Experimental Study on the Use of Lime Sludge for Construction: An Example for Sustainability

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ABSTRACT: Drinking water treatment plants annually produce significant amount of lime sludge during water purification procedures. They are typically stored in lagoons and disposed as solid waste. This presents a significant economic burden to daily operations. This study investigates a sustainable development strategy from beneficial utilization of this material. An experimental program is implemented to address the technical issues related to application of this material in the construction of soil embankment, where lime is commonly used as soil stabilizers. Specific topics associated with the engineering applications of lime sludge treated soils include: the effects of dry versus wet mix procedures for the introduction of lime sludge into soils, procedures to determine the optimal content of lime sludge, and the long term durability of lime sludge treated soils under freezing-thawing cycles. This study aims to help develop a sustainable strategy to utilize lime sludge for routine construction activities.

INTRODUCTION

Soil stabilization has performance and economic benefits in providing pavement with a rugged base supporting. Because of this, it has been popularly applied under difficult soil and construction conditions. A global chemical stabilization design was recently 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 a rain and reduce weather delays; 6) Provide a uniform and superior subgrade for the pavement, andimproveperformance 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 example, in a recent presentation delivered by Ohio DOT engineers, for a single project in the I-71 lane expansion, the use of global subgrade stabilization was estimated to lead to better subgrade strength and result in 3.8 cm (1.5”) reduction in asphalt thickness. This would have saved $12.0 million in the construction cost.

Given the large quantities of lime required for implementing global soil stabilization, it is to 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 is the lime sludge produced from the residuals generated by drinking water plants.

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

Proper design procedures for introducing lime sludge into soils need to be developed in response to the mineral and chemical characteristics of lime sludge to achieve the optimal performance. Besides, the long term durability of lime sludge treated soils needs to be verified. This paper introduces the study on lime sludge design for transportation applications. It investigates the feasibility of using lime sludge as a substitute of regular lime used in road construction. Design issues such as the mixing procedures of lime sludge, the optimum lime sludge content and the long term performance under freeze-thaw cycles typical of northern States such as Ohio are investigated.

BACKGROUND

Lime is commonly used for drinking water treatment 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 (Martin 2008). A huge quantity of lime sludge is generated each year from the normal operation of drinking 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 has produced over 400,000 tons of lime sludge (dry weight basis) (Fig. 1). There are thousands of drinking water plants similar as Massillon water plant in the U.S.

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 regulations. Disposal of lime sludge in municipal solid waste landfills poses a major 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.

Possible ways of reusing lime sludge have been studied (Baker et al. 2005, Maher et al. 1993, Watt and Angelbeck 1977). 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 (Baker et al. 2005). 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 (Baker et al. 2005).

FIGURE 1 Photo lime sludge storage lagoon at Massillon, OH

CHARACTERISTICS OF LIME SLUDGE

Lime sludge samples were collected from the lagoon of Massillon water plant. It appears to be paste with a high natural water content (over 90% on the gravimetric basis). 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.

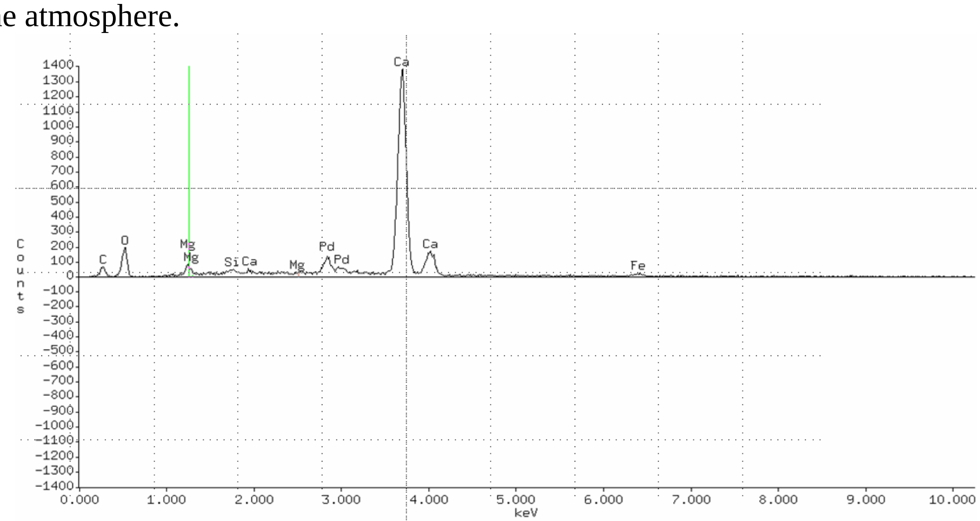

FIGURE 2 EDX Spectral of Measured Dry Lime Sludge Sample.

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

	Lime Sludge		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 this SEM image, the dry lime sludge appears to be uniform fine particles resembling those of silts. The size of particles is in micron.

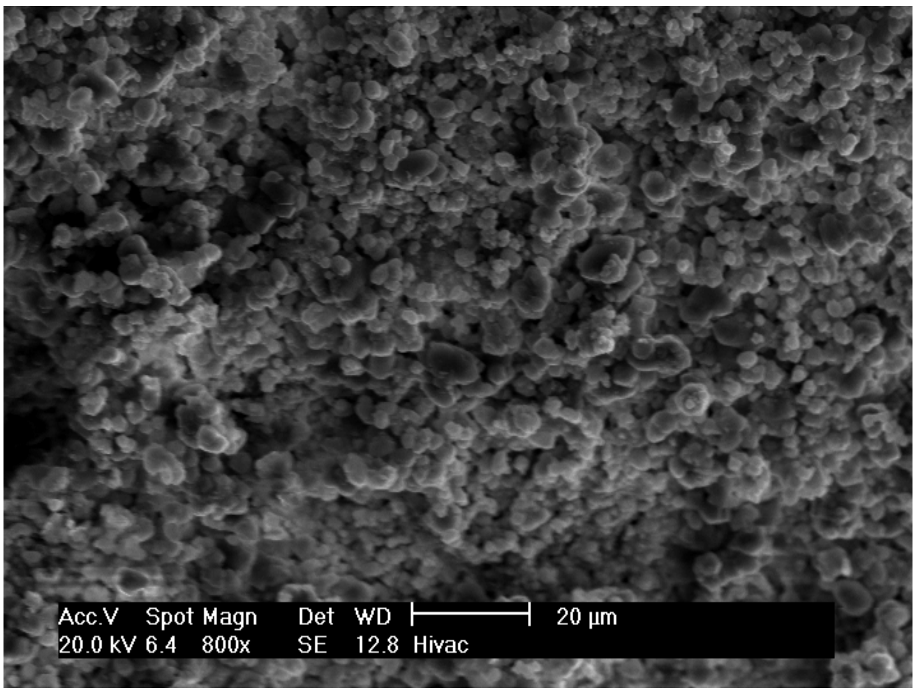

FIGURE 3 SEM Image of Lime Sludge Sample.

DESIGN PROCEDURES

From design consideration, a few design 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. A cohesive soil collected in Cleveland area was used in this benchmark study. The soil is a glacial till and classified as CH by Unified Soil Classification System (USCS). Soil specimens for unconfined compressive strength test were prepared using Harvard Miniature Compactor. The wet soil with specified water content was compacted into the mold in three layers, each layer being compacted with 25 blows. By controlling the soil mass for compaction of each layer, uniform and parallel specimens can be obtained with high repeatability. The specimens were then extruded by use of a corresponding specimen extruder. A standard soil specimen in cylinder shape has a height of 71mm and a diameter of 33mm. All specimens were cured in a standard moisture curing room for three days before tests were performed.

Optimal Content of Lime Sludge

The optimal lime content for soil stabilization is generally determined by use of ASTM D6276 (*ASTM*). This standard specifies the optimal lime content as the minimal lime content that produces a pH value of 12. 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 lime sluge 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 5 shows the results of pH value versus the lime-soil mass ratio. The data on 100% scale is the pH value of pure lime sludge solution. Test results in Figure 4 indicate that all the pH values are smaller than 12, a value required for optimal lime content for soil stabilization as specified by ASTM D6276. This is the case even for the pure lime slurry. For this reason, the optimum lime sludge content can not be determined using ASTM D6276. The low pH value corroborated the results from the EDX analyses. Carbonization of lime sludge is the possible cause of reduction on the active base components that can be created in the solution.

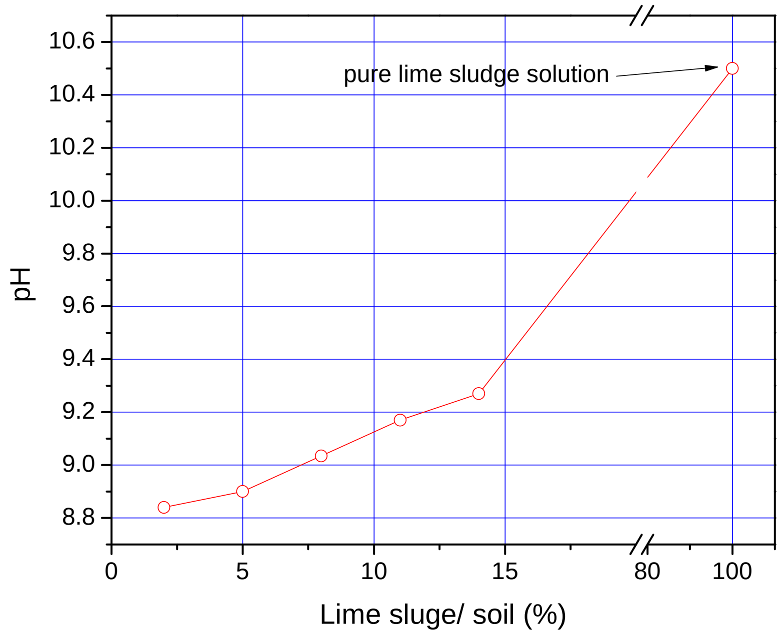

FIGURE 4 pH Test for estimating Soil-Lime Sludge Proportion.

As an alternative method to determine the optimal lime sludge content, unconfined compressive strength tests were conducted on soil mixed with different concentration of dry lime sludge. Unconfined compressive strength is a control parameter for road fill design. Achieving a compressive strength greater than 345kPa can help to significantly reduce the potential for settlement in deep fills((Ferguson and Levorson 1999). Unconfined compressive strength tests were conducted on lime sludge treated soil specimens to study the effect of dry/wet mix method on soil strength and find the optimum soil-lime sludge ratio.

According to ASTM D5102 (ASTM 2005), a loading rate (strain controlled) of 0.02mm/s was applied during the compression test. According to this standard, the unconfined compressive strength was 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.

Specimens were prepared using Harvard miniature compactor at five different lime sludge contents (dry weight base) of 0%, 5%, 10%, 15% and 20%. Three repetitive specimens were prepared for each lime content. The dry mix method was used to study of sensitivity of stabilized soil strength on lime sludge content. In this method, soil and lime sludge powder was first mixed before water was introduced. The physical properties and results of unconfined compression tests are shown in Table 3. This table indicates that the specimens were prepared with high quality control, as indicated by the close range of mass and water contents for each group of specimens. The prepared specimens were wrapped by plastic wrap and sealed in a zip bag. Specimens were cured for three days in a curing room before the unconfined compression test were conducted.

TABLE 3 Effect of Lime Sludge Content on Unconfined Compressive Strength

Sample No.	15w 0L #1	15w 0L #2	15w 0L #3	15w 5L #1	15w 5L #2	15w 5L #3
Dry unit weight (g/cm^3)	1.77	1.74	1.85	1.80	1.76	1.73
Water content (%)	13.6	13.61	13.02	12.7	12.69	12.48
Sample No.	15w 10L #1	15w 10L #2	15w 10L #3	15w 15L #1	15w 15L #2	15w 15L #3
Dry unit weight (g/cm3)	1.76	1.76	1.72	1.66	1.68	1.69
Water content (%)	12.61	12.41	12.24	11.78	11.68	11.57
Sample No.	15w 20L #1	15w 20L #2	15w 20L #3			
Dry unit weight (g/cm3)	1.74	1.72	1.74			
Water content (%)	11.65	11.36	11.46			

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

Figure 5 shows example of stress strain curves for soil specimen treated with lime sludge versus that of a natural untreated soil specimen. The treated soil in the figure has a lime sludge content of 15%. This figure shows lime sludge helps to increase the modulus of the natural soil. The improvement of the compressive strength of lime sludge treated soil versus that of the natural soil specimen can also be clearly seen in this figure.

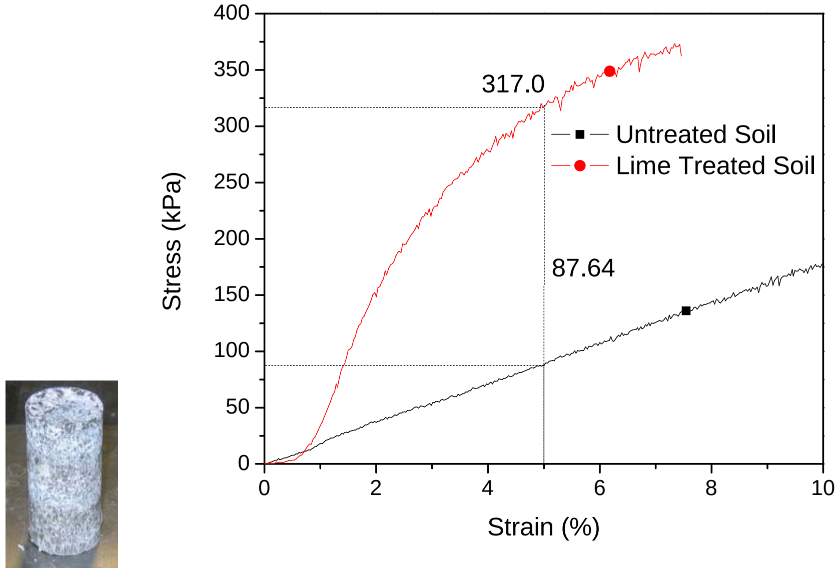

FIGURE 5 Deformation behaviors of soil specimen treated with lime sludge versus that of natural untreated soil specimen

Figure 6 shows the variation of the average unconfined compression strength (average of test results on the three repetitive specimens of the same group) 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 figure. This might correspond to the optimal lime sludge content for use as stabilizer for this soil. By examining the compression curves, it was also noticed that the treated soil specimens appears to show more brittle types of failure at higher lime sludge content.

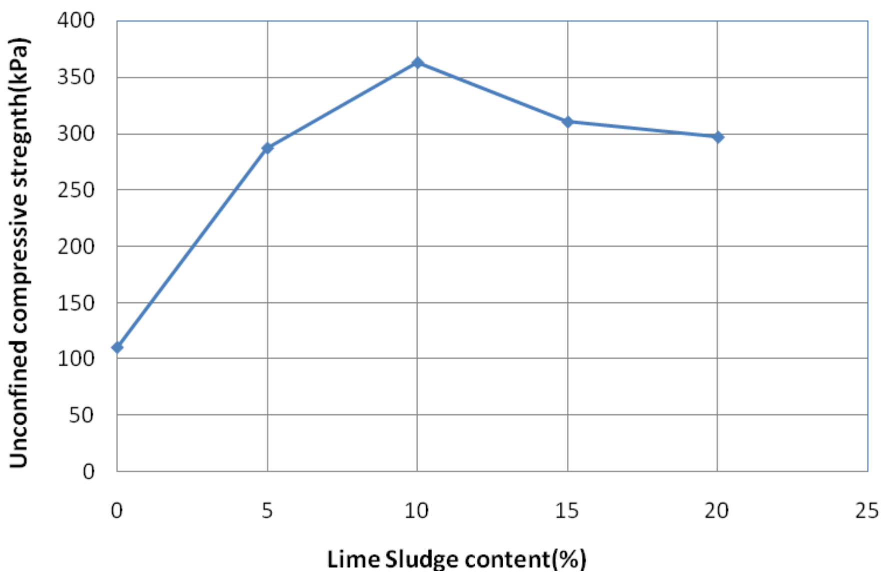

FIGURE 6 Lime sludge Content versus Unconfined Compressive Strength.

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 storage 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. For this purpose, soil specimens were prepared using both dry mix and wet mix procedures. Three repetitive specimens were prepared by each method 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 3, which again indicates that the quality of specimens was uniform. The specimens were wrapped by plastic wrap and sealed in a zip bag. They were also cured for three days in a moisture curing room. The unconfined compression tests were then conducted on each specimen. Table 3 summarizes the compressive strength of different specimens. After discarding a possible outlier, the average unconfined compressive strength of specimens by dry mix procedures (around 138 kPa) is not significantly different from those prepared by wet mix procedures (133 kPa).

TABLE 3 Effect of Dry/Wet mix on Unconfined Compressive Strength

Sample	dry mix 15w 5L #1	dry mix 152 5L #2	dry mix 152 5L #3	wet mix 15w 5L #1	wet mix 152 5L #2	wet mix 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.

Effect of Freeze/thaw on Soil Strength

Another important aspects investigated in this paper is on the long term durability of lime sludge treated soils subjected to cold region weather conditions. In the cold region, 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 were performed to test the resistance of the lime treated soil to freeze/thaw cycles. Two comparative groups of specimens were prepared at 15% water content. The Group One of specimens include 6 repetitive specimens with the introduction of an optimal lime sludge content (10%). The Group Two specimens include 6 repetitive specimens without introduction of lime sludge. Three specimens from Groups 1 and 2 respectively (altogether 6 specimens) 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 three specimens from Groups 1 and 2 respectively were placed under the normal curing temperature.

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. Results from this limited set of data provided the following observations: 1) freeze-thaw cycles caused the reduction of compressive strength for both natural soils and soils treated by lime sludge. 2) 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.

CONCLUSION

Beneficial utilization of lime sludge in transportation 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 demonstrated the positive effects of lime sludge treatment in improving the soil mechanical performance properties as well as improving the durability under freeze-thaw cycles. Continue refinement of mix design and performance evaluation could provide a way to effectively utilize lime sludge as an economic and sustainable development strategy.

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