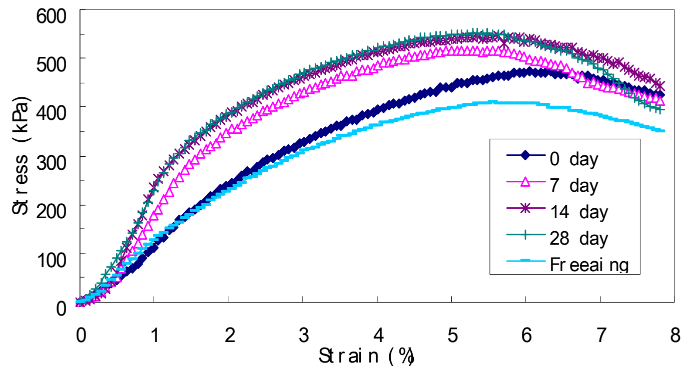
a. Lime sludge percentage 5%



b. Lime sludge percentage 10%

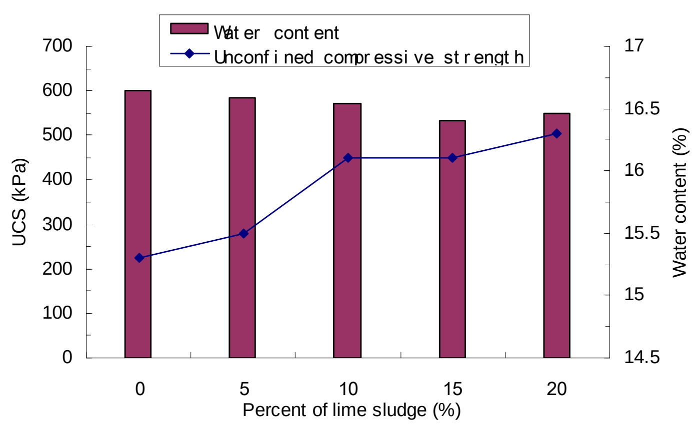


c. Lime sludge percentage 15%

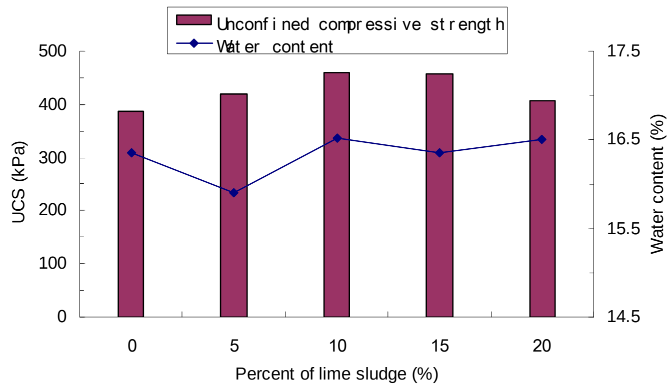


d. Lime sludge percentage 20%

Figure 20 The Effect of Changing Curing Time and Condition on the Stress-Strain Behavior



a. Curing 7 Days



b. Curing 28 Days

FIGURE 21 Lime sludge Content versus Unconfined Compressive Strength

Figure 22 plots the development of unconfined compressive strength with time. The strength development was faster in the early age (within 7 days) and gradually become stable at around 28 days.

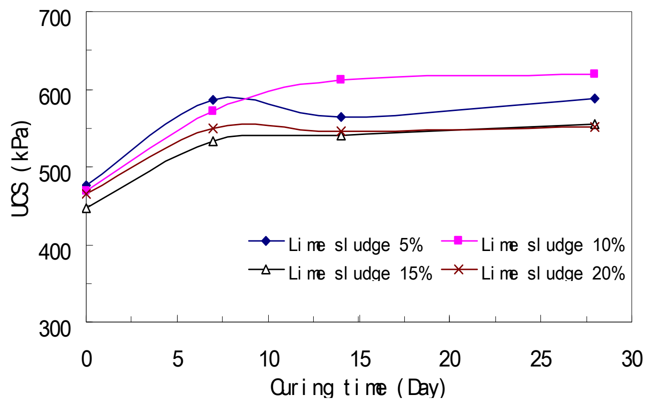


Figure 22 The Relationship of Curing Time to the Unconfined Compressive Strength with Different Lime Sludge Percentage

Soil 5

Figure 23 shows the stress strain curves of Soil 5 specimens treated with different percentage of lime sludge. The lime sludge slightly increased the strength, modulus and brittleness of treated soil.

Figure 24 shows the variations of the unconfined compression strength of treated soil versus lime sludge content. However, the improvement effect is not so obvious. An optimal lime sludge content is estimated to be around 10% based on the trend of strength variation in Fig. 24.

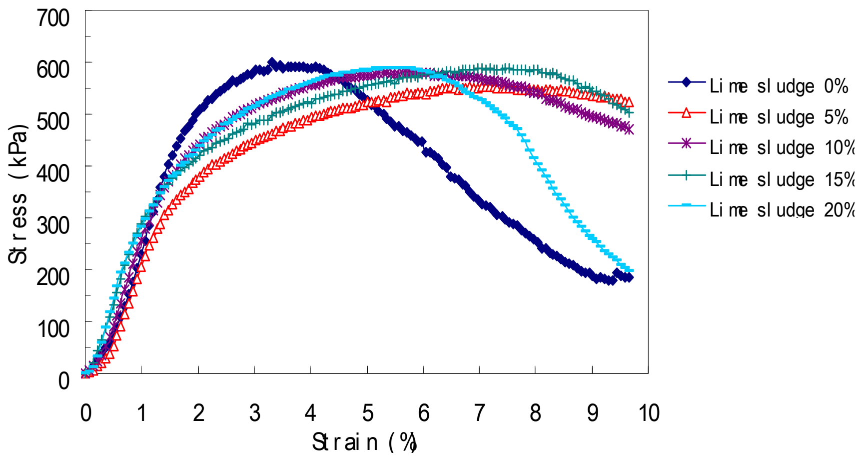


Figure 23 Stress-Strain Relationship of Soil Specimens with Different Lime Sludge Incorporating Ratio

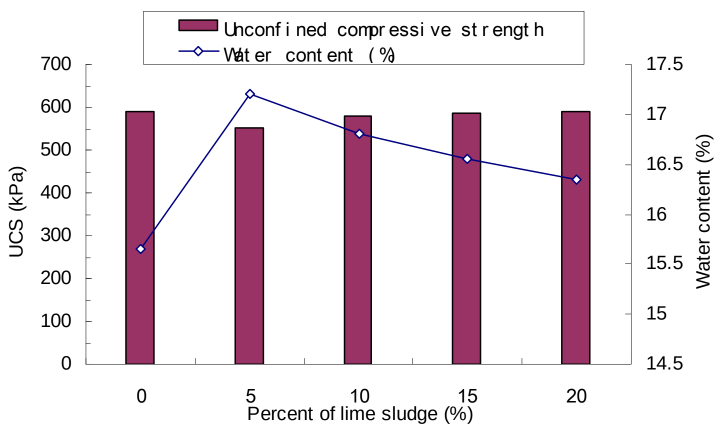


FIGURE 24 Lime sludge Content versus Unconfined Compressive Strength

Cleveland clay soil

Figure 25 shows the typical stress strain curves for Cleveland clay soil specimen treated with lime sludge versus that of a natural untreated soil specimen. The treated soil in the figure has lime sludge content of 15%. This figure shows lime sludge helps to increase the modulus and brittleness of treated soil. The improvement of soil strength of treated soil can be seen again in Figure 26.

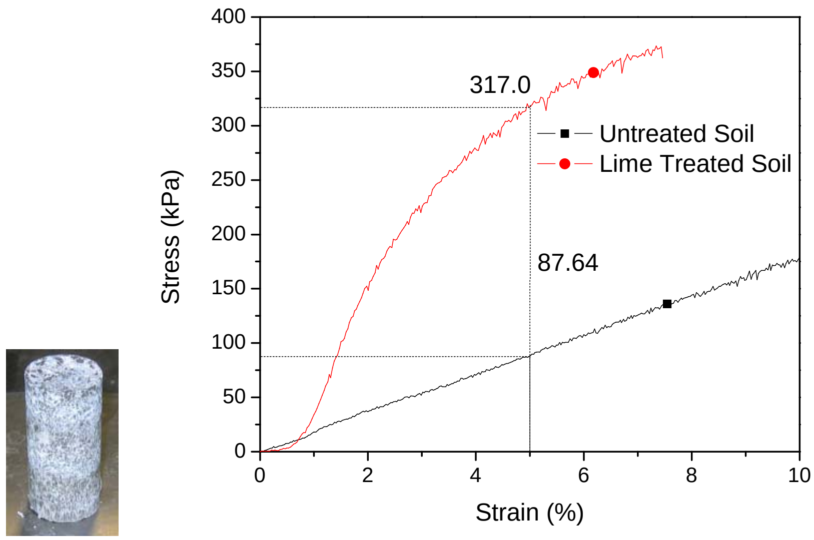


FIGURE 25 Deformation behaviors of soil specimen treated with lime sludge versus that of natural untreated soil

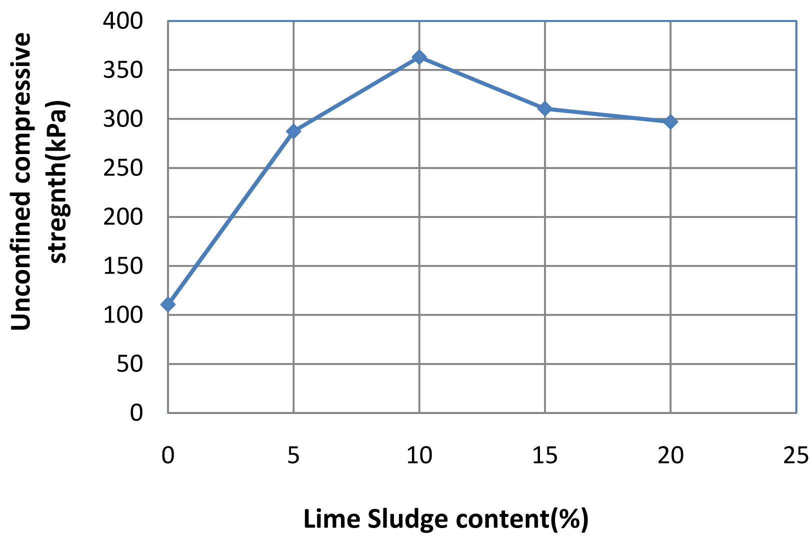


FIGURE 26 Lime sludge Content versus Unconfined Compressive Strength

Figure 26 shows the variation of the average unconfined compression strength versus lime sludge content. The figure shows that the strength of soil mixture first increases as lime sludge content increases; it then starts to decrease when the lime sludge content is larger than 10%. An optimal lime sludge content of around 10% can be estimated from the plot. This might correspond to the optimal lime sludge content. By examining the compression curves, it is found that treated soil appears to have become more brittle at higher lime sludge content.

Figure 27 summarizes the effects of lime sludge content on the unconfined compressive strength for different types of soils. A general trend is the introduction of lime sludge does not significantly affect the strength of soils 1A, 1B, 2, 3, and 5 (all belongs to low plastic soils according to USCS classification or A-6 according to AASHTO). The introduction of lime sludge does increase the strength of the Cleveland local clay (a high plastic soil according to USCS system or A-7 soil).

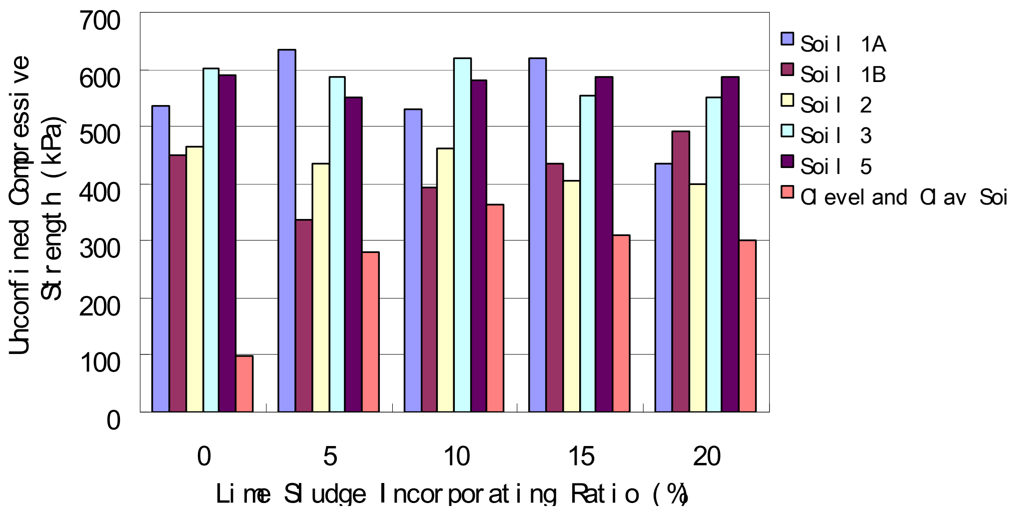


Figure 27 Effect of Unconfined Compressive Strength on Lime Sludge Ratio of Different Soil

OBSERVATION 1: 1) ***the experimental data indicates that the commonly used method for optimal lime content design (i.e. ASTM D6276) does not apply to lime sludge. Unconfined compressive strength can be used instead to design the optimal lime sludge content; 2) the introduction of lime sludge does not significantly affects or slightly reduces the strength of low plastic soils (A-6); it increases the strength of high plastic soils (A-7)***

2. Effect of Dry/Wet Mix on Soil Strength

Different procedures are used to introduce lime into soil mix, i.e., dry mix method, where the lime powder is directly mixed with soil; and wet mix method, where the lime powder is first mixed with water to produce lime slurry, which is then sprayed and mixed with soil. From the economic aspect, due to the high water content of lime sludge in lagoon, the cost of drying lime sludge is high. Introducing lime sludge as slurry is a technically and economically more feasible approach. Experiments were designed to evaluate the effects of dry versus wet mix method on the effects of soil stabilization.

Soil samples were prepared using dry mix and wet mix procedures. Three specimens were then prepared using the Harvard miniature compactor. The density and water content of these specimens were controlled so they achieved uniform physical properties. The properties of test specimens are shown in Table 10, which again indicates quality of specimens were uniform. Finished specimens were wrapped by plastic wrap and sealed in a zip bag. Specimens were cured for three days in a curing room. Unconfined compression tests were then conducted on the specimens. The average unconfined compressive strength of specimens by dry mix procedures is not significantly different from those prepared by wet mix procedures.

TABLE 10 Effect of Dry/Wet mix on Unconfined Compressive Strength

Sample	dry 15w 5L #1	dry 152 5L #2	dry 152 5L #3	wet 15w 5L #1	wet 152 5L #2	wet 152 5L #3
Dry unit weight (g/cm3)	1.86	1.85	1.77	1.85	1.82	1.81
Water content (%)	13.07			12.82		
Unconfined Compression Strength (kPa)	122.0	155.9	214.4 (possibly outlier)	105.4	133.1	161.6

Note: the following nomenclature convention is used for specimens: e.g., 15w 5l #1, 15w stands for water content is 15%; 5L means 0% percent of lime sludge; #1 is the first repetitive of the three specimens of the same kind.

OBSERVATION 2: ***dry mix versus wet mix does not significantly affects the effects of lime sludge on soil mechanical properties.*** Considering the high moisture content of lime sludge and the energy requirement to dry it up, introducing lime sludge via wet mix (i.e. as a slurry) should be economically feasible.

3. Effect of Freeze/thaw on Soil Strength

The long term durability of subgrade is an important engineering issue in cold regions. Another important aspects investigated in this study is on the long term durability of lime sludge treated soils under cold environment. In cold regions, a major factor affecting the durability of lime sludge treated soils are the seasonal freeze-thaw effects. This is a major concern for its use in road construction. A group of tests for five types soil were performed to test the resistance of the lime treated soil to freeze/thaw cycles. Five comparative groups of specimens about different soil with different lime sludge percentage were prepared at given water content. The test programs are summarized in Table 4 to Table 9.

The specimens from the same groups were placed into a temperature controlled room, where freeze-thaw cycles were produced by accurately controlling the temperature. Altogether 12 freeze/thaw cycles were applied. The remaining specimens from the same groups were placed under the normal curing temperature.

Figures 27, 30, 32 plot examples of stress-strain curves of lime sludge treated soil specimens subjected to 12 cycles of freezing-thawing cycles.

Figures 28, 29, 31 and 33 plot the comparisons of unconfined compression strength of different types of soils specimens before and after freezing-thawing cycles.

Three major observations can be made from Figures 28, 29, 31 and 33:

1) the freezing-thawing cycles caused reduction of the unconfined compression strength for most soils;

2) the percentage in the reduction of soil strength due to freezing-thawing is typically lower for soils with introduction of lime sludge;

3) soil specimens treated with lime sludge typically show higher unconfined compressive strength than untreated soil specimens.

Soil 1A

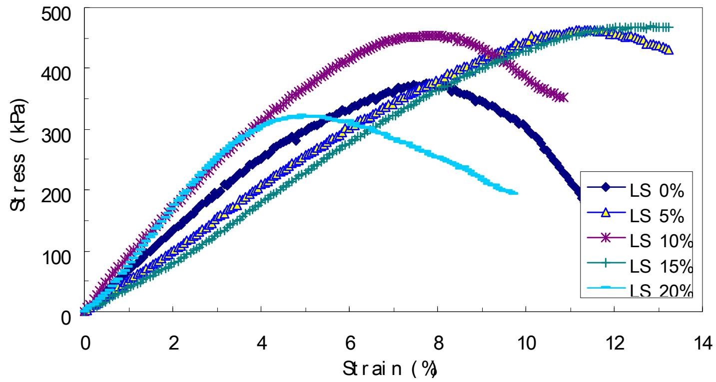


Figure 27 Stress-Strain Curves for Soil Specimens Treated with Different Lime Sludge Ratio subjected to Freeze-Thawing Cycles

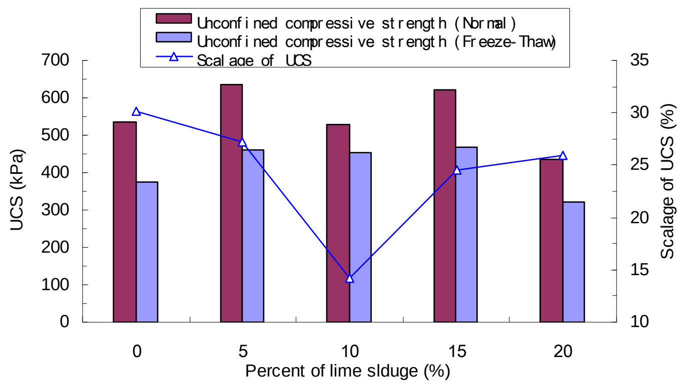


Figure 28 Lime Sludge Content versus Unconfined Compressive Strength under Normal Curing versus Subjected to Freezing-Thawing

Soil 2

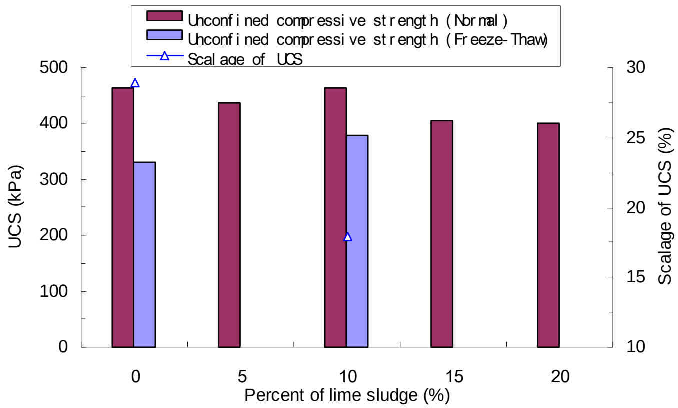
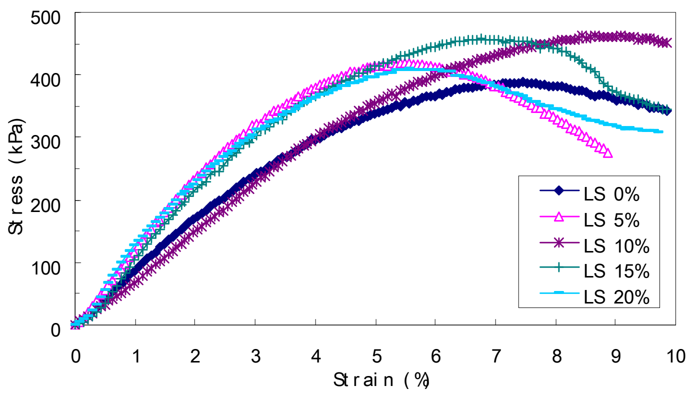


Figure 29 Lime Sludge Content versus Unconfined Compressive Strength under Normal Curing versus Subjected to Freezing-Thawing

Soil 3



Freezing

Figure 30 Stress-Strain Curves for Soil Specimens Treated with Different Lime Sludge Ratio subjected to Freeze-Thawing Cycles

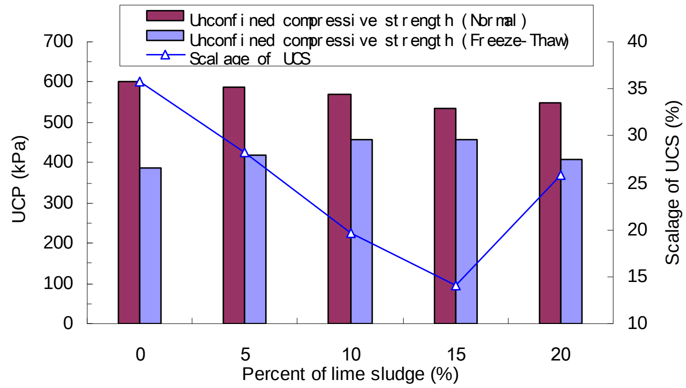


Figure 31 Lime Sludge Content versus Unconfined Compressive Strength under Normal Curing versus Subjected to Freezing-Thawing

Soil 5

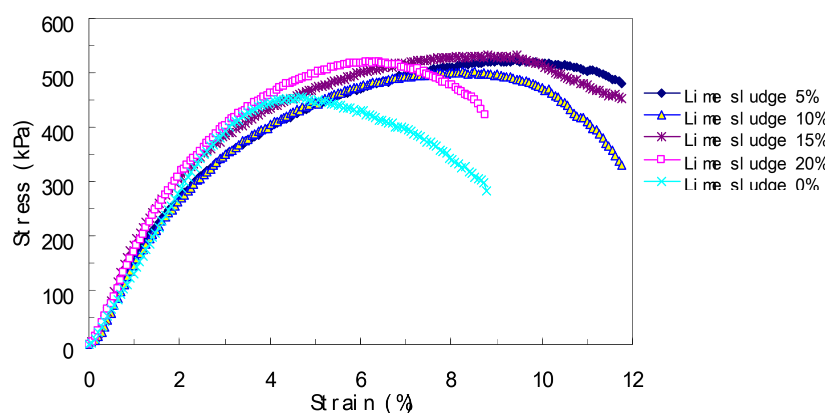


Figure 32 Stress-Strain Curves for Soil Specimens Treated with Different Lime Sludge Ratio subjected to Freeze-Thawing Cycles

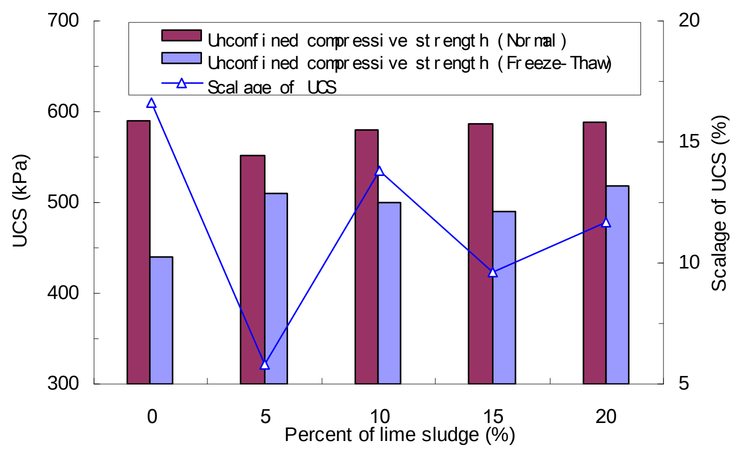


Figure 33 Lime Sludge Content versus Unconfined Compressive Strength under Normal Curing versus Subjected to Freezing-Thawing

Cleveland clay soil

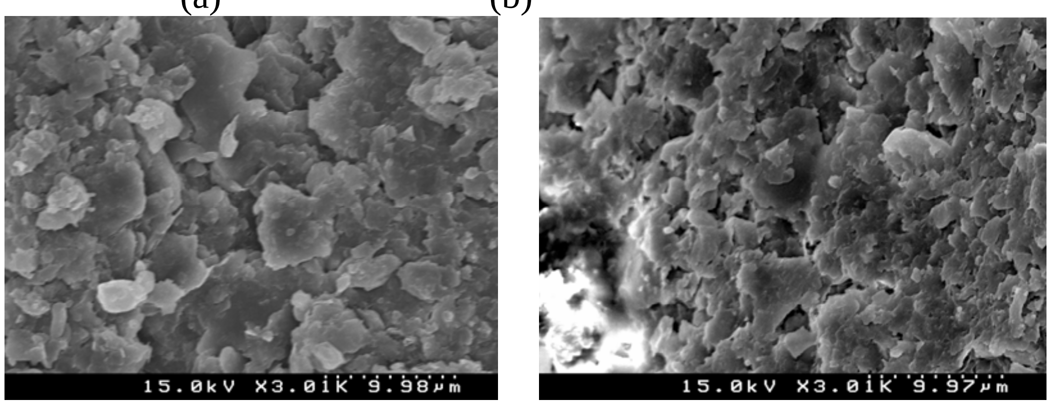
The original natural soil specimens were found to have an average unconfined compressive strength of 98.2kPa, while the original soil specimens that went through freeze/thaw cycles has an average unconfined compressive strength of 65.2kPa. For the lime sludge treated soil specimens, those cured at regular curing conditions had an average compressive strength of 363 kPa, while those undergone through the same freeze/thaw cycles has an average confined compressive strength of 196.2kPa. the lime sludge treated soil specimens have much higher strength than the natural soil specimens even after freeze-thaw cycles. These observations point to the positive effects of lime sludge treatment in improving the soil mechanical performance properties as well as improving the durability under freeze-thaw cycles.

OBSERVATION 3: ***1) freeze-thaw cycles caused the reduction of compressive strength for both natural soils and soils treated by lime sludge. 2) the percentage in the reduction of soil strength due to freezing-thawing is typically lower for soils with introduction of lime sludge; 3) soil specimens treated with lime sludge typically show higher unconfined compressive strength than untreated soil specimens.***

Micro-Mechanism of Lime Sludge for Soil Stabilization

Figure 34 show the SEM image of natural soil and that treated by lime sludge. It was found that the introduction of lime sludge changed the texture of soils. Lime sludge appears as particles in the range of silts adhered to natural soil particles. This might be responsible for the improvements of soil mechanical properties such as the freeze-thaw resistance.

(a) (b)



a. Nature soil **b. Soil treated with lime sludge**

Figure 34 SEM Image of Soil Sample

SUMMARY AND RECOMMENDATIONS

Beneficial utilization of lime sludge in transportation construction presents an opportunity to achieve sustainable utilization of a precious natural resource. Chemical analyses indicate lime sludge has similar chemical components as commercial hydrated lime. Common procedures for determining the optimal lime content for soil stabilization based on pH values are found not applicable for lime sludge. Instead, performance criteria based on unconfined compression tests need to be utilized. Lime sludge was found to increase the soil deformation modulus and reduce the plastic behaviors. Wet mix and dry mix methods do not appear to significantly affect the strength of lime sludge modified soil. Considering of the economic factors associated with drying lime sludge, lime sludge can be introduced in the slurry format via the wet mix procedure. The existing testing data indicated that lime sludge does not significantly improve the unconfined soil strength. Lime sludge however demonstrated the positive effects in reducing the plasticity of soils and improve the freeze/thaw durability. The long term performance evaluation could provide data to quantify the effectiveness of lime sludge as an economic and sustainable material. Upon further validation of long term field performance, lime sludge could be incorporated as a candidate material in the ODOT materials Supplement specifications (No. 1120) for Design of Chemical Stabilization.

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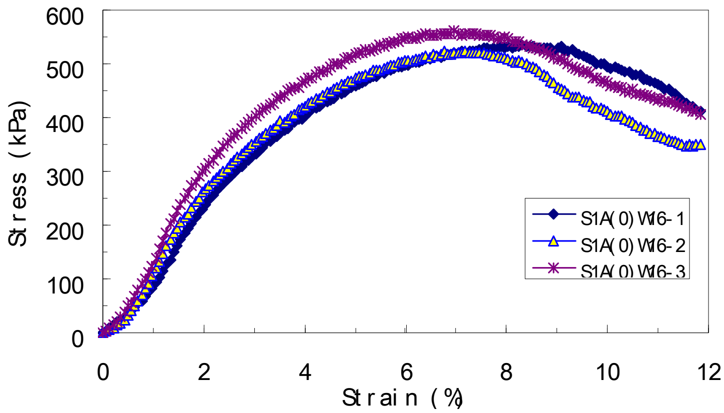
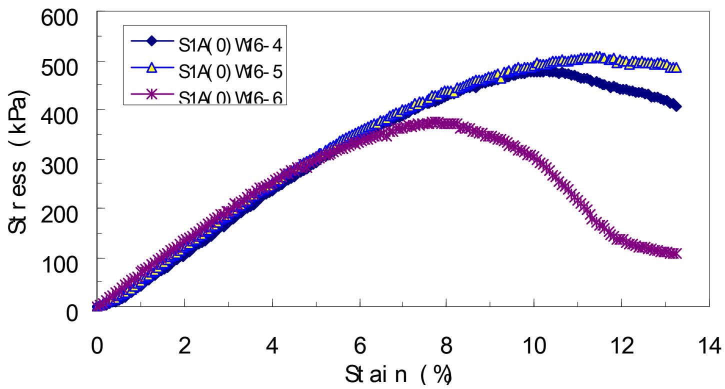
6. Ferguson, E. G., Levorson S. M. Soil and Pavement Stabilization with Self-Cementing Coal Fly Ash, American Coal Ash Association, Alexandria, VA, May, 1999.
7. ASTM D5102. Standard Test Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures. (www.astm.org).
8. Ohio Department of Transportation, (2010). Supplementary Specifications for Chemically Stabilized Soils, April 2010, 7p.

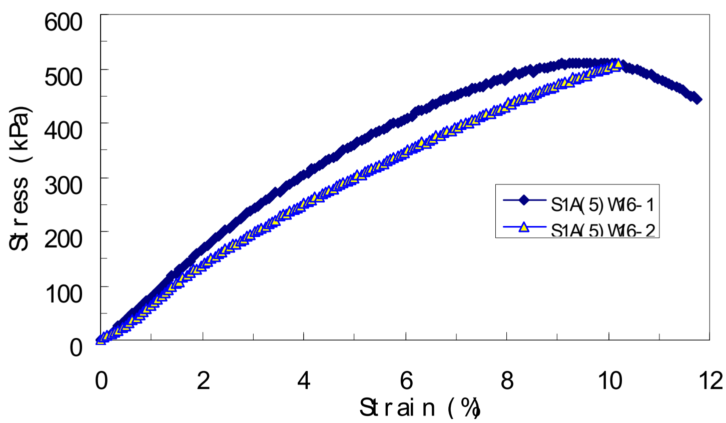
APPENDICES

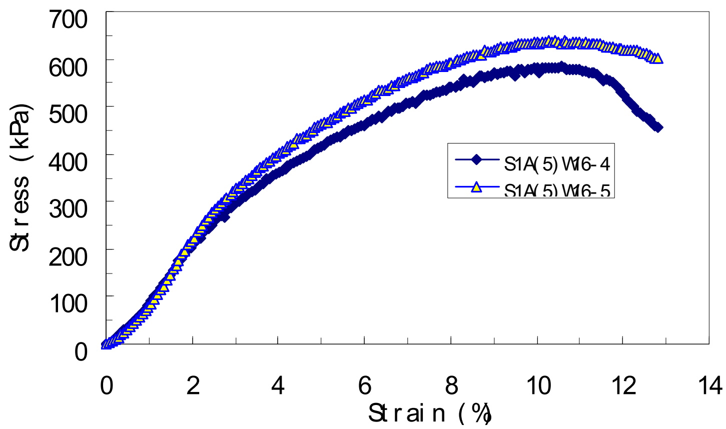
Example stress-strain curves from unconfined compression tests on different soil specimens. ***The convention of notation for the soil specimens are shown in Tables 4 to Table 9.***

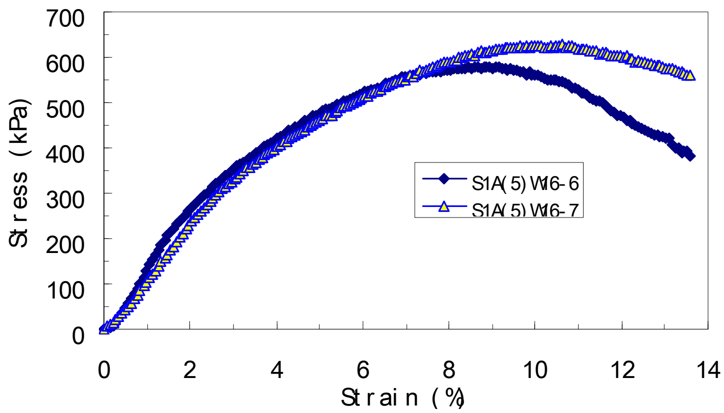
Soil 1A

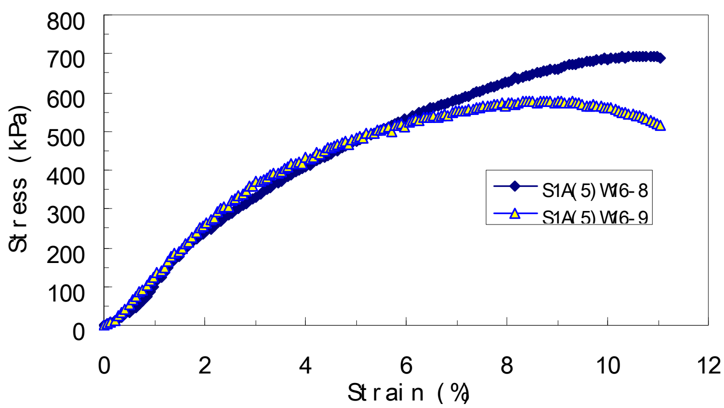

Stress (kPa)
Strain (%)
S1A(0)W16-1
S1A(0)W16-2
S1A(0)W16-3

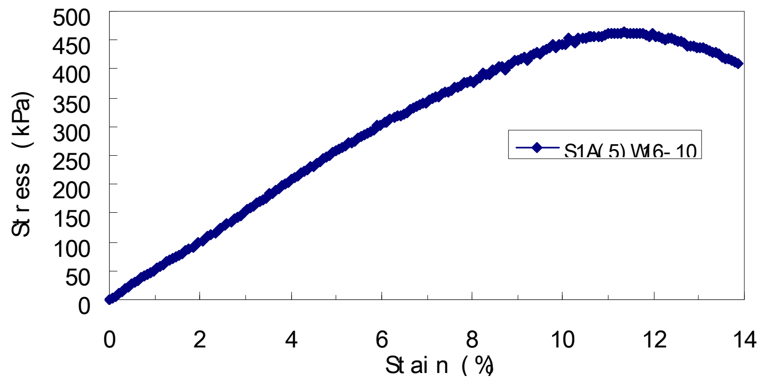

Stress (kPa)
Stain (%)
S1A(0)W16-4
S1A(0)W16-5
S1A(0)W16-6


Stress (kPa)
Strain (%)
S1A(5)W16-1
S1A(5)W16-2

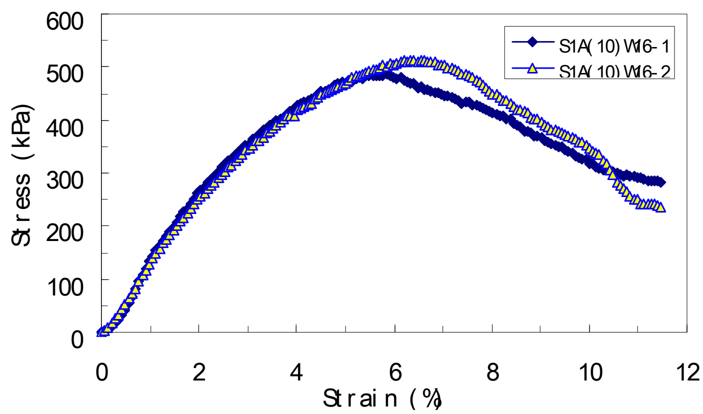

Stress (kPa)
Strain (%)
S1A(5)W16-4
S1A(5)W16-5


Stress (kPa)
Strain (%)
S1A(5)W16-6
S1A(5)W16-7

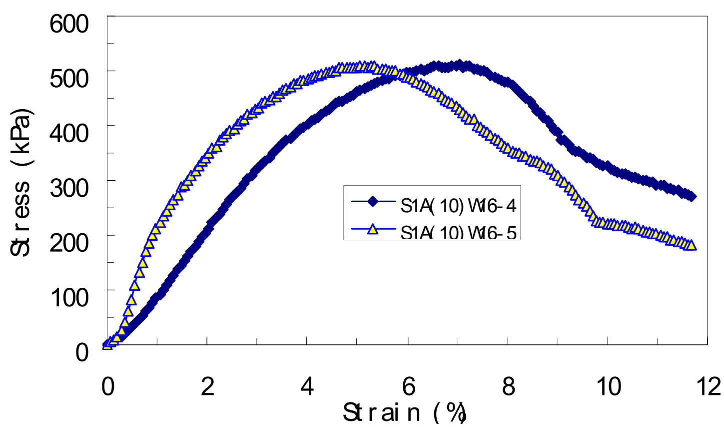

Stress (kPa)
Strain (%)
S1A(5)W16-8
S1A(5)W16-9



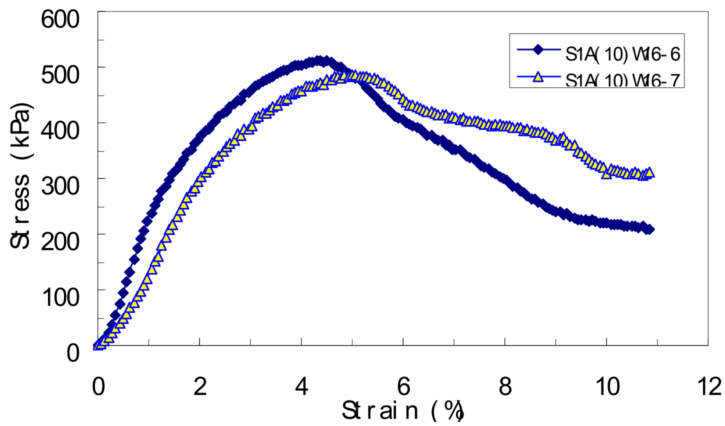
Stress (kPa)
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
Stain (%)
S1A(5) W16-10

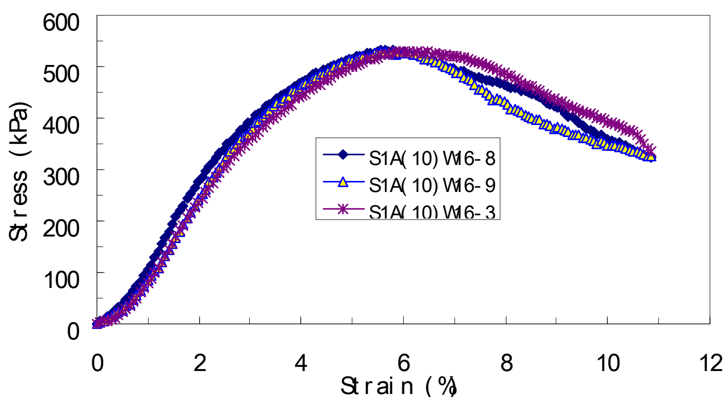


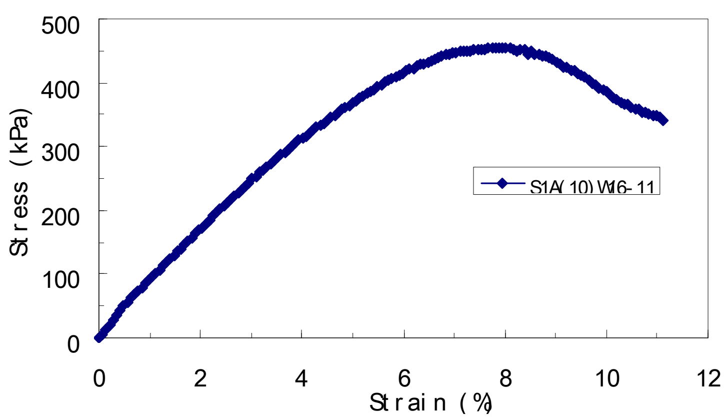
Stress (kPa)
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Strain (%)
S1A(10) W16-1
S1A(10) W16-2

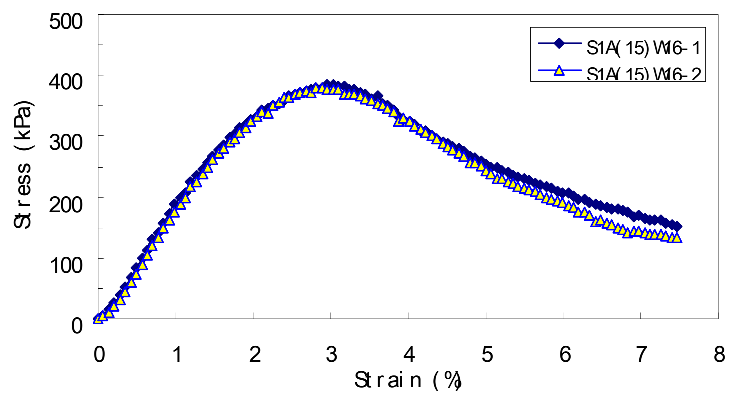


Stress (kPa)
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Strain (%)
S1A(10) W16-4
S1A(10) W16-5

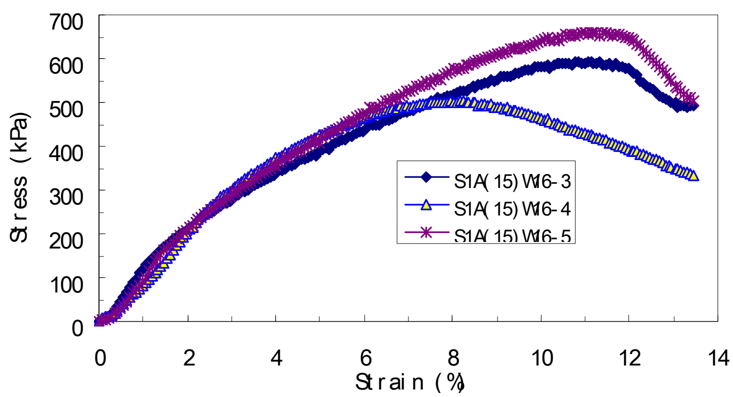

600
500
400
300
200
100
0
Stress (kPa)
0
2
4
6
8
10
12
Strain (%)
S1A(10)W16-6
S1A(10)W16-7


600
500
400
300
200
100
0
Stress (kPa)
0
2
4
6
8
10
12
Strain (%)
S1A(10)W16-8
S1A(10)W16-9
S1A(10)W16-3

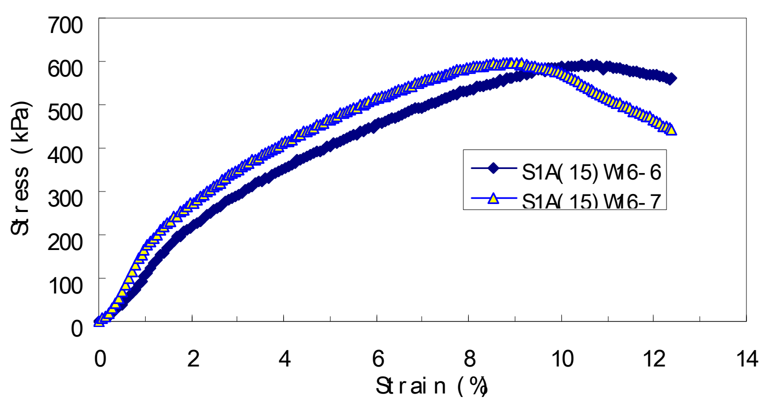

500
400
300
200
100
0
Stress (kPa)
0
2
4
6
8
10
12
Strain (%)
S1A(10)W16-11



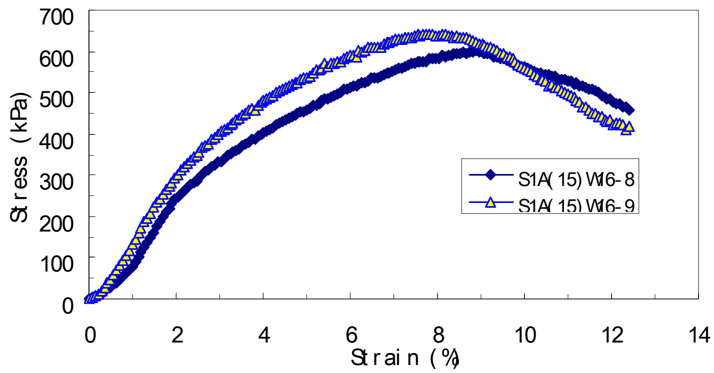
500
400
300
200
100
0
Stress (kPa)
0 1 2 3 4 5 6 7 8
Strain (%)
S1A(15)W16-1
S1A(15)W16-2



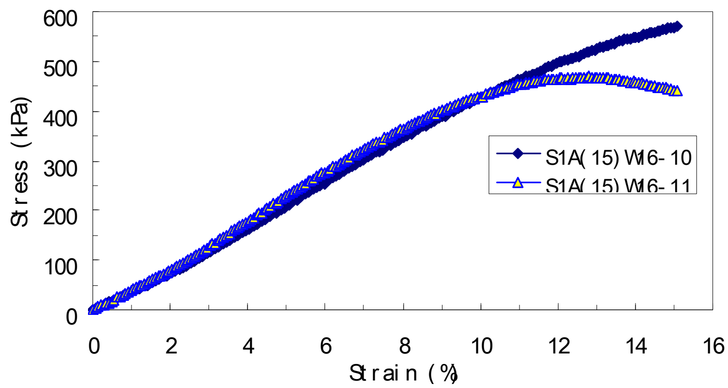
700
600
500
400
300
200
100
0
Stress (kPa)
0 2 4 6 8 10 12 14
Strain (%)
S1A(15)W16-3
S1A(15)W16-4
S1A(15)W16-5



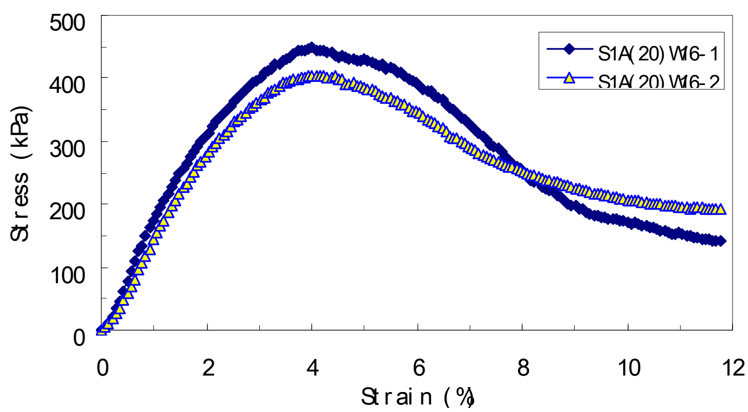
700
600
500
400
300
200
100
0
Stress (kPa)
0 2 4 6 8 10 12 14
Strain (%)
S1A(15)W16-6
S1A(15)W16-7



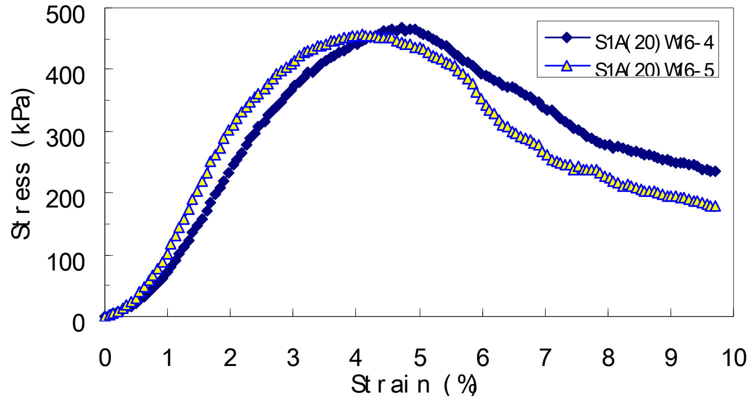
Stress (kPa)
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
Strain (%)
S1A(15)W16-8
S1A(15)W16-9

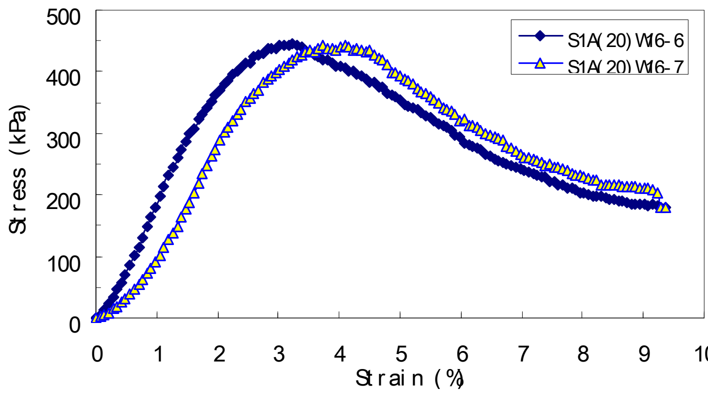


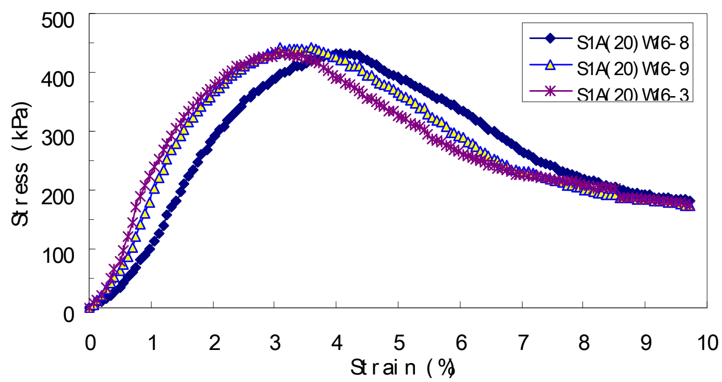
Stress (kPa)
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
Strain (%)
S1A(15)W16-10
S1A(15)W16-11

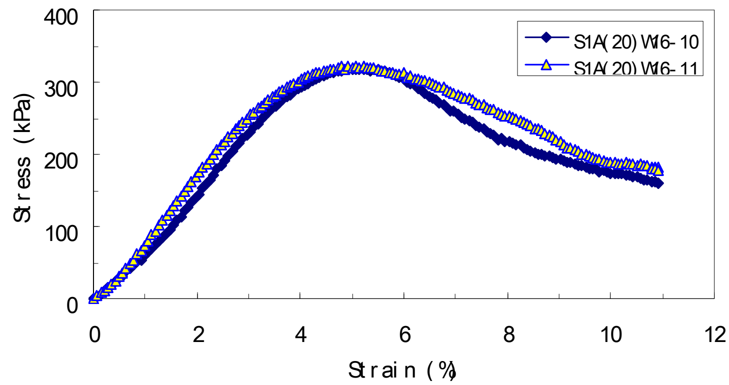


Stress (kPa)
500
400
300
200
100
0
0
2
4
6
8
10
12
Strain (%)
S1A(20)W16-1
S1A(20)W16-2

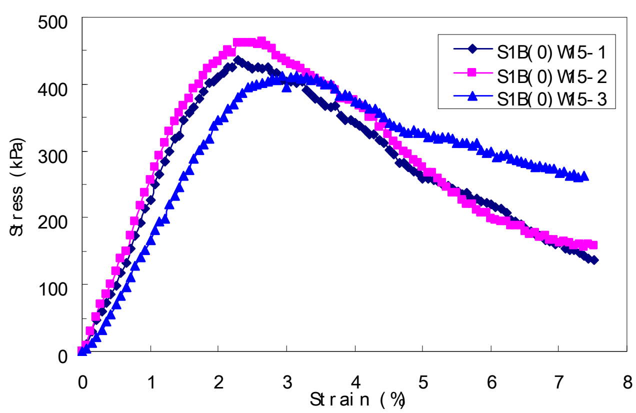

S1A(20)W16-4
S1A(20)W16-5
Stress (kPa)
Strain (%)

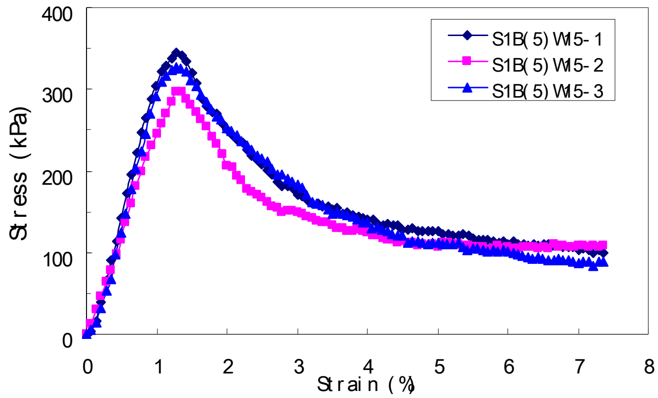

S1A(20)W16-6
S1A(20)W16-7
Stress (kPa)
Strain (%)


S1A(20)W16-8
S1A(20)W16-9
S1A(20)W16-3
Stress (kPa)
Strain (%)

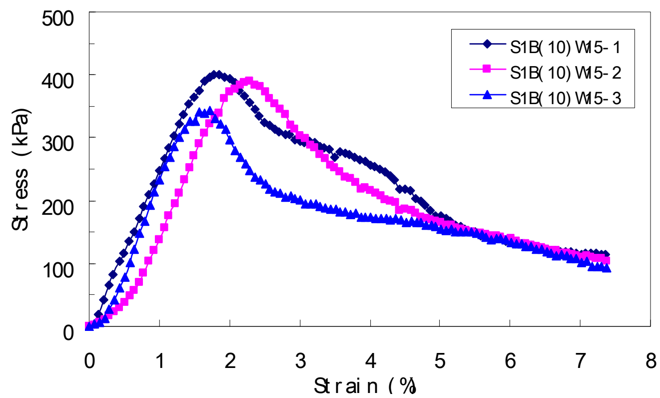

400
300
200
100
0
Stress (kPa)
0
2
4
6
8
10
12
Strain (%)
S1A(20)W16-10
S1A(20)W16-11

Soil 1B

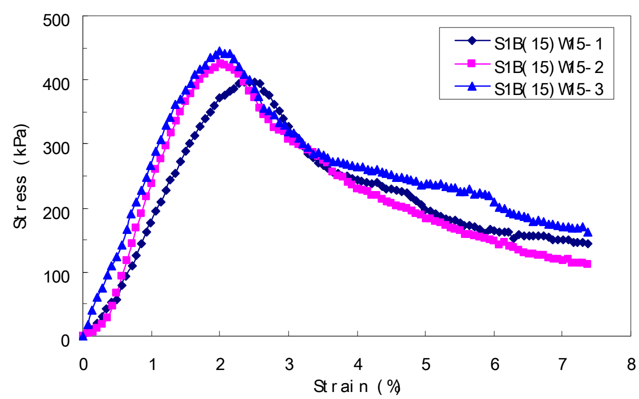

500
400
300
200
100
0
Stress (kPa)
0
1
2
3
4
5
6
7
8
Strain (%)
S1B(0)W15-1
S1B(0)W15-2
S1B(0)W15-3



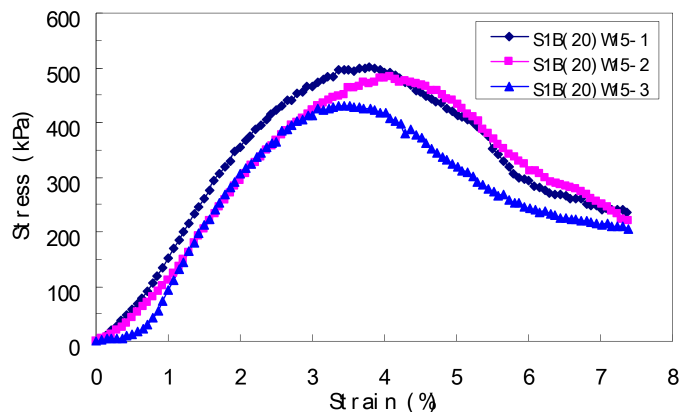
S1B(5)W15-1
S1B(5)W15-2
S1B(5)W15-3
Stress (kPa)
Strain (%)

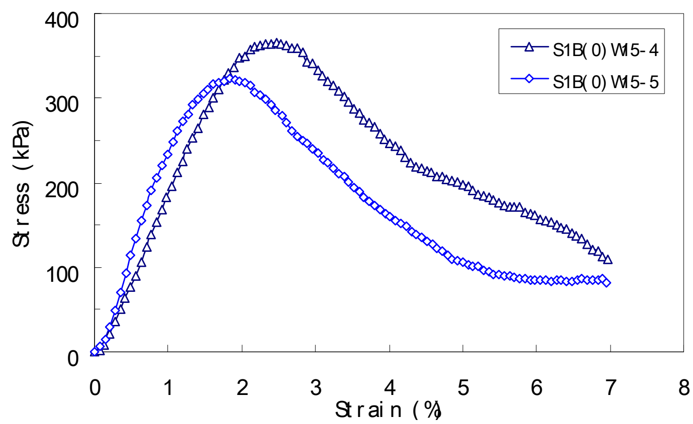


S1B(10)W15-1
S1B(10)W15-2
S1B(10)W15-3
Stress (kPa)
Strain (%)

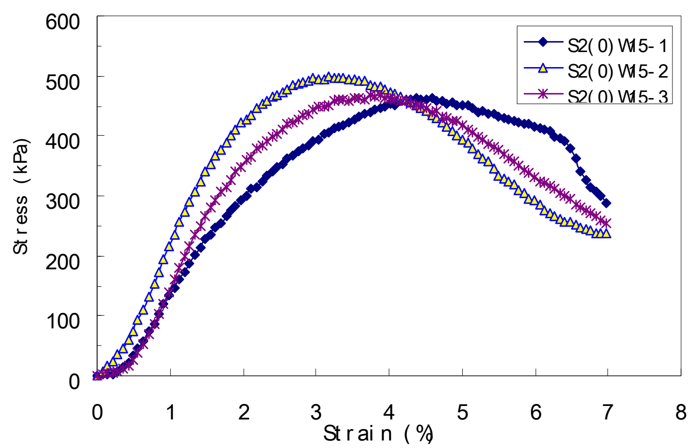


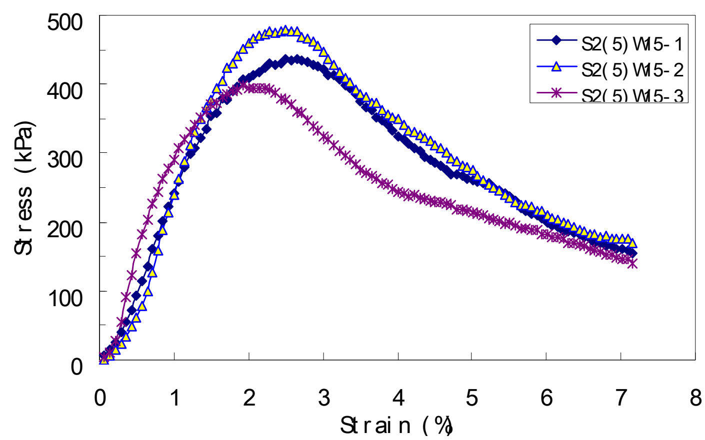
S1B(15)W15-1
S1B(15)W15-2
S1B(15)W15-3
Stress (kPa)
Strain (%)

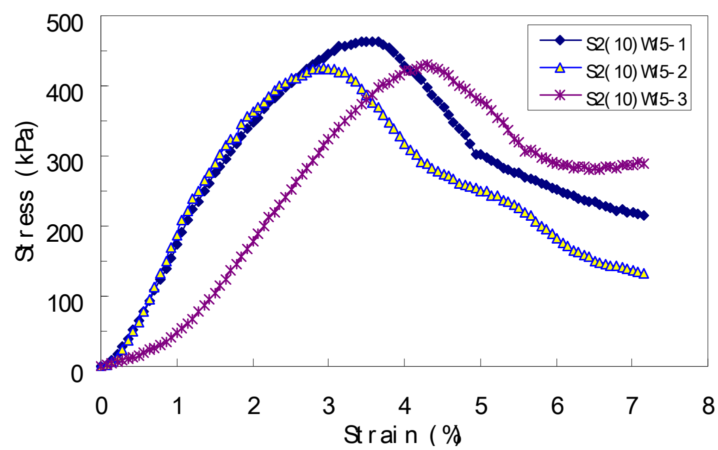

600
500
400
300
200
100
0
Stress (kPa)
0
1
2
3
4
5
6
7
8
Strain (%)
S1B(20)W15-1
S1B(20)W15-2
S1B(20)W15-3

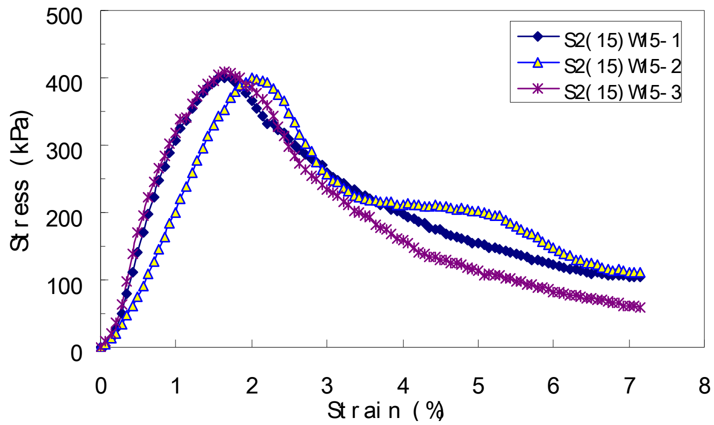

400
300
200
100
0
Stress (kPa)
0
1
2
3
4
5
6
7
8
Strain (%)
S1B(0)W15-4
S1B(0)W15-5

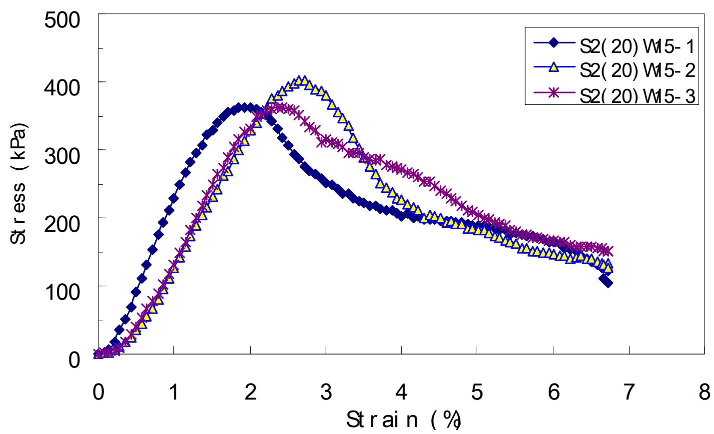
Soil 2

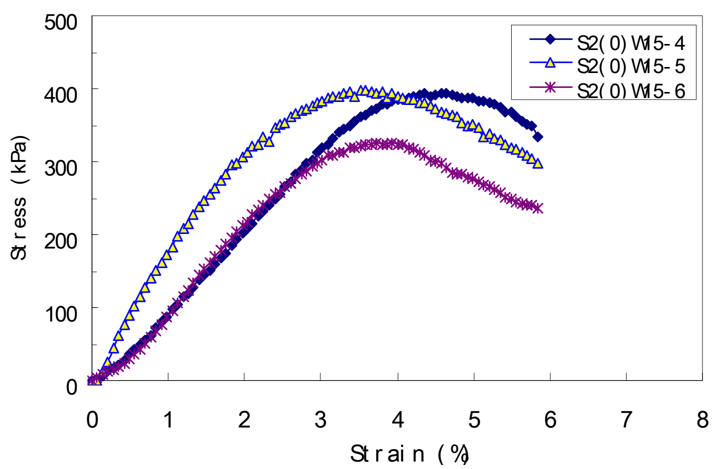

Stress (kPa)
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
Strain (%)
S2(0)W15-1
S2(0)W15-2
S2(0)W15-3

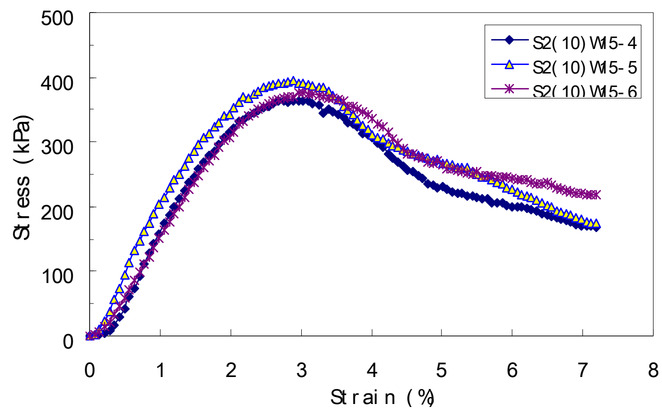

Stress (kPa)
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
Strain (%)
S2(5)W15-1
S2(5)W15-2
S2(5)W15-3


Stress (kPa)
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
Strain (%)
S2(10)W15-1
S2(10)W15-2
S2(10)W15-3


Stress (kPa)
Strain (%)
S2(15)W15-1
S2(15)W15-2
S2(15)W15-3
0
100
200
300
400
500
0 1 2 3 4 5 6 7 8

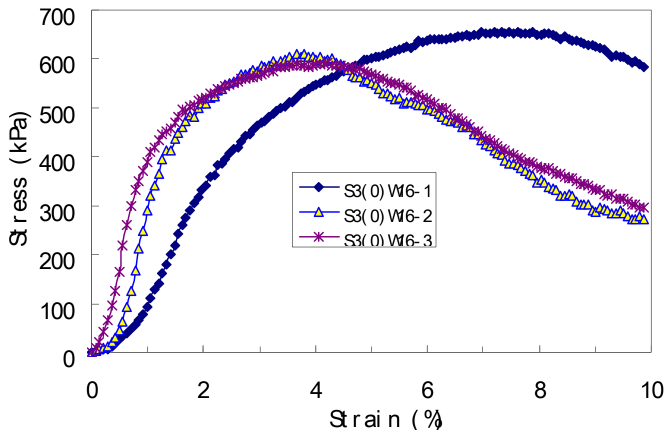

Stress (kPa)
Strain (%)
S2(20)W15-1
S2(20)W15-2
S2(20)W15-3
0
100
200
300
400
500
0 1 2 3 4 5 6 7 8


Stress (kPa)
Strain (%)
S2(0)W15-4
S2(0)W15-5
S2(0)W15-6
0
100
200
300
400
500
0 1 2 3 4 5 6 7 8

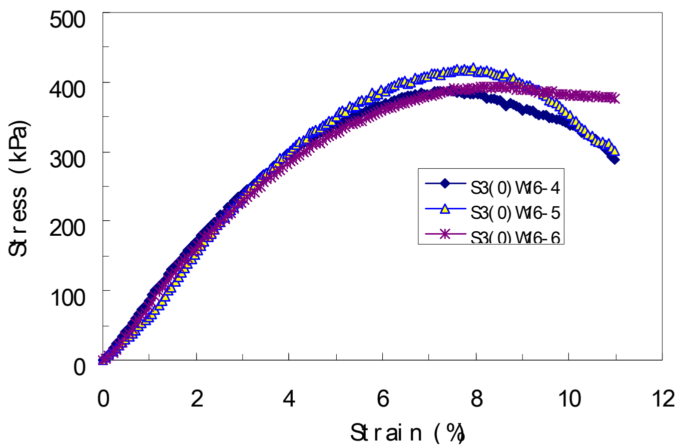


S2(10)W15-4
S2(10)W15-5
S2(10)W15-6
Stress (kPa)
Strain (%)
0
100
200
300
400
500
0
1
2
3
4
5
6
7
8

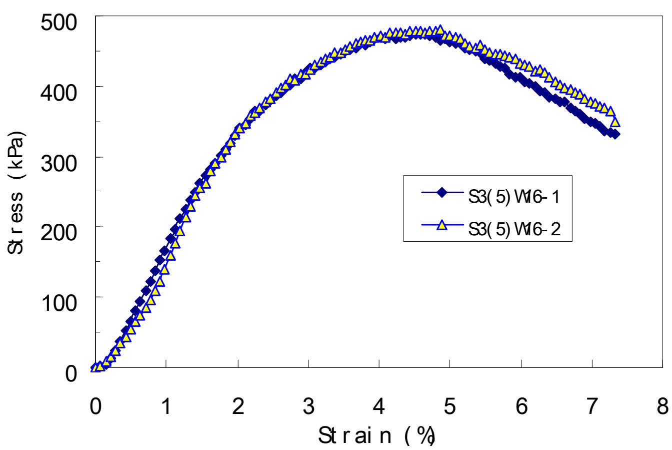
Soil 3



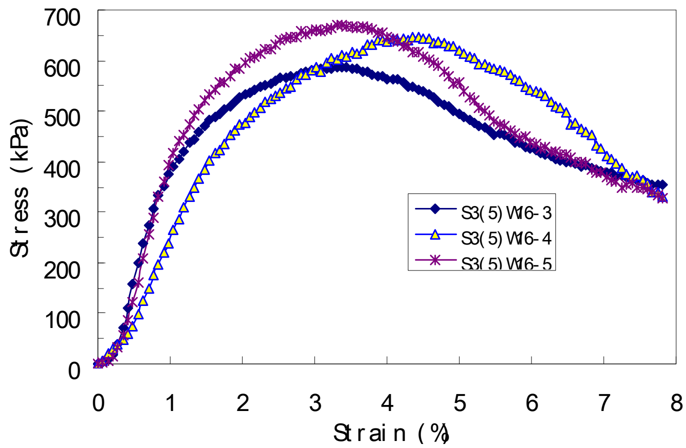
Stress (kPa)
Strain (%)
S3(0)W16-1
S3(0)W16-2
S3(0)W16-3



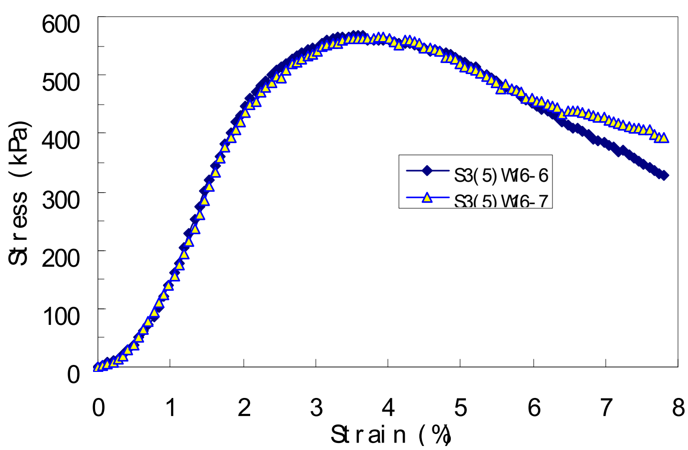
Stress (kPa)
Strain (%)
S3(0)W16-4
S3(0)W16-5
S3(0)W16-6



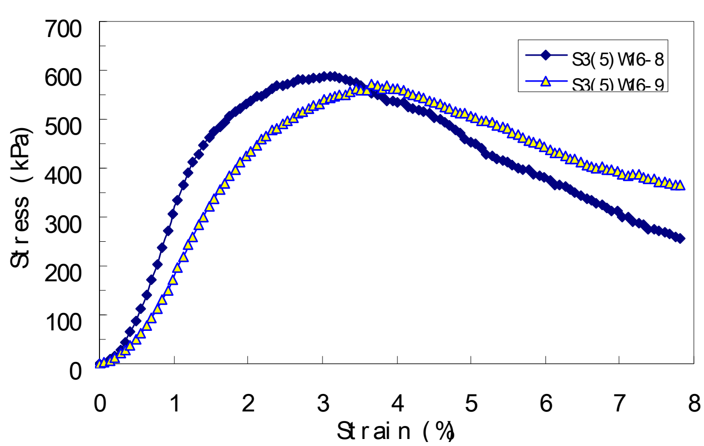
Stress (kPa)
Strain (%)
S3(5)W16-1
S3(5)W16-2



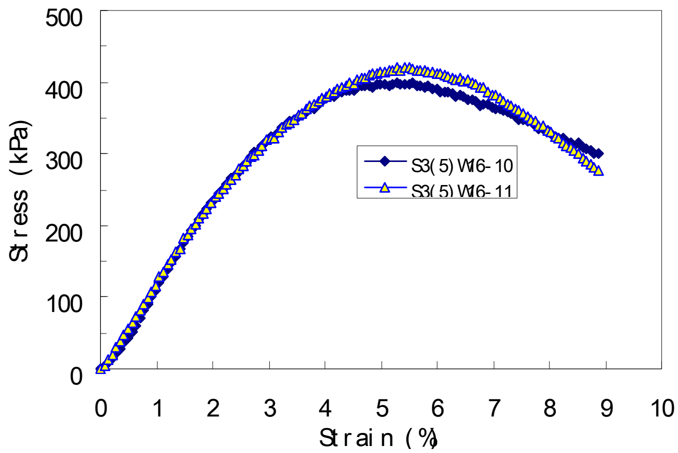
700
600
500
400
300
200
100
0
Stress (kPa)
0
1
2
3
4
5
6
7
8
Strain (%)
S3(5)W16-3
S3(5)W16-4
S3(5)W16-5

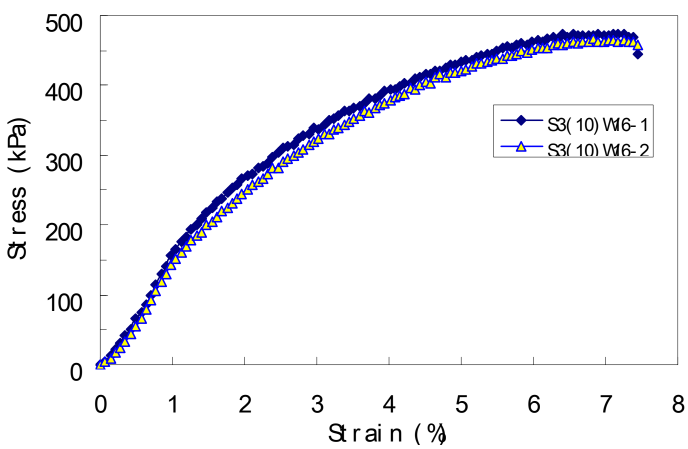


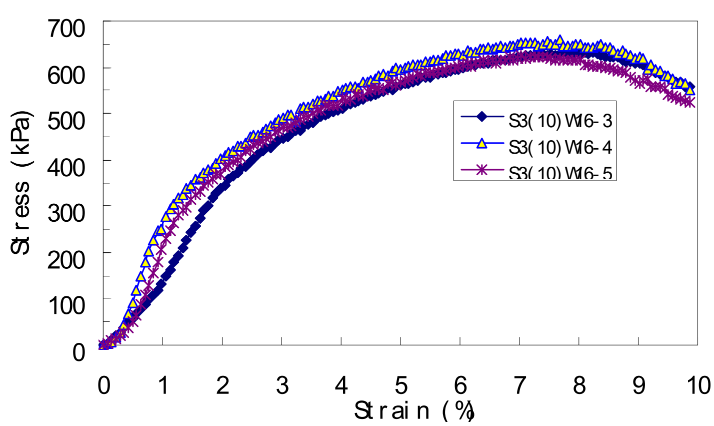
600
500
400
300
200
100
0
Stress (kPa)
0
1
2
3
4
5
6
7
8
Strain (%)
S3(5)W16-6
S3(5)W16-7

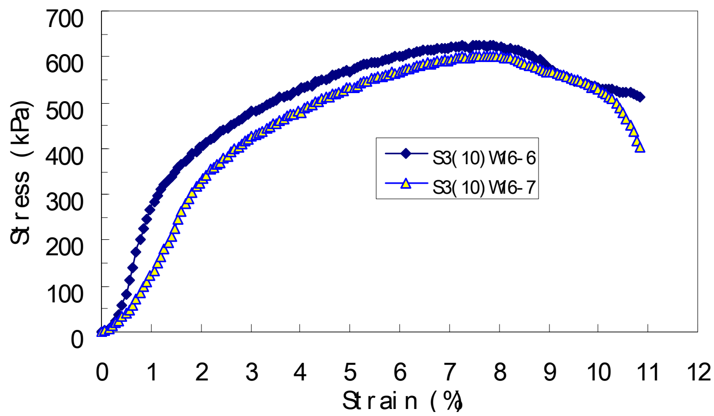


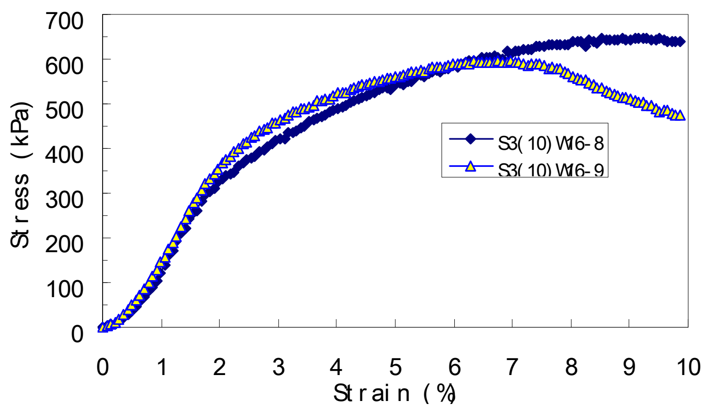
700
600
500
400
300
200
100
0
Stress (kPa)
0
1
2
3
4
5
6
7
8
Strain (%)
S3(5)W16-8
S3(5)W16-9

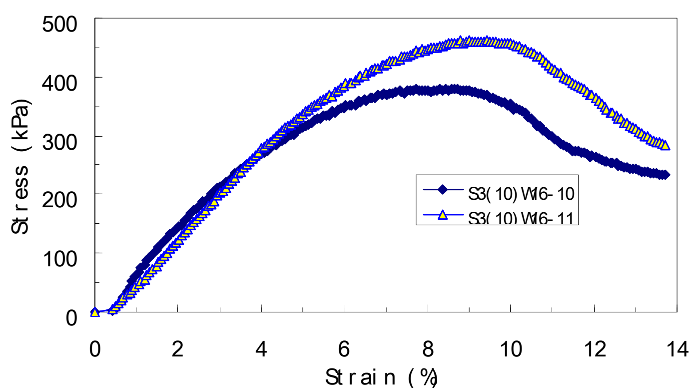

500
400
300
200
100
0
Stress (kPa)
0 1 2 3 4 5 6 7 8 9 10
Strain (%)
S3(5)W16-10
S3(5)W16-11

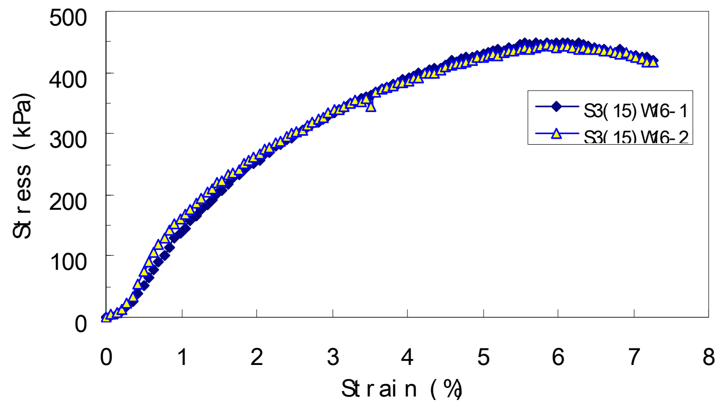

500
400
300
200
100
0
Stress (kPa)
0 1 2 3 4 5 6 7 8
Strain (%)
S3(10)W16-1
S3(10)W16-2


700
600
500
400
300
200
100
0
Stress (kPa)
0 1 2 3 4 5 6 7 8 9 10
Strain (%)
S3(10)W16-3
S3(10)W16-4
S3(10)W16-5

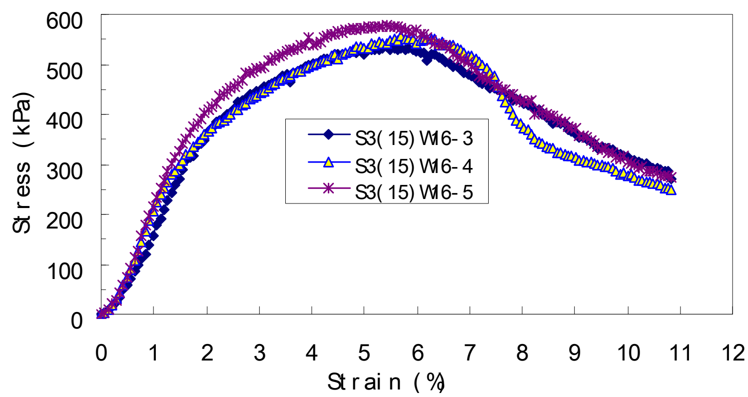

Stress (kPa)
Strain (%)
S3(10)W6-6
S3(10)W6-7


Stress (kPa)
Strain (%)
S3(10)W6-8
S3(10)W6-9

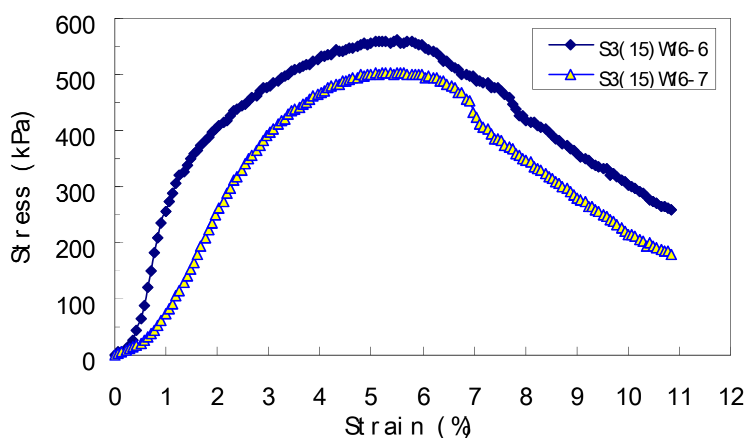

Stress (kPa)
Strain (%)
S3(10)W6-10
S3(10)W6-11



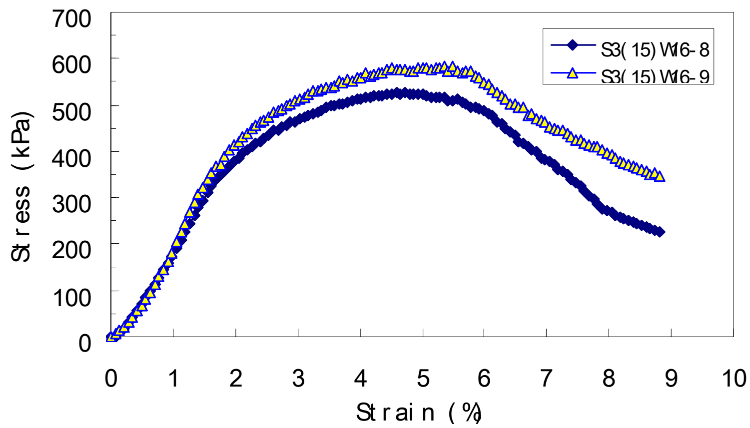
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8
Stress (kPa)
Strain (%)
S3(15)W16-1
S3(15)W16-2

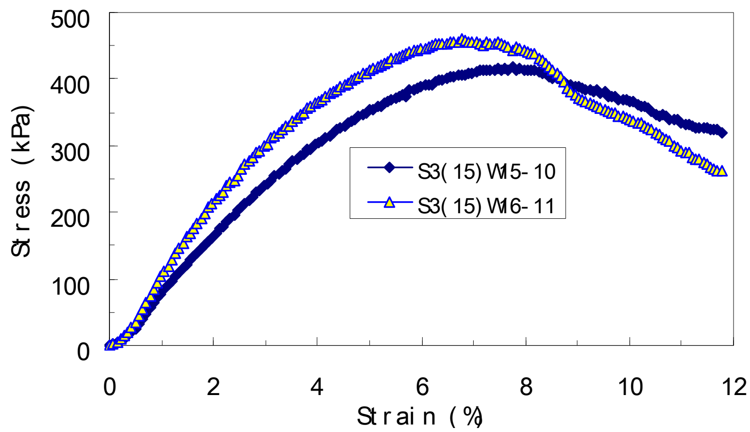


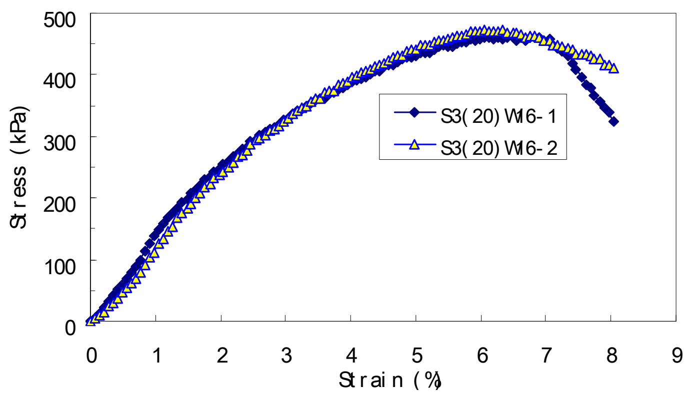
600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Stress (kPa)
Strain (%)
S3(15)W16-3
S3(15)W16-4
S3(15)W16-5

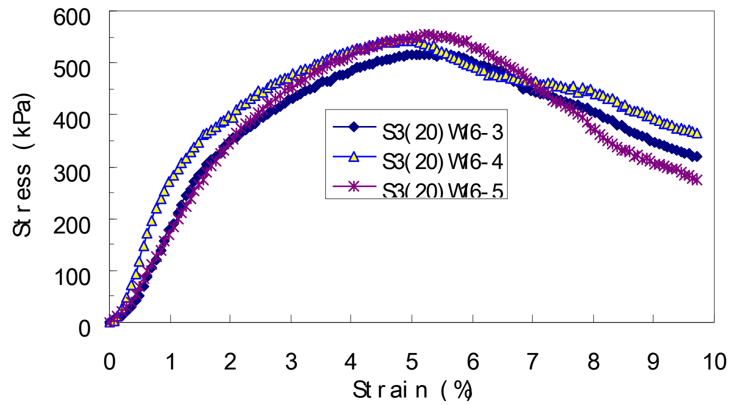


600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Stress (kPa)
Strain (%)
S3(15)W16-6
S3(15)W16-7

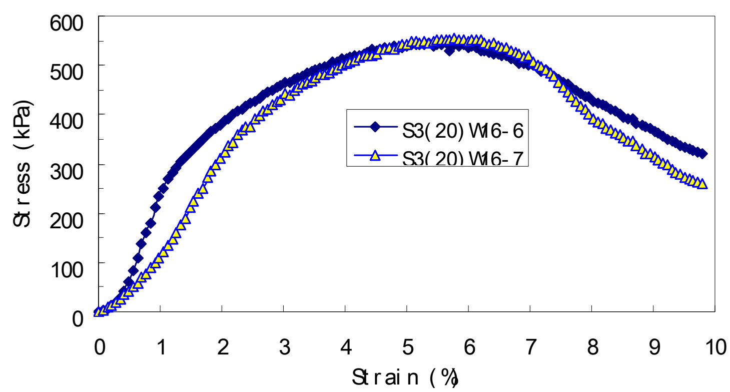

S3(15)W16-8
S3(15)W16-9
Stress (kPa)
Strain (%)


S3(15)W15-10
S3(15)W16-11
Stress (kPa)
Strain (%)

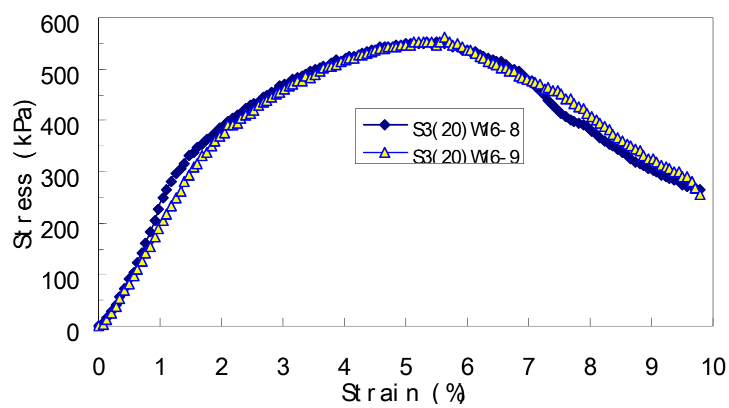

S3(20)W16-1
S3(20)W16-2
Stress (kPa)
Strain (%)



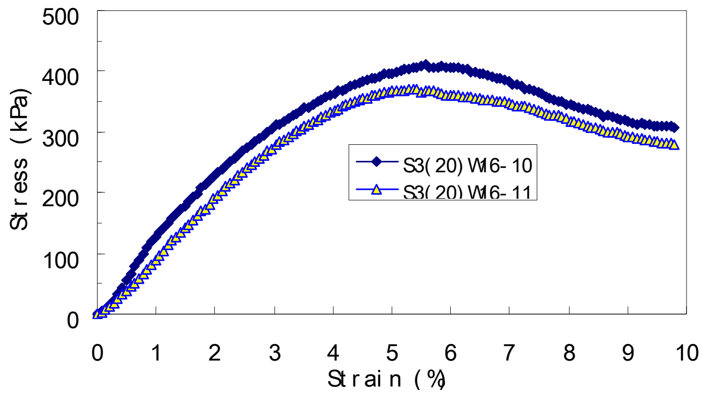
Stress (kPa)
Strain (%)
S3(20)W16-3
S3(20)W16-4
S3(20)W16-5



Stress (kPa)
Strain (%)
S3(20)W16-6
S3(20)W16-7

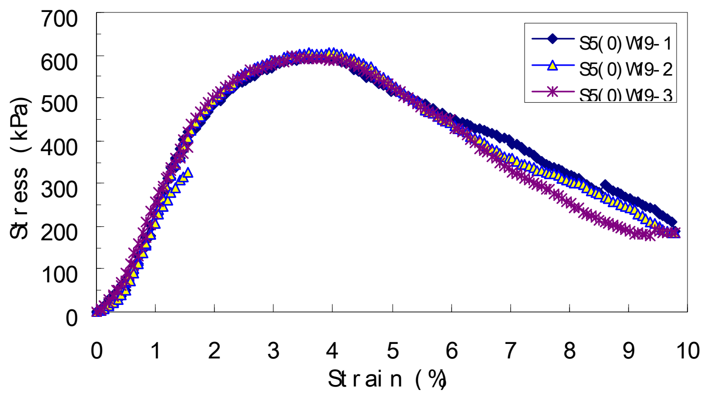


Stress (kPa)
Strain (%)
S3(20)W16-8
S3(20)W16-9

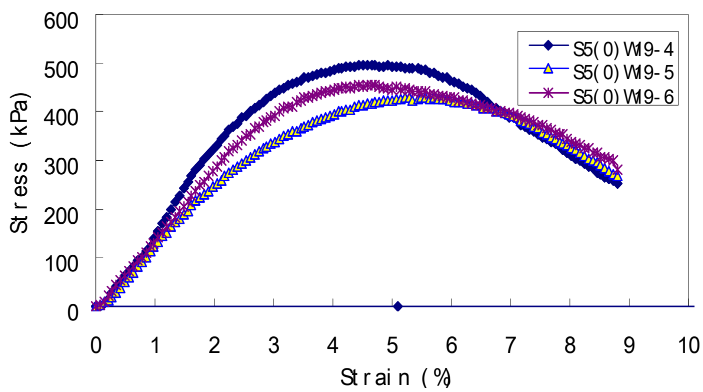


500
400
300
200
100
0
Stress (kPa)
0 1 2 3 4 5 6 7 8 9 10
Strain (%)
S3(20)W16-10
S3(20)W16-11

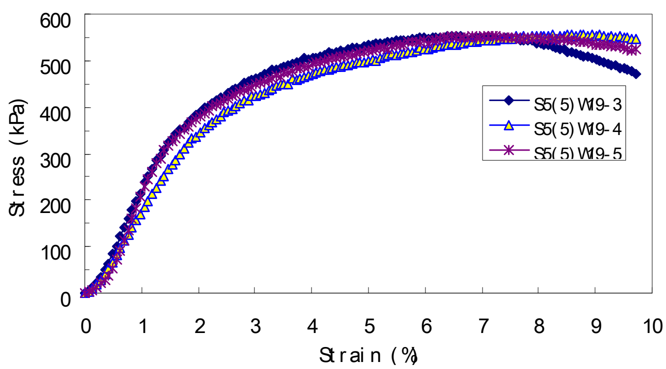
Soil 5



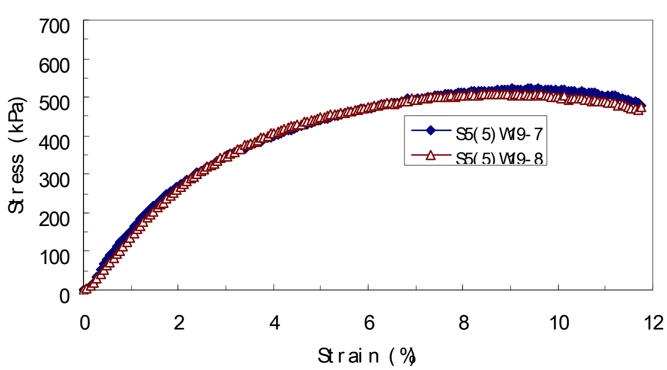
Stress (kPa)
Strain (%)
0
100
200
300
400
500
600
700
0
1
2
3
4
5
6
7
8
9
10
S5(0)W19-1
S5(0)W19-2
S5(0)W19-3



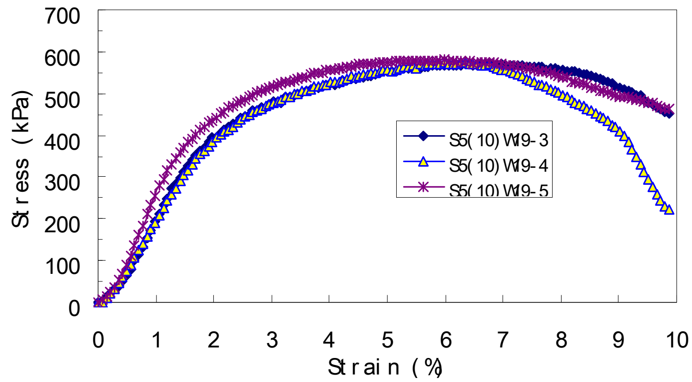
Stress (kPa)
Strain (%)
0
100
200
300
400
500
600
0
1
2
3
4
5
6
7
8
9
10
S5(0)W19-4
S5(0)W19-5
S5(0)W19-6

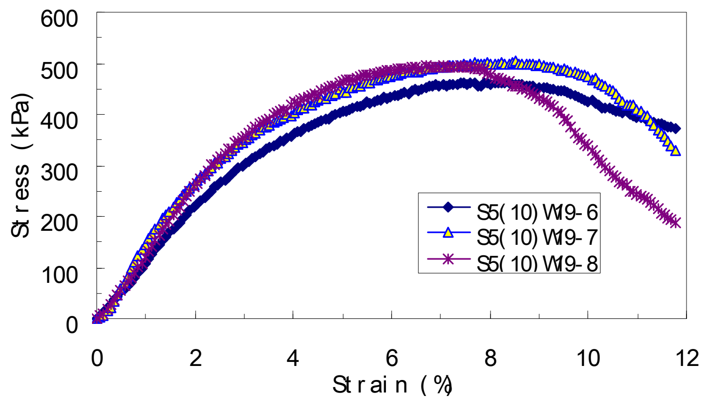


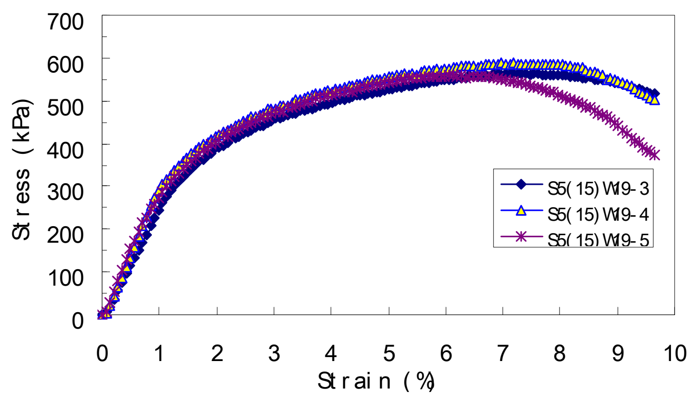
Stress (kPa)
Strain (%)
0
100
200
300
400
500
600
0
1
2
3
4
5
6
7
8
9
10
S5(5)W19-3
S5(5)W19-4
S5(5)W19-5

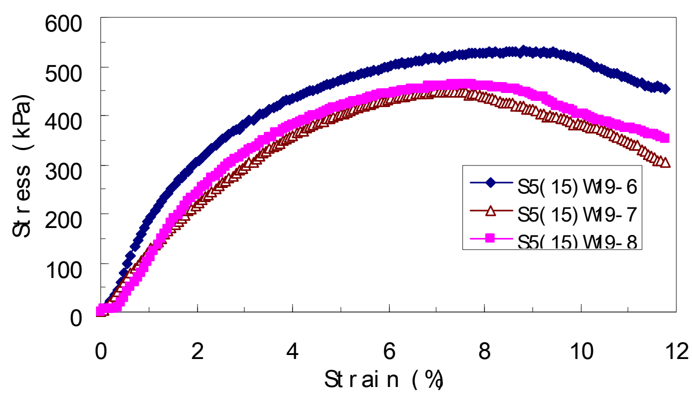


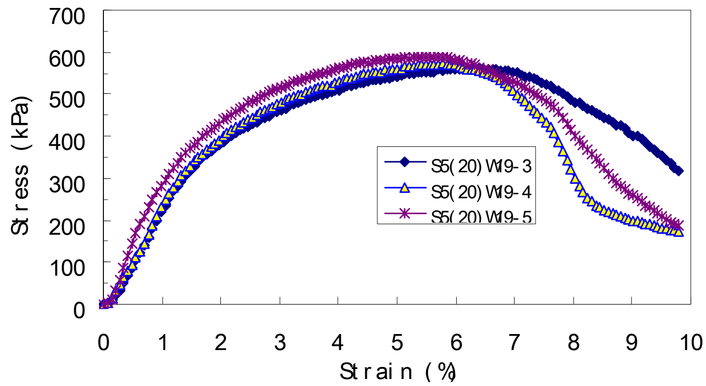
Stress (kPa)
Strain (%)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12
S5(5)W19-7
S5(5)W19-8


Stress (kPa)
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
Strain (%)
S5(10)W19-3
S5(10)W19-4
S5(10)W19-5

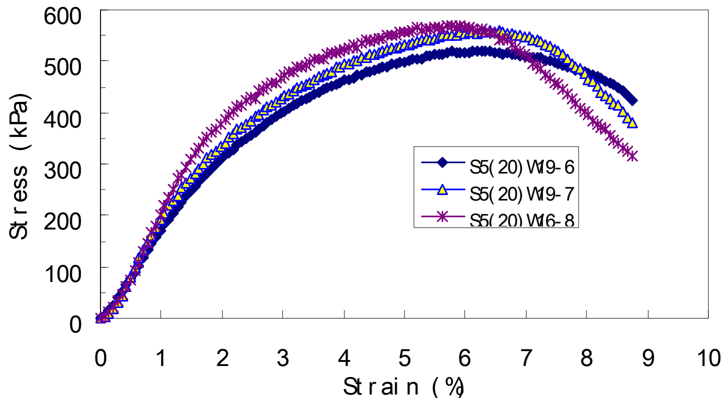

Stress (kPa)
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Strain (%)
S5(10)W19-6
S5(10)W19-7
S5(10)W19-8


Stress (kPa)
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
Strain (%)
S5(15)W19-3
S5(15)W19-4
S5(15)W19-5


Stress (kPa)
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Strain (%)
S5(15)W19-6
S5(15)W19-7
S5(15)W19-8



Stress (kPa)
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
Strain (%)
S5(20)W19-3
S5(20)W19-4
S5(20)W19-5



Stress (kPa)
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
Strain (%)
S5(20)W19-6
S5(20)W19-7
S5(20)W16-8