Lime and Fly Ash Admixture Improvement of Tropical Hawaiian Soils

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A study was performed to evaluate the soil improvement and stabilization potential of several tropical Hawaiian soils. These improvement techniques included stabilization with locally generated high-quality fly ash, and locally available hydrated lime admixtures. Use of these admixtures has shown tremendous potential as an economical method to upgrade the geotechnical properties of several "poor to marginal" types of tropical Hawaiian soils. The study shows such improvements as increase of unconfined compressive strengths; increases in California bearing ratio (CBR) of more than 10-fold; reduction in plasticity; reduction in swell to less than 10 percent of the unstabilized values; greatly increased workability; and changes in moisture-density relationships resulting in lower maximum dry densities, higher optimum water content, and less variation of dry density from the maximum over a much wider range of water contents.

Studies on lime, fly ash, and lime-fly ash stabilization have been conducted on soils in the many regions around the world (see examples in Reference section). Currently several states in the continental United States have written specifications for these applications. Organizations such as the National Lime Association and the American Coal Ash Association have been instrumental in accumulating and disseminating the results of research and case studies in which this type of soil improvement has been applied. In addition, the Beneficial Use of Coal Ash Act implemented by the Federal Highway Administration in 1987 provides an incentive to states by increasing federal funding for projects in which significant amounts of coal ash are used.

The study of using such admixtures to upgrade and enhance the engineering properties of tropical soils of volcanic origin has been extremely limited. This has been partially because the types of equipment and technology for field mixing necessary for achieving the desired results of admixture improvements have not until recently been readily available in certain locations. Furthermore, the unique differences among these soils and those from the more temperate climates and more common geologic settings that have been much more widely studied and tested, have left local authorities with some skepticism about the improvement that may be attained for these soils. Unfortunately, this has led to a lack of good understanding about the engineering properties and characteristics of these soils that may be significantly enhanced by the use of lime and fly ash admixtures. There are currently, and will be in the future, more and more instances of desired construction in tropical regions where significant deposits of these often undesirable soils are found. The recent introduction of coal-burning power generation to Hawaii has given an incentive to evaluate the useful benefits of an industrial byproduct while providing a very low-cost material that continues to be proven to be of great engineering benefit as a soil admixture in various other regions of the world.

Tropical volcanic soils have significant differences from the more commonly studied (and documented) soils of temperate climates as they have been generated from volcanic parent rock and have been weathered under conditions of high temperatures and humidity with well-defined alternating wet and dry seasons. Among the types of soils that are of particular interest are (*a*) the highly expansive, high plasticity, so-called "adobe" colluvial clays commonly found on the flanks and at the base of valleys between eroding silica poor basaltic lava flows; (*b*) residual volcanic soils typically found weathered in place with widely varied degree of weathering in a saprolitic structure; and (*c*) partially weathered lateritic soils, which are continually leached by rain water, causing a tendency for deterioration of its strength characteristics. Some of these soil types are considered to have particularly "poor" engineering characteristics, exhibiting expansive properties, high plasticity, poor workability, and low strength. An added problem often encountered with these types of soils is their tendency to retain high natural moisture contents that complicate the achievement of desired optimum construction and compaction properties. Many of the regions of the world that have these types of soil conditions are developing areas for which there will continue to be much new engineered construction.

Many of the Hawaiian soils present engineering problems that can be adequately solved by the use of certain types of lime and fly ash soil admixtures. Until recently, the only record of stabilization of these soils were a few early attempts using lime admixtures, which were very costly and of only marginal success. The mechanics of modern field mixing techniques applicable to difficult soils, together with a renewed interest in stabilization of these soils, has sparked an interest in the improvements that may be possible with locally available admixtures. A new electric cogeneration plant, now in service in Hawaii, is generating a fly ash with significant lime content, which by itself or with additional lime would provide an inexpensive source of high-quality stabilizing admixture. The use of this material for soil stabilization would be beneficial for improving soils for development and construction purposes, while at the same time using an industrial waste product that might otherwise require costly transportation and disposal in a region where waste disposal sites are in very short supply.

Presented in this paper is a study of the changes in engineering properties of a variety of these soils with the addition of lime and fly ash admixtures as exemplified through a series of laboratory tests.

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PROBLEM IDENTIFICATION

Tropical Hawaiian Soils

The Hawaiian soils have been formed from the weathering of volcanic rock and debris over a period of millions of years. The soils have unique characteristics because of a combination of their volcanic origin and the weathering conditions of tropical heat and humidity. Most of these soils contain a substantial amount of iron and aluminum (*1*). Among the soils tested in this study were a range of "poor to marginal" clayey soils from various areas of Oahu, Hawaii, that have been known to present problems in construction and possess a variety of undesirable characteristics. The generally undesirable properties include low strengths, high plasticity, poor workability, difficult compaction, and high swell potential.

Soils Investigated

The soils tested include two highly plastic "adobe" clays from Manoa and Palolo Valleys, a plastic clay from Kapolei, a silty clay from Kailua, and a silty-clayey soil from Kaneohe consisting of moderate to highly weathered saprolite. These soils represent a range of different "troublesome" soils found in Hawaii and are similar in nature to many other tropical soils found in comparable geologic and climatic regions elsewhere in the world.

The Manoa and Palolo clays are classified as CH soils according to the unified soil classification system [Unified Soil Classification System (USCS), ASTM D-2487], and have a high percentage of high-activity smectite clays. These clays present problems of excessive expansive characteristics, which have caused much damage to structures built in and on them, as well as low shear and compressive strengths, low CBR values, and high plasticity [with plasticity index (PI) values greater than 50 and liquid limits (LLs) above 100]. These soils may also have high natural water contents with values as high as 200 to 300 percent. The high LLs and PI values exhibited by these soils also provide an indicator of further potential problems with engineering properties and workability of these soils.

The Kapolei silty clay (CH) contains considerable histosols. It has a fairly low compressive strength and CBR, poor workability, and a steep compaction curve that makes it difficult to compact to a high relative density in the field.

The Kailua silty clay (MH) may also have a high moisture content in the field. It belongs to the oxisols (soils with low activity clays), and exhibits a high plasticity, low compressive strength and CBR value, and a moderately high swell potential.

The Kaneohe soil is a silty clay that classifies as MH according to USCS with a significant percentage of halloysite. It contains low-activity clays and is characterized by "low specific surfaces, low surface charge densities, or both" (*1*). This soil typically has a relatively high moisture content in the field in the range of 55 to 75 percent and its compaction characteristics are subject to variability depending on the way it is handled before and during compaction (i.e., drying, remolding, and so on). The soil undergoes irreversible changes in a number of its geotechnical properties upon drying. In general this soil has a moderately low compressive strength and low CBR value.

Each of these soil types was tested with combinations of fly ash and fly ash mixed with 3 percent lime. Only the MH soils were treated with higher percentages of lime without fly ash.

ADMIXTURE STABILIZATION REACTIONS

The addition of lime, fly ash, and lime-fly ash mixtures causes two basic sets of reactions with the soil: (*a*) short-term ("immediate") reactions and (*b*) long-term reactions. The details and theory of these reactions, along with discussion of the physical, chemical, and mineralogical processes involved, have been topics of several earlier studies [for example, Diamond and Kinter (*2*), Usmen and Bowders (*3*), and Glenn and Handy (*4*), and others]. The immediate effect of the introduction of lime or fly ash to the soil (including the lime already present in the fly ash) is to cause flocculation and agglomeration of the clay particles caused by ion exchange at the surfaces of the soil particles. The result of these short-term reactions is to enhance workability and provide an immediate reduction in swell, shrinkage, and plasticity.

The long-term reactions are accomplished over a period of time (many weeks, months, or even years may be required for completion of these reactions) depending on the rate of chemical breakdown and hydration of the silicates and aluminates. This results in further amelioration and binds the soil grains together by the formation of cementitious materials. For cementation to occur, there must be a sufficient source of pozzolans available. Pozzolans are a source of silica or alumina with high surface area that are available for hydration by alkali or alkali earth hydroxides to form cementitious products in the presence of moisture at ordinary temperatures. Soils that do not contain a suitable amount of pozzolans will not react with lime admixtures. Fly ash provides a source of pozzolans for those deficient soils. The extent and reaction rate is affected by "fineness" of the soil, which gives greater surface area, chemical composition of both the fly ash and the soils to be mixed with it, and the temperature, moisture content, and amount of stabilizer used (*3*).

FBC Fly Ash Generated in Hawaii

Until recently, Hawaii was the only state in which fly ash was not available (*5*). Coal is now being imported from Indonesia by Applied Energy Services, Inc. (AES Barber's Point, Inc.) as an energy source for electric power generation from a recently constructed plant that began operation in late 1992. This plant is expected to produce roughly 80,000 yd^3 of ash per annum.

The fly ash is generated using recently developed advanced combustion and emissions control technologies that use a fluidized bed of limestone. This produces an ash (FBC ash) that differs substantially from the typical pulverized coal (PC) class *F* and *C* fly ashes, because (*a*) it contains a significant amount of calcined (CaO) and sulfated sorbent ($CaSO_4$) from the limestone injected, and (*b*) the ash is derived from burning the coal at a lower temperature (1550°F for FBC as opposed to typically 2500°F for PC), and instead of being glassy like the PC ash, the FBC fly ash is composed of dehydroxylated (calcined) clays and other minerals in their oxide form.

The ash used as soil admixture in this study was actually a blend of fly ash (collected by cyclone from the upper regions of the combustion furnace) and bottom ash collected by gravity at the bottom of the furnace mixed in proportions of 75:25 (fly ash to bottom ash by dry weight), representing the approximate proportions actually generated from the coal burning process.

To a large extent the physical and the chemical properties of the fly ash and the bottom ash determine the optimum amount to

be used for enhancing the properties of the soils. These properties also give a general idea about the compounds formed upon hydration and reaction with the soil. Both a test burn ash and the actual fly ash generated from on-line production of the cogeneration plant were analyzed for elemental analysis by the X-ray flourescence method at the University of Hawaii. Although the locally produced fly ash has significant percentages of total lime already (on the order of 20 percent by dry weight), further addition of lime to the blend when mixed with soils enhances the stabilizing characteristics. The fly ash "blend" itself may be close to the lime retention point (as evidenced by high pH) but when mixed with soil the total percentage of lime is greatly reduced. Thus a further addition of lime may be beneficial when longer-term cementing strength gains are desired.

Lime Admixture Used

The lime used as a stabilizing agent for these studies was obtained from Brewer Environmental Industries, Inc., on Oahu. The lime is a hydrated commercial grade and was not analyzed.

TESTS PERFORMED ON HAWAIIAN SOILS

General Testing Methodology

A series of six types of laboratory tests was performed on each of the soils. These tests were first performed on recompacted soil specimens without admixture followed by additional tests in which fly ash (fly ash blend 75:25) and lime were added in different amounts in order to evaluate the changes in engineering properties of the soils with the addition of these admixtures. Six batches of each soil with admixture were prepared. These mixes consisted of one with 15 percent (by total weight) fly ash, one with 25 percent fly ash, one with 15 percent fly ash plus an additional 3 percent lime, and one each with 3 percent, 5 percent, and 7 percent lime. The test results were compiled and analyzed, and conclusions drawn from them.

Mixing was done without pulverizing either the soil or admixture, to more closely approximate the type of mixing that might be achieved in the field. The soils were mixed with the admixture and water was added (if needed) to raise the moisture content above the plastic limit (PL) of the soil. Pre-curing was allowed for 24 hr, after which the various tests were performed or samples prepared. All recompacted specimens were prepared to approximately 90 percent of the relative compaction defined by Modified Proctor Compaction tests performed on each sample mixture, at a moisture content within 2 percent of the optimum moisture content (OMC).

Test Results

The tests performed on the soils with and without admixtures included

1. Grain size analyses,
2. Atterberg Limit tests,
3. Modified Proctor compaction,
4. Free swell (expansion with nominal load),
5. CBR: value and swell, and
6. Unconfined compression.

Grain Size Analyses

Grain size analyses consisted of standard sieve analyses and wet sieving through the #200 sieve in order to properly classify each of the soils. For the soils tested in this study, all were classified as fine grained with only small percentages of coarse-grained fragments. The purpose of performing the #200 sieve analysis was to check the variation in percent fines for the soils with and without admixtures, because lime treatment has previously shown a marked decrease in "fines content." The results for all of the soils were not collected as it became apparent during the testing that the complications of separating the effect of adding the fly ash (which contained a high percentage of −#200 particles) obscured the results.

Atterberg Limit Tests

The Atterberg Limits assist in soil identification and classification, as well as providing other indicators of possible problems such as swell potential and workability. The PL is generally low and the LL is high for the CH and MH clays tested, which may indicate problems of excessive swell. One of the aims of these experiments was to measure changes of LL and PL with the addition of lime, fly ash, and lime-fly ash admixtures. Previous investigations have shown a marked reduction in PI (the difference between the LL and the PL) with the addition of lime to similar types of soils [Diamond and Kinter (*2*), and others]. It was speculated that the addition of lime, fly ash, and lime-fly ash mixes should have comparable results, considering the basic reactions involved.

The Atterberg limit tests were performed on the cured soil after a further air drying to a moisture content near or slightly below its expected PL, generally to a moisture content of about 20 percent. In most soils there are substantial time-dependent changes in the PLs (PL) and LLs. The trend for most cases reported appears to be a higher plasticity (PI) after 2 days of curing compared with the value recorded just after the addition of lime, and a subsequent decrease after curing periods of 7 to 28 days (*6*). Therefore, the reduction in plasticity as a result of admixture addition determined after 2 days of curing—as was generally the case in these experiments—may well be conservative.

The LL for the natural soils ranged from as high as 141 and 123 for the Manoa and Palolo clays, respectively, to 60 for the Kapolei clay. The LL decreased for all of the soils tested with increased amounts of stabilizing admixture. For the CH clays with initially high LL, there was a sharp decrease in LL with the addition of 15 percent fly ash and a smaller additional decrease with 25 percent fly ash. The Kailua soil reacted similarly but from a lower initial LL. For the other silty soils, there was a gradual decrease in LL with the addition of fly ash. The LL for soils treated with lime alone decreased with increased amounts of lime added up to a point, after which further addition of lime tended not to reduce the LL significantly.

The PI for all the soils decreased with increased amounts of lime, and also decreased with increased amount of fly ash added with the exception of Kapolei clay. Addition of fly ash reduced the PI for the CH clays by more than 50 percent, whereas addition

of lime caused two of the three silty-clay soils to become nonplastic. The changes tended to be initially more dramatic, and less so with additional admixture added. For the silty soils, the decrease in PI was more gradual with the addition of fly ash. Although some of the soils showed some decrease in PL with the addition of lime, the change in LL was more than enough to offset that decrease, so that the overall plasticity (PI) continually decreased. The decrease in plasticity is shown in Figure 1 as changes in the PI for the varied amounts of lime and fly ash added to the soils.

With the decrease in PI and LL, the engineering properties of the high-plasticity soils are improved. Additionally, the change in Atterberg Limits along with changes in apparent grain size distributions resulted in altering the USCS classification of the CH clays to MH, and some MH soils to ML (inorganic silts).

Modified Proctor Compaction

Many of the engineering properties of a soil, such as shrink and swell potential, compressive strength, and CBR value, permeability, compressibility, and stiffness, are dependent on the moisture and density at which the soil is compacted. Generally a high level of compaction of the soil enhances the most important soil parameters of the soil. Therefore, achieving the desired degree of relative compaction necessary to meet specified or desired properties of a soil is of great importance.

A common problem encountered with the tropical soils is that of a natural water content much higher than optimum. For soils in the field that have such a high moisture content, the increase in OMC and reduction of maximum dry density of the soil with the addition of lime or fly ash admixture, allows the desired relative compaction to be more easily achieved. There is less of a need for the soil to be dried to a lower moisture content before compaction, which in many cases is impractical if not nearly impossible. In addition, the typical "flattening" of the compaction curves that typically occurs with the addition of lime or fly ash admixtures makes it easier to achieve this minimum required density over a wider range of possible moisture contents. This change in the shape and characteristics of the peak of the compaction curve can allow for significant savings in time, effort, and energy.

Some of the tropical soils of Hawaii (typically the andisols) have compaction properties that vary with "the gradation, crushing strength of the coarse factor, method of pre-treatment or sample preparation, mineral composition and compactive effort" (7). Mitchell and Sitar listed four different moisture-density curves for the same soil for compaction of samples: from the natural state, air dried with each point representing a fresh sample, air dried and using the same sample, and oven dried. The procedure chosen in the laboratory to compact the soil should be representative of the same method in which it is compacted in the field. Ideally the soil in the field should be allowed to dry to within a specified range of moisture content before it is compacted. Therefore the most appropriate method for laboratory test preparation is to air dry the moist sample to the desired moisture and use a fresh batch to plot each point on the curve.

The soils and soil mixtures prepared by remolding for testing in this study were first mixed with fly ash (and water if needed) while moist, and then allowed to cure for a period of up to 2 days before compaction. The gradual decrease in maximum dry density and increase in OMC with the addition of greater amounts of lime and fly ash to the various soils tested are shown in Figure 2. Significant changes were noted for each of the soils with the addition of fly ash, whereas only modest changes were seen for those soils tested with lime admixture.

Free Swell Test

The free swell test was performed on remolded specimens of soil and soil mixtures in the laboratory with a nominal load of approximately 7 kPa in order to measure the maximum amount of swell (swell potential) for the soil. Free swell tests were performed by compacting the soils at the OMC in standard 6.35-cm-diameter consolidation molds in five layers with a Harvard miniature compactor by delivering approximately the same energy to each layer as that used in the modified Proctor test, to 90 percent of the maximum dry density as attained by the modified Proctor test.

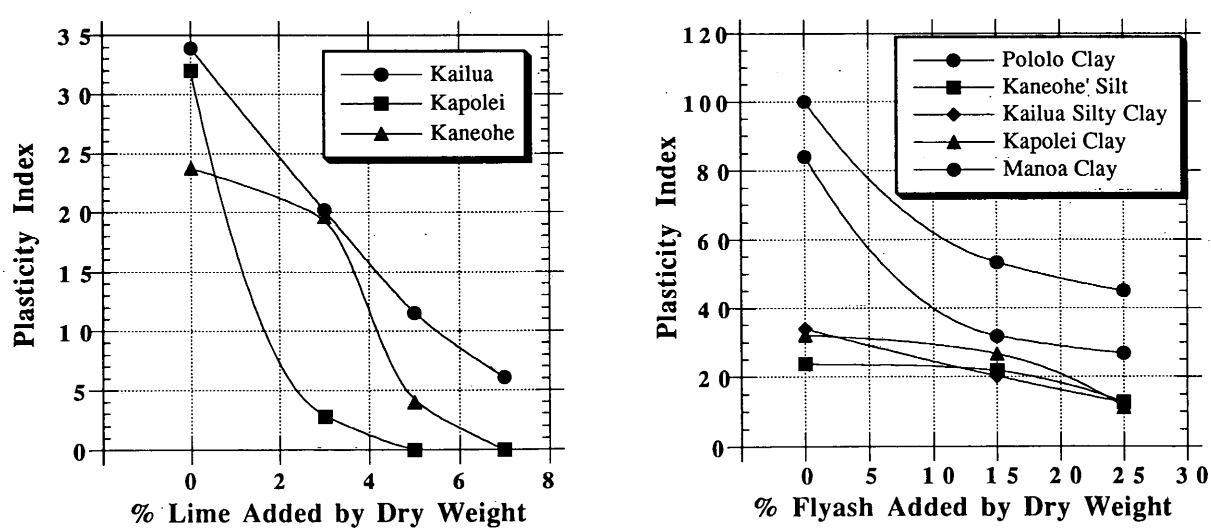

FIGURE 1 Variation of plasticity index with varied amounts of lime and fly ash.

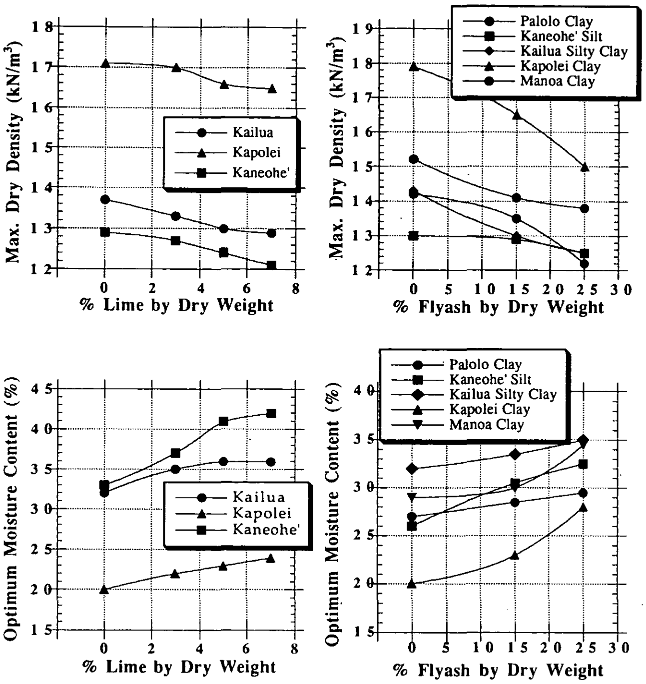

FIGURE 2 Variation of maximum dry density and optimum water content with varied amounts of lime and fly ash.

Tests were performed on specimens after approximately 4 days of curing. During the tests a continuous supply of water was maintained so that water had access to the sample bottom and that water was drawn in through the base of the cell to the soil. The soil specimens were allowed to swell for 2 to 4 days or until the daily measured displacement was less than 3 percent of the total displacement measured, after which the percent swell was calculated.

As expected, there was a decrease in swell potential for all the soils tested with admixtures. The results of the free swell tests for the soils with varied amounts of admixtures are shown in Figure 3. Results of the tests performed in this study showed that the addition of fly ash greatly reduced the swell for the smectite clays and to a lesser degree for the other soils tested. Lime added to the various soils all but eliminated the free swell measured for each of the soils tested with as little as 3 to 5 percent lime by dry weight of the soil. When using fly ash as an admixture, the most notable decrease was for the smectite clays for which the swell was reduced to less than 25 percent of that of the untreated soil. A further reduction of the swell potential was observed for all the soils tested, with the addition of lime to the fly ash and soil mixture.

The limited reduction in swell for the Kailua silty clay with fly ash alone may indicate incomplete reactions because of a shortage of lime. Addition of lime to the soil or the use of fly ash with a higher lime content may result in a reduction of swell because of further reaction with the pozzolans present in the soil and fly ash.

California Bearing Ratio

The CBR value is an indicator of soil strength and bearing capacity that is widely used in the design of the base and subbase material for pavement. Lime–fly ash-stabilized soils are often used for the construction of these pavement layers and also for embankments. The CBR is therefore a familiar indicator test used to evaluate the strength of soils for these applications.

According to the state-of-the-art report on lime stabilization by the Transportation Research Board (*8*), the CBR is "not appropriate for characterizing the strength of cured soil-lime mixtures," can only be used as a comparison, and has little practical significance or meaning as a measure of strength of stability other than as a relative indicator test.

The measurement of swell is an integral part of the CBR test. The CBR swell value differs from the free-swell value in that there is a significant surcharge on the soil specimen. The CBR swell values measured during this study consistently decreased with the addition of lime.

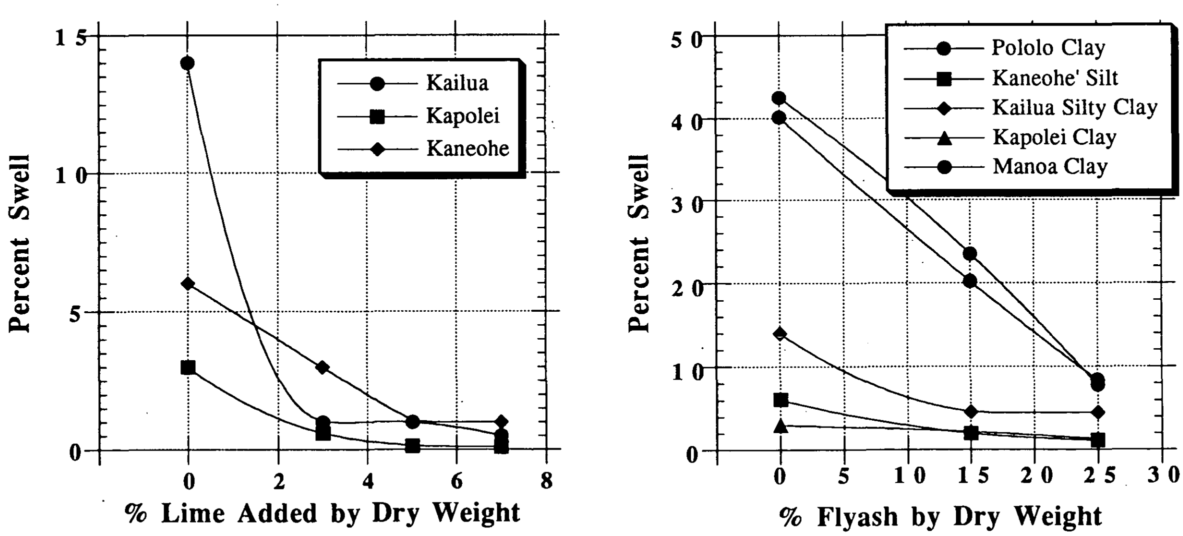

FIGURE 3 Variation of free swell with varied amounts of lime and fly ash.

To simulate the compaction carried out in the field, the soil-lime-fly ash mixtures were compacted to 90 percent of the maximum dry density as obtained from the modified Proctor compaction after curing at the OMC. Specimens were then soaked in water for a further 96 hr under a surcharge weight of 5.72 kg. After swell was measured, the CBR values were then recorded according to ASTM standards (method D-1883).

All of the soils tested had initially very low CBR values. With the addition of fly ash there was a gradual increase for all the soils, although the fly ash alone did not increase the CBR value by much. The most significant increase using fly ash admixture was for the Kapolei clay, for which the CBR increased to 10.8 from 5. A deficiency in the lime content of the fly ash-soil mixtures may be the reason for the low CBR values. When 3 percent lime was added to the 15 percent fly ash and soil mixture, there was a dramatic increase in CBR. For the soils tested with the addition of lime, dramatic increases in CBR were noted with as little as 3 percent lime, and much smaller increases with further addition of lime.

The CBR swell was reduced nearly linearly with the addition of different amounts of fly ash, and when lime or lime-fly ash mixtures were used with only 3 percent lime, the swell was reduced to 1 percent or less for all the soils.

The variation of CBR values obtained for the various soils and admixture combinations tested is shown in Figure 4.

Unconfined Compression Test

The compressive strength of a soil is an important factor in evaluating the design criteria for use as a pavement construction material. The lime and fly ash stabilization of soil in most cases tends to increase the strength of the soil and therefore it becomes not only a cost-effective and efficient material for use in embankment construction and earth fills, but also compares favorably with asphalt construction as an approach to upgrading unpaved roads.

The gain in strength of lime and fly ash-stabilized soil is primarily caused by the formation of various calcium silicate hydrates and calcium aluminate hydrates. The exact products formed, however, vary with the kind of clay mineralogy and the reaction conditions, including temperature, moisture, and curing conditions.

In undertaking a study of the optimum amount of fly ash to be used for the best strength gain results, two papers were used as guidelines. One study (*9*) used eight different fly ashes and two limes to study the variation in strength properties of four natural soils (a dune sand, a friable loess, an alluvial clay, and a highly plastic gumbotil) with different mixes of lime and fly ash. A second study was performed using lime and industrial wastes for the stabilization of volcanic ash soils or loams in Japan with lime mixed with industrial waste ash (*10*). The soils tested in the second study may be similar in many regards to some of the regional soils found in Hawaii. The changes in properties for different mixes were correlated to the intensities measured through the X-ray diffraction method (*10*).

When lime is to be mixed with fly ash, it has been suggested that for "a given ratio of lime to fly ash, the compressive strength of the lime-fly ash-soil mixture will increase with an increase in the amount of lime and fly ash used" (*11*), although there has been some discussion that there may be an upper limit at which no further strength gain should be expected.

Strength gains for clayey soils treated with lime have been reported through many case studies for roadways and airport runway subgrades. The strength gains have typically been reported as comparative CBR values and as increased unconfined compressive strengths, as used for soil cements.

The unconfined compressive strength tests in this study were performed on soils compacted to 90 percent RC based on the modified Proctor compaction results. The soils were first mixed with the lime and fly ash, to which water was then added. The soil mixtures were allowed to cure for one day, after which the soil specimens were compacted at optimum moisture. Samples were the same size as the mold used for the modified Proctor compaction (101.6 mm diameter, 116.43 mm height). ASTM method, designation D-5102, was followed in tests in which specimens were cured at a temperature of approximately 22°C. Each specimen was sealed in airtight polythene sheets. Cured specimens

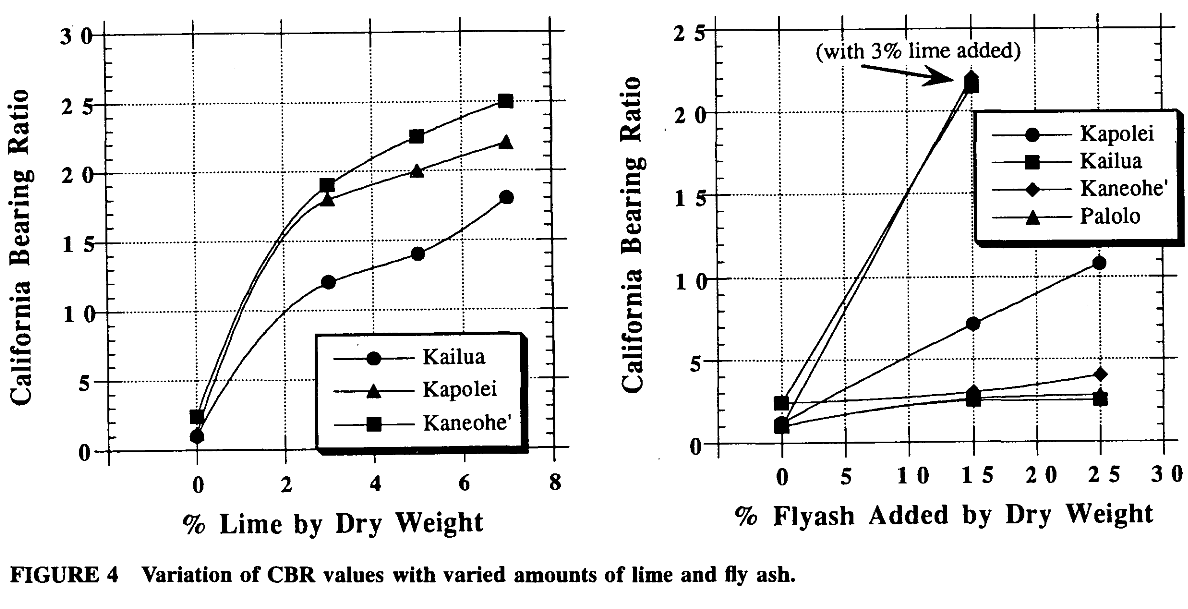

FIGURE 4 Variation of CBR values with varied amounts of lime and fly ash.

TABLE 1 Unconfined Compressive Strengths (kPa) for Soils Tested With and Without Lime and Fly Ash

	Palolo				Kaneohe							Manoa			
%Ash	0	15	25	15	0	15	25	15	0	0	0	0	15	25	15
% Lime	0	0	0	3	0	0	0	3	3	5	7	0	0	0	3
1-Day	347	200	98	358	517	245	209	862	352	400	414	349	120	203	332
7-Day		349	289	388		302	249	861	461	517	1117		307	259	395
28-Day		651	395	470		397	299	1676	862	1082	1862		599	350	484

	Kapolei							Kailua						
%Ash	0	15	25	15				0	15	25	15			
% Lime	0	0	0	3	3	5	7	0	0	0	3	3	5	7
1-Day	444	523	962	885	272	173	184	433	451	195	572	291	332	330
7-Day		914	1368	1599	433	465	839		500	396	951	323	417	753
28-Day		1134	1993	1951	1143	1276	2306		659	520	1238	577	728	1110

were then randomly picked for testing after 1, 7, and 28 days. Maximum stresses recorded for the soils are presented in Table 1.

For some of the soils there was an initial loss in compressive strength with the addition of fly ash, but strength was typically regained and increased with time. Studies have shown that fly ash-stabilized soils continue to gain significant strength at a fairly steady rate for at least 90 days. It is suggested that further aging would also provide significantly greater strength gains for these soils. An explanation for this initial loss in unconfined compressive strength is that as the soils are altered into more friable, "less clayey" form, their cohesive strength may decline while their frictional strength is increased. This hypothesis was supported by performing a few undrained triaxial tests on those soils for which there was a significant loss of unconfined strength reported. The results of the triaxial tests confirmed that the treated soils had an initial strength gain when confined and that the strength continually increased with time.

Some additional tests were performed with the 3 percent lime added to the 15 percent fly ash and soil mixtures (3:15:82). Tests were also performed on soils stabilized with 3, 5, and 7 percent lime. The results of those additional tests showed that a significant increase in the unconfined strengths could be expected for the 3:15:82 mixtures (typically twice that of the 15 percent fly ash mixtures), and that those strengths achieved were considerably greater than those achieved for the mixtures with up to 7 percent lime without fly ash.

CONCLUSION

These studies have demonstrated the potential for stabilization and improvement of a variety of "poor to marginal" quality tropical soils with locally available materials. The local Hawaiian soils tested appear to be especially well suited for improvement by lime admixture stabilization, exemplified by dramatic improvements in critical geotechnical properties shown by laboratory tests. The studies also showed potential for dramatic improvement with a low-cost, high-quality admixture generated as an industrial by-product from a coal-burning electrical cogeneration plant. Although the locally available fly ash by itself is lime rich with more than 20 percent total lime content by weight, when used as a soil admixture at 15 percent by dry weight of the soil, the lime content is dramatically diluted to 3 to 4 percent. Using a blend of the fly ash with a small percentage of additional lime produces even more dramatic results while still providing a cost-effective alternative to designing with (or disposing of) these soils. Test results show that treatment with lime, fly ash, or a combination of fly ash and lime, can be an effective and cost-efficient method of soil stabilization. The study also shows that to attain desired attributes and engineering properties for some of the tropical soils, use of the fly ash may provide better results than a much more expensive treatment by lime alone where more than double the amount of lime was added to the soil. This result is most likely because of the source of pozzolans provided by the fly ash that may not be available from the natural soils.

Although many projects have been completed and approved on the basis of past experience and research done on lime, fly ash, and lime-fly ash admixture stabilization in other geologic and climatic environments, these stabilization methods have not yet been generally accepted or widely applied in Hawaii. These preliminary tests represent the beginning of the verification of applicability of lime and the locally generated ash as practical and cost-efficient soil improvement admixtures to the local soils.

ACKNOWLEDGMENTS

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REFERENCES

1. Uehara, G. Soil Science for the Tropics. In *Proc., American Society of Civil Engineers Geotechnical Engineering Division Specialty Conference, Engineering and Construction in Tropical and Residual Soils,* New York, N.Y., 1982, pp. 13.
2. Diamond, S., and E. B. Kinter. Mechanisms of Soil-Lime Stabilization: An Interpretive Review. In *Highway Research Record 92*, HRB, National Research Council, Washington, D.C., 1965, pp. 83–96.
3. Usmen, M. A., and J. J. Bowders, Jr. Stabilization Characteristics of Class *F* Fly Ash. In *Transportation Research Record 1288*, TRB, National Research Council, Washington, D.C., 1990, pp. 59–60.
4. Glenn, G. R., and R. L. Handy. Lime-Clay Mineral Reaction Products. In *Highway Research Record 29*, HRB, National Research Council, Washington, D.C., 1963, pp. 70–82.