

# Stabilization of Water Treatment Plant Sludge for Possible Use as Embankment Material

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The compaction, compressibility, and shear strength behavior of an alum sludge both untreated and treated with additives are presented. The significance of the sludge behavior in terms of landfill/embankment design and construction is discussed. The additives used were a slake lime, a fly ash, and a local clay sand; the additive content was 60 percent by dry weight of sludge. The standard Proctor comparative effort and the conventional consolidation test were used for testing. The shear strength was determined using both the laboratory fall cone penetration test and the consolidated undrained triaxial compression test with pore pressure measurements. The moisture-density relation is not that of the typical one-hump curve. Instead, the dry density decreases with increasing water content from a maximum near zero water content. The additives appear to have an insignificant effect on the compaction curve. However, the additives improve the plasticity, compressibility, and shear strength behavior considerably. The untreated sludge has a high effective angle of internal friction, but the undrained shear strength is low, especially at high water content. Both the untreated and treated sludges are sensitive and highly thixotropic. It is concluded that admixture stabilization is an effective method of improving sludge properties for easier handling and also for increasing the volume of disposed sludge. Although the stabilized sludge within the range of conditions investigated is still too compressible and without sufficient shear strength for embankment construction, the potential for use of stabilized sludge as an embankment material can be enhanced through further dewatering or raising additive content or both.

Water treatment plant sludge is the residue generated from the various coagulation processes used in producing potable water (1). According to the National Academy of Sciences (2), the amount of sludges derived from treatments of both drinking and waste water has doubled between 1972 and 1990 because of population growth, industrial development, and upgrading of treatment plants as mandated by various federal and local legislation. Thus, disposal of the ever-increasing volume of water treatment sludge has become a national problem.

The traditional disposal methods for water plant sludge include ocean barging; direct discharging into streams, storm sewers, or sanitary sewers; lagooning; and land applications. Because of economic reasons and the decreasing availability of land and more stringent regulations regarding the ultimate disposal of sludges, considerable attention has been directed toward the method of landfill disposal. Besides serving the purpose of disposing of the unwanted sludge, sludge landfills

can possibly be used as roadway embankments, dikes, and for other engineering applications.

Water plant sludge has a high water content and is plastic, sensitive, and compressible. Without treatment, it is difficult to handle and to landfill to an economic height with a desired slope. This study is concerned with using the admixture stabilization method to improve sludge properties and with evaluating the possibility of using the stabilized sludge for embankment construction.

## PRESENT STATE OF KNOWLEDGE

The geotechnical properties required for design and performance analysis of sludge landfills include mainly compaction, compressibility, and shear strength. The present state of knowledge of these properties of both untreated and treated water plant sludges is presented.

In one of the few available studies on this subject matter, Raghu et al. (3) performed the modified Proctor compaction test on a lime/alum/polyamine coagulant water plant sludge obtained from the Jersey City Water Treatment Plant. The compaction water content varied from about 55 to 72 percent. The compaction curve exhibited the typical one-hump shape having an optimum water content of approximately 65 percent and a maximum dry unit weight of about 51 lb/ft<sup>3</sup> (pcf). Elsewhere, Environmental Engineering & Technology, Inc. (4) reported the results of standard Proctor compaction tests on a coagulant sludge that had been stored at a water plant in Oklahoma for an extended time. The test results also showed the typical one-hump compaction curve. The optimum moisture content and maximum dry unit weight were approximately 17 percent and 105 pcf, respectively.

Raghu et al. (3) also conducted a conventional consolidation test to determine the coefficient of permeability of the coagulant sludge. No compressibility behavior of the sludge was presented, however. Using the method of dewatering under different pressure differentials, Knocke and Wakeland (5) investigated the compressibility of four sludges—alum (low density), alum (high density), conditioned alum, and lime sludges. They reported that the average coefficient of compressibility for the first three alum sludges ranged between 0.94 and 0.97, whereas that of the lime sludge was 0.79, indicating that the lime sludge is considerably less compressible than the alum sludge. The coefficient of compressibility is not the compression index; the relation between the two is not yet available.

Available information on the shear strength property of water treatment plant sludge concentrates mainly on the undrained strength with regard to sludge handleability (or workability). Most studies used the vane shear test method to determine the strength. Novak and Calkins (6) studied five sludges using a torvane and reported that 0.04 tsf is the minimum undrained shear strength for easy handling of the sludge. This minimum shear strength value is about 2.5 times lower than 10 kPa (0.104 tsf) currently used in West Germany and the Netherlands. Using both a torvane and a viscometer, Huang (7) presented, among others, a relationship between the undrained shear strength and solids concentration for two sludges. It was pointed out by Knoke and Wakeland (5) that water treatment plant sludge undergoes marked strength increase due to thixotropic hardening. However, little information on the thixotropic behavior of sludge is currently available.

For improving the handling characteristics of water treatment plant sludge, Farrel et al. (8) investigated the effectiveness of lime stabilization. They reported that the addition of a quicklime to an alum sludge resulted in an increased shear strength because of the formation of a calcium-aluminum compound. However, research findings from Europe indicated that sludge treatment with quicklime did not always lead to an increase in shear strength to more than 10 kPa (4).

The preceding account indicates that the current knowledge on geotechnical properties of water treatment plant sludge is limited. For the effective design and performance analysis of sludge disposal landfills, fundamental properties such as compaction, compressibility, and shear strength are essential. In addition, the potential use of stabilized sludge for embankment construction cannot be evaluated without the necessary geotechnical properties of stabilized sludge. The results of a study that addresses this research need are presented in this paper.

## TEST SLUDGE AND ADDITIVES

The sludge investigated is an alum sludge obtained directly from a water treatment plant in Chesapeake, Virginia. Some sludge samples were also obtained from a landfill in Chesapeake using plastic tubes having 2-in. ID with wall thickness of  $\frac{1}{8}$  in. The test sludge is the treatment residue of high-color, low-turbidity raw water. It was dewatered using the centrifuge method. It has a specific gravity, liquid limit, plastic limit, and plasticity index of 2.26, 550 percent, 239 percent, and 311 percent, respectively. The sludge contains 66 percent silt size and 20 percent clay size particles with a median size of 0.013 mm. It is classified as CH according to the unified soil classification system. The activity is equal to 15.6, which is many times higher than that of common clay minerals. On the basis of the behavior of clays, the abnormally high activity value suggests that the test sludge is very sensitive, highly compressible, and expansive. The sludge received directly from the treatment plant has a water content of about 714 percent and a wet unit weight of approximately 67 pcf, whereas the field samples have water contents ranging between 270 and 669 percent and wet unit weights varying from 67 to 73 pcf.

The additives used for stabilization were a slaked lime, a fly ash, and a natural soil. The slaked lime was obtained from Bellefonte, Pennsylvania. The fly ash is of Class C type (i.e.,

self-cementing) obtained from Indiana and Michigan Electric Company at Rockport, Indiana. The local soil is a clayey sand and is classified as SC according to the unified classification system. It contains about 14 percent silt size and 5 percent clay size particles with a median particle size of approximately 0.6 mm; its liquid limit and plastic limit values are 39 and 19 percent, respectively.

The additive content was arbitrarily chosen at 60 percent by dry weight of sludge. The specific gravities of the treated sludges are 2.46, 2.44, and 2.44, and the liquid limits are 272, 305, and 297 percent for the lime-, fly ash-, and soil-treated sludges, respectively. The data indicate a large decrease in liquid limit due to treatment.

## COMPACTION BEHAVIOR

The standard Proctor compaction curves of the untreated and treated sludges are shown in Figure 1. The zero-air-void curve (ZAVC) is plotted using the specific gravity value of the untreated sludge. It is seen that the shape of the compaction curves is different from that of the usual one-hump curve; the dry unit weight decreases from a maximum near zero water content, then decreases as the water content increases. Such a moisture-density relation is rarely seen. The one-hump compaction curve has been obtained for other waste treatment plant sludges (3,4). Although sludge type will certainly influence the shape of the compaction curve, other factors such as the effect of drying and rewetting, as briefly described later, may also play an important role. An in-depth study of this subject is warranted.

According to the compaction curve, to reach the maximum dry density, the molding water content must be as low as possible. The data also indicate that mixing with any of the three different additives has little effect on the compaction behavior, although the addition of slaked lime slightly lowers the dry unit weight when the molding water content is low.

The compaction test was executed from the wet side rather than from the dry side as specified in the ASTM standard test procedures. This deviation is necessary to accommodate the unusual behavior of the test sludge. Upon drying, the sludge particles attract together to form flocs. Each floc is strongly held together so that it is difficult to break apart to make possible a uniform mixture with water. Furthermore, when the sludge is dried below a certain water content and rewetted, it loses its original cohesive characteristic and becomes a sandy material. For all of these reasons, the compaction test was started from a high water content, which was then decreased gradually by air drying inside the laboratory. For air drying, the sludge was spread in a drying pan and was periodically stirred and the flocs broken apart by hand to make the water distribution as uniform as possible.

## CONSOLIDATION BEHAVIOR

The consolidation test was performed on both untreated and treated sludges. The treated sludges were cured for 2 and 4 weeks. The void ratio versus logarithm of pressure relation ( $e$ -log  $p$  curve) of the untreated and treated sludges is shown in Figure 2. As shown, the shape of the  $e$ -log  $p$  curves for

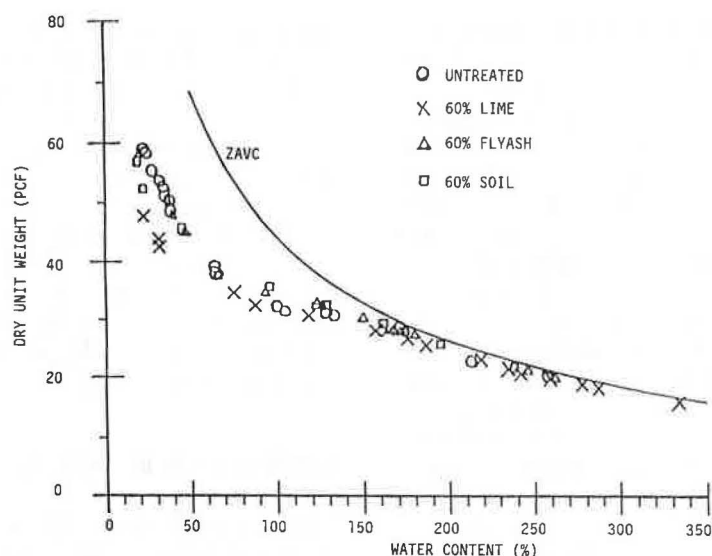


FIGURE 1 Compaction curves of test sludge with and without additives (13).

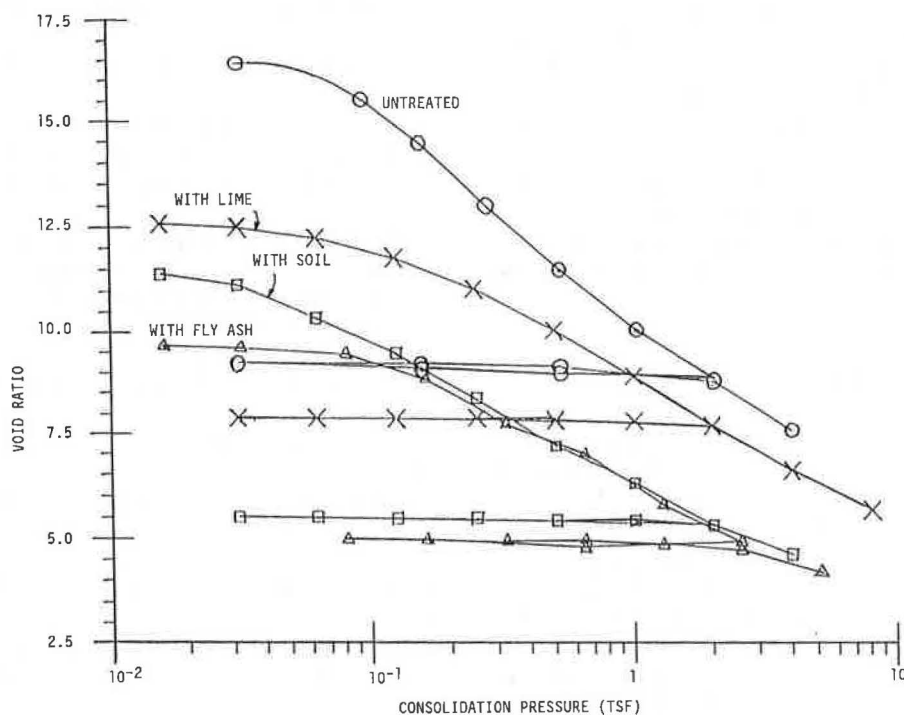


FIGURE 2 Void ratio versus consolidation pressure of treated and untreated sludges.

the treated sludges is similar to that of the untreated one, but the initial void ratio is much lower. Table 1 gives the initial void ratio together with water content and compression index. The smaller initial void ratio of the treated sludge is attributable to the decreased water content due to mixing of the additives. For a saturated soil, the initial void ratio equals water content times specific gravity. Because the specific gravity of the treated sludge is only slightly higher but the water content is considerably lower than that of the untreated one,

the initial void ratio of the treated sludge will be lower than that of the untreated one.

The water content and initial void ratio vary among the various treated sludges. The data indicate that the water content is lowest for the fly ash-treated sludge and about equal between the soil- and lime-treated sludges (Table 1). Although the reason why the water content of fly ash-treated sludge is lowest is not yet known, it may be related to possible pozzolanic reaction of fly ash. The pozzolanic reaction may

TABLE 1 CONSOLIDATION TEST RESULTS

Test Material	Water Content (%)	Initial Void Ratio	Compression Index
Untreated Sludge	766.8	17.33	6.69
Soil Treated Sludge	466.4	11.38	4.04
Lime Treated Sludge	2-wk cured	443.9	10.92
	4-wk cured	511.8	12.59
Fly Ash Treated Sludge	2-wk cured	404.1	9.86
	4-wk cured	395.9	9.66

depress the diffuse double layer and cause the original highly dispersive sludge particles to flocculate, resulting in drainage of free water. There may also be uptake of water in pozzolanic reaction. The consequence of either or both of these two effects will be a much lower water content than for sludge without pozzolanic reaction. The data also indicate only a small difference in water content between 2- and 4-week cured fly ash-treated sludges. This suggests that within 1 month of curing, the effect of curing time on water content change caused by chemical reaction, if any, is negligible.

As seen, the values of the compression index are high. Furthermore, the compression index of the untreated sludge is considerably higher than that of the treated ones. Among the various treated sludges, only a slight variation in compression index is seen. The lower compression index of the treated sludges can be attributed to the decreased interparticle repulsion caused by the additives. As a result of the reduced interparticle repulsive force, particles flocculate to form more stable flocs and, therefore, the compression index decreases.

The decompression index of the untreated sludge is extremely low, as is the decompression index of the treated sludges, as shown by the slopes of the decompression curves (rebound curves) in Figure 2. Because of the highly dispersive nature of the structure of sludge particles, the low decompression index can be expected.

## SHEAR STRENGTH BEHAVIOR

The shear strength of untreated sludge, both plant and field samples, was determined using the consolidated undrained triaxial compression test with pore pressure measurements. Three confining pressures ranging from 15 to 55 psi were used. The initial water content ranged between 326 and 477 percent, and the final water content varied from 247 to 345 percent. The laboratory fall cone penetration test was also used to determine the undrained shear strength of both untreated and the various treated sludges.

The shear strength parameters and pore pressure parameter at failure ( $A_f$ ) obtained from the triaxial compression tests are summarized in Table 2. A close agreement between the plant and field samples data is seen. The values of  $A_f$  indicate that the test sludge is behaving as a possibly normally consolidated soil with a high sensitivity, according to Skempton (9). The effective internal friction angle ( $\phi'$ ) is unusually high. As noted before, the test sludge has a plasticity index (PI) equal to 311 percent, which is also abnormally high. When  $\sin \phi'$  and PI values are entered into the correlation developed by Kenney (10) and Olson (11) and reported by Mitchell (12),

TABLE 2 SHEAR STRENGTH PARAMETERS OF UNTREATED SLUDGES

	Total Stress		Effective Stress		Pore Pressure Parameter, $A_f$
	c (psi)	$\phi$ (°)	c' (psi)	$\phi'$ (°)	
Plant Sample	0.6	19.3	1.0	42.3	0.75
Field Sample	0.7	19.0	1.2	44.0	0.80

the data point lies far above the extended correlation, as shown in Figure 3. On the basis of this comparison, it can be expected that the behavior of the test sludge cannot be predicted using the data base established for natural soils.

The undrained shear strength of the untreated sludge obtained from the cone penetration test is plotted against solids content in Figure 4. The solids content is defined as the ratio between the weight of the solid phase and the total sludge weight expressed in percent. This definition is normally adopted by the environmental engineer in dealing with sludges. According to this definition, the solids content can be related to the water content as follows:

$$\text{Solids content (\%)} = \frac{1}{1 + \frac{\text{water content (\%)}}{100}} \times 100 \quad (1)$$

The data in Figure 4 demonstrate that, as would be expected, the undrained shear strength increases with increasing solids content. The rate of increase is slow at the beginning, then intensifies at higher solids content. The curve eventually should level off at a high solids content, although no such trend appears in the range of solids content studied.

To investigate the thixotropic behavior of the test sludge, the undrained shear strength was determined for both remolded and cured specimens. The test specimens were prepared at four water contents, which were chosen arbitrarily: 511.9, 634.2, 737.1, and 804.4 percent. For each water content, the cone penetration resistance was measured at different curing times after remolding. The specimens were sealed and cured at room temperature. Details of specimen preparation, curing, and testing are available elsewhere (13). The variation of undrained shear strength with curing time obtained is shown in Figure 5. Curing results in an increase in the undrained shear strength. Initially, the strength increases rapidly; the rate of increase decreases with curing time and eventually levels off.

The curves in Figure 5 indicate that the amount of strength gain due to curing and the rate of strength increase at the initial curing stage are greater when the sludge water content is lower. From these curves, the maximum shear strength for each water content is obtained and the strength gain ratio, defined as the ratio between the cured and remolded strengths, is computed. The computed strength gain ratios are plotted against water content in Figure 6. The data indicate that the strength gain ratio increases to a maximum, then decreases with increasing water content. The maximum strength gain ratio of about 8.0 occurs at a water content of approximately 740 percent. On the basis of the range of strength



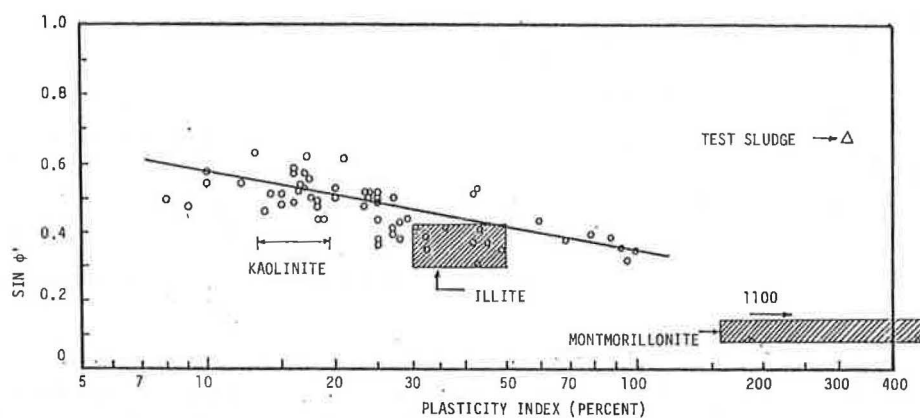


FIGURE 3 Relationship between  $\sin \phi'$  and plasticity index for normally consolidated soils (12).

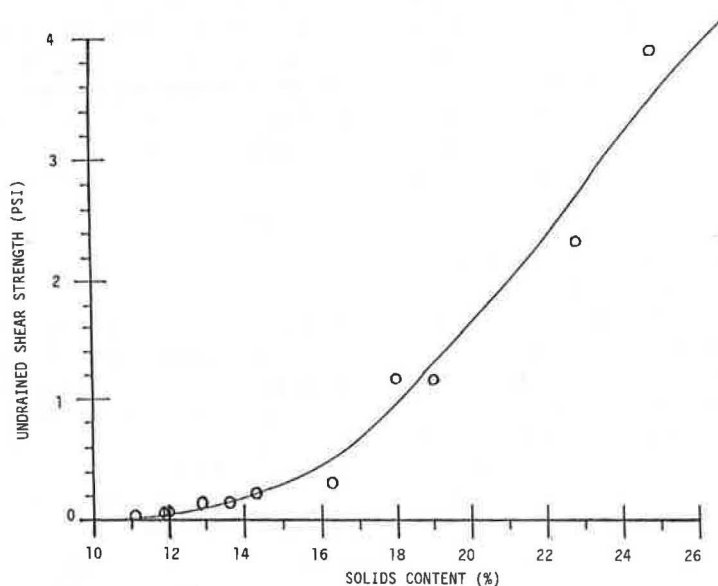


FIGURE 4 Undrained shear strength of untreated sludge determined from cone penetration test versus solids content (13).

gain ratios, if the untreated test sludge was a soil, it could be classified as very sensitive to slightly quick clay according to Rosenqvist (14).

The change in strength gain ratio with water content can be explained using Mitchell's hypothesis on thixotropy. According to Mitchell (12), the saturated clay soil can be characterized as a clay-water-electrolyte system. Before remolding, the system is everywhere in an equilibrium condition. In terms of interparticle forces, the attractive force is balanced with the repulsive force. Remolding causes particle displacement and reorientation and thus disrupts the balanced interparticle forces. After remolding, the system tends to return to the original equilibrium condition. The process of restoration may involve particle reorientation or readjustment of the diffuse double layer or both.

When the water content is low, the particles are closely spaced. At a close interparticle spacing, significant interparticle attractive force exists to catalyze restoration of the system to the original equilibrium condition. On the other hand,

however, the particles are tightly restrained, making any reorientation difficult. As a result, only a limited strength regain is possible after remolding. When the water content is high, the interparticle spacing is large so that the interparticle repulsive force dominates. Under the influence of interparticle repulsion, restoration of the system to the original equilibrium condition would be more difficult, and, therefore, strength regain after remolding would be limited. Thus, there would be an optimum water content at which a significant interparticle attraction exists, and at the same time particles are not tightly restrained for readjustment.

The curing time required to attain the maximum strength gain also varies with water content. Within the range of water content investigated, the higher the water content, the shorter the curing time, as shown in Figure 6. The shorter curing time at higher water content can be attributed to the decreased restraint of sludge particles, so that the particles can readjust themselves to the equilibrium condition existing before remolding.

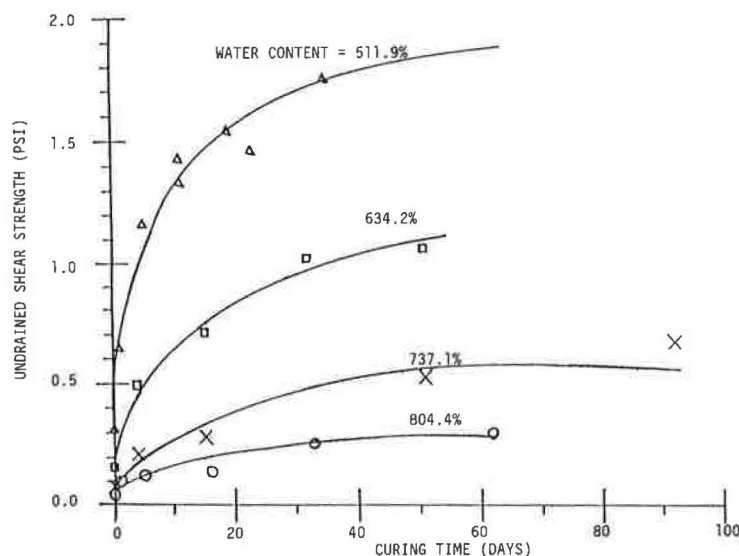


FIGURE 5 Undrained shear strength versus curing time for untreated sludge at different water contents.

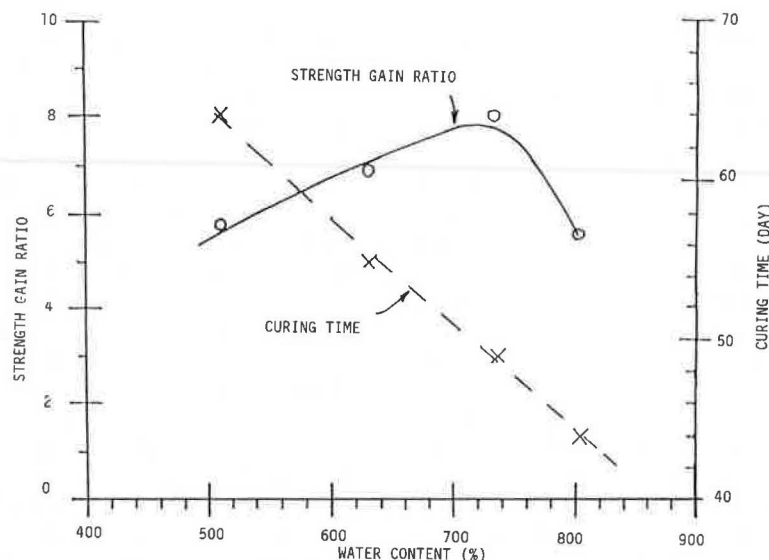


FIGURE 6 Strength gain ratio and curing time versus water content of untreated test sludge.

The effect of additives on the undrained shear strength of the test sludge is shown in Figure 7, which presents the undrained shear strength versus curing time for both untreated and treated sludges. Before treatment, the water content of the sludge equals 513.5 percent, which was arbitrarily chosen. After mixing with the additive (60 percent by dry weight of sludge), the water content became 311.5 percent. As shown, the shear strength increases with curing time following the trend of Figure 5. The data points for treated specimens are more scattered than the untreated one, possibly due to mixing. Although mixing was done by hand as thoroughly as possible, it appears that the mixture was far from uniform.

Despite data scatter, the trend is clear that the additives result in higher shear strengths; the amount of strength increase is greatest for lime, followed by fly ash, then soil. The values

of cured and uncured strength are given in Table 3. Also included in Table 3 is the strength gain ratio. The results seem to indicate that although the increased strength is greatest for lime and smallest for soil, the soil-treated sludge has the highest strength gain ratio, followed by fly ash, then lime treatment. The cause for this effect is yet to be investigated.

#### ENGINEERING SIGNIFICANCE

For landfill and embankment construction, the sludge must have sufficient strength to support its own weight plus the load induced by construction operations. The strength can be enhanced by increasing the density, which can be accomplished by either compaction or consolidation or both.

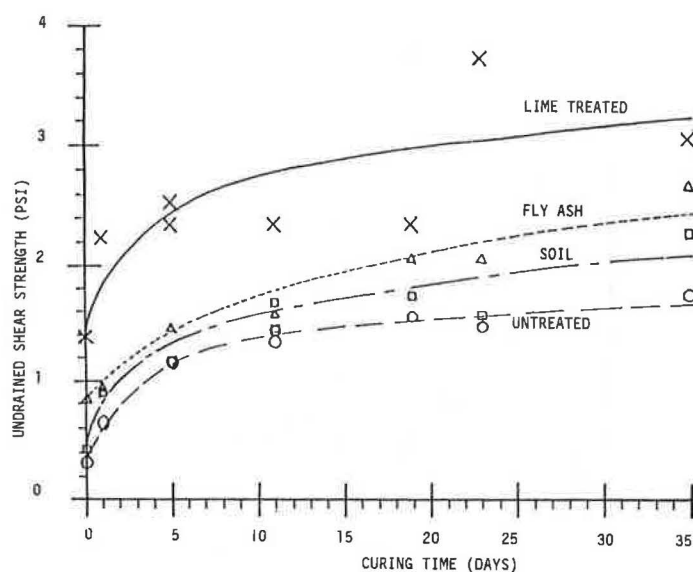


FIGURE 7 Undrained shear strength versus curing time for untreated and treated sludges.

Increasing sludge density is also necessary to maximize the volume of disposed sludge.

The compaction curve shown in Figure 1 indicates that the dry unit weight of the untreated test sludge can be quadrupled from about 15 to 60 pcf when the water content is decreased from about 350 to 20 percent. To attain the maximum dry density, the water content must be as low as possible. However, because dewatering the sludge to a very low water content requires a considerable amount of time and effort, it may be more economical to compact the sludge at a higher water content. The determination of the optimum compaction water content requires considerations of not only the dry density but also economic factors.

Regardless of the type of additive, the various treated sludges investigated behave essentially the same as the untreated sludges. One point that needs to be made clear is that admixing will decrease the water content. As a result, the dry unit weight of the sludge/additive mixture will become higher than that of the sludge alone at the premixing water content. Thus, the benefit of admixture treatment can be reaped shortly after mixing, compared with the considerable time and effort required for sludge dewatering. Furthermore, the negligible effect of additive type on compaction behavior suggests that the desired dry unit weight can be attained by mixing with any material.

Under its own weight, the sludge landfill/embankment will undergo consolidation settlement. The amount of settlement is proportional to the compression index. Since the compression index of the treated sludges is only about one-half to two-thirds of the treated sludge (Table 1), the ultimate settlement of landfills/embankments constructed of treated sludge will be only about one-half to two-thirds of untreated ones. Such a magnitude of reduction in consolidation settlement is significant when considering the potential application of treated sludge as an embankment material.

The effective internal friction angle of the untreated sludge (Table 2) is high, indicating that the sludge has good potential for long-term stability. The undrained shear strength, espe-

cially at high water content, is low but increases rapidly with decreasing water content. Thus, to make a landfill/embankment stable at a desired height and slope angle, the water content must be as low as possible. Under a constant water content, the sludge undergoes thixotropic strength gain; the strength gain makes the landfill/embankment more stable as time elapses. Because the sludge is sensitive to disturbance, the remolded strength should be used in the design and stability analysis of landfill/embankment slopes for the as-constructed condition to account for possible disturbance effects due to transportation and construction operations.

Admixing stabilization improves the remolded shear strength of sludge drastically, by a factor of more than four times for lime, almost three for fly ash, and about 1.5 for soil (Table 3). As a result of the strength improvement, the height of a landfill with a trapezoidal cross section will also increase by a factor of about 4, 3, and 1.5 for lime, fly ash, and soil treatment, respectively, assuming equal wet unit weights. The landfill slope will also become more stable with time, similar to the untreated sludge.

In summary, admixing stabilization makes the sludge less plastic and therefore easier to handle. Upon mixing, the water content decreases and dry density increases. Also, stabilization decreases the compressibility and increases the shear strength. The improvement in shear strength and dry density increases the volume of disposed sludge. The reduction in compressibility decreases the landfill settlement.

TABLE 3 UNDRAINED SHEAR STRENGTH OF UNTREATED AND TREATED SLUDGES

Sludge	Remolded	Cured	Strength Gain Ratio
Untreated	0.30 psi	1.70 psi	5.7
Treated with Soil	0.42	2.10	5.0
Treated with Fly Ash	0.82	2.50	3.0
Treated with Lime	1.39	3.25	2.3

For use of the stabilized sludge as an embankment material, the compressibility of sludge must be much lower and the undrained strength much higher. All of these may be accomplished by either further dewatering the sludge before mixing or increasing the additive content or, both.

## SUMMARY AND CONCLUSIONS

The compaction, compressibility and shear strength behaviors of an alum sludge both untreated and treated with a slake lime, a fly ash, and a local soil were presented. The additive content is 60 percent by dry weight of sludge. The standard Proctor compactive effort and the conventional consolidation test were adopted for the determination of compaction and compressibility behaviors. The shear strength was determined using both the laboratory fall cone penetration test and the consolidated undrained triaxial compression test with pore pressure measurements.

The results of the study indicate that the compaction curve is not that of the typical one-hump shape. Instead, the dry density decreases from about 60 pcf at approximately 20 percent water content to about 15 pcf at 330 percent water content. The additives appear to have an insignificant effect on the compaction curve. However, the additives decrease the compression index to about one-half to two-thirds of the untreated sludge. The untreated sludge has a high effective internal friction angle. The undrained shear strength of untreated sludge is low, especially at high water content. The addition of lime, fly ash, and soil increases the remolded shear strength by a factor of more than 4 times, almost 3 times, and about 1.5 times the untreated strength, respectively. Both untreated and treated sludges are sensitive and highly thixotropic.

It is concluded that admixing stabilization improves the workability, compaction, compressibility, and shear strength properties of the sludge tremendously. For the range of conditions investigated, the treated sludge is still too compressible and without sufficient strength for use as an embankment material. However, both compressibility and shear strength can be improved by either dewatering further or raising the additive content or both. The potential of using treated sludge for embankment construction can be enhanced by improving the compressibility and shear strength properties.

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