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I am submitting herewith a thesis written by Jo K. House entitled "Soil Stabilization Potential of Portland Cement Stack Dust." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

B. Dan Marks, III, Major Professor

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Accepted for the Council:

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SOIL STABILIZATION POTENTIAL OF PORTLAND CEMENT STACK DUST

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee

Jo K. House

December 1976

1305112

ACKNOWLEDGEMENTS

The author wishes to express sincere appreciation to his thesis and major advisor, Dr. B. Dan Marks, III, for his personal guidance and direction and to committee members, Professor A. B. Moore and Dr. William L. Grecco for their attention to this research project.

Thanks is extended to Messrs. Curtis Allin and Tom Young for their assistance in the laboratory and for the printing of this thesis.

J. E. "Buck" Reedy of the Ideal Cement Company is also to be thanked for his assistance in this project.

A sincere appreciation is also offered to Mrs. Judy Adkins for her dependable assistance and patience in typing this report.

Finally, the author wishes to extend a special thanks to his family for their patience and understanding.

ABSTRACT

During the production of portland cement, a fine material designated as stack dust is collected throughout the manufacturing process. Some of the stack dust is returned to the production process, however, generation of such large quantities of the material renders complete utilization impossible.

Excessive quantities of the stack dust must be stockpiled or disposed of by special procedures.

The purpose of this study was to investigate the feasibility of utilizing stack dust as a soil stabilization additive. A laboratory testing program was developed to determine the effect of varying percentages of stack dust upon two distinctively different soil types.

Atterberg limits, moisture-density relationships and unconfined compressive strengths were utilized in the study to evaluate the stabilization potential of the stack dust.

Evaluation of the test results obtained throughout the study indicated that the stack dust influenced physical and engineering properties in a similar manner to that of portland cement.

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CHAPTER I

INTRODUCTION

Although crude cement mixtures and lime additives were utilized as mortars and material stabilizers as long ago as the Roman Ages, increased technology has made portland cement, hydrated lime, and quicklime common soil stabilizers within the last half century.

Portland cement and lime treatment of soils are both classified as chemical treatment or stabilization. The processes of hydration of cement and the reaction of lime and colloidal clay involve very similar chemical reactions.

Portland cement stabilization of soil is primarily dependent upon the cementation of individual soil grains into a stable matrix. Consequently, portland cement has been found to be most successful in the stabilization of silty and sandy soils which possess little or no cohesion.

Conversely, lime stabilization is most effective in cohesive type soils. Lime stabilization is primarily dependent upon the chemical reactions between the hydrous aluminates and silicates that compose clayey soils and the calcium ions supplied from lime to form cementitious compounds. Lime treatment is currently considered to occur in two distinctive phases; namely lime modification and lime stabilization. Lime modification involves the addition of low percentages of lime to produce increased workability and reduced plasticity. Lime modification is not considered to produce any significant soil strength gains. Lime stabilization is the phase of lime treatment that is responsible for producing an increase of

the soil strength. Strength increases are dependent upon large percentages of lime which promote pozzolanic reactions that form cementitious compounds similar to those formed during cement hydration.

During recent discussions with representatives of the Ideal Cement Company, interest was expressed concerning the stabilization potential of the stack dust collected during the production of portland cement. An investigation of several chemical analyses revealed that the stack dust was obviously a low grade cement containing rather high percentages of quicklime and hydrated lime.

The objective of this study was to determine the potential of stack dust generated from portland cement production for stabilization of the range of soils that would normally be stabilized by the addition of either portland cement or lime.

The scope of this study involved the treatment of a silty sand material, which would normally be treated with portland cement, and a moderately plastic residual clay, which would normally be treated with lime, with percentages of stack dust that were considered to be economical and usable in subgrade stabilization.

Physical property response, as well as unconfined compression tests, which are normally performed for evaluation of soil stabilization, were utilized for evaluation of the stabilization potential of the stack dust.

CHAPTER II

LITERATURE REVIEW

I. INTRODUCTION

The utilization of chemical additives to upgrade low quality or problem soils and materials is certainly no new engineering concept. The utilization of a crude hydrate lime and sodium chloride dates back to the construction of the Apian Way and other roads constructed during the Roman Empire.

Chemical additives which are used most often in modern highway construction are portland cement and hydrated lime. Mechanisms involved in the stabilization of soils by these additives are quite different in many respects; however, chemical reactions which occur in both stabilization processes are very similar.

Generally, portland cement stabilization, which results in soil-cement, results from the cementitious action of the portland cement which occurs during hydration. Consequently, portland cement is normally utilized in the stabilization of soils which possess single-grain characteristics. Soils that may be grouped into this category include silts, clayey sand, fine grained sands, and relatively clean sands. Conversely, lime stabilization is used most effectively in soils with a large fraction of clay size particles. The lime reacts with hydrates of silica and and alumina from clay soils. Lime stabilization differs from cement stabilization in that increasing amounts of cement added to soils provide

higher strength whereas excessive amounts of lime added to soils acts as a low strength filler material.

The purpose of this chapter is to present the basic concepts and theories of lime-soil and cement-soil interactions and how they are applied to lime and cement stabilization.

II. MECHANISMS OF SOIL CEMENT

Major Compounds of Portland Cement

An enormous amount of research and study has been conducted to determine characteristics and composition of compounds that comprise portland cement. However, existing knowledge of the compounds is not completely adequate or without controversy.[1] Most researchers do agree that there are four major "compounds," "minerals," or "phases" that comprise portland cement. The term phase has often been used instead of compound in discussions of portland cement because none of the four major compounds has an exact composition. According to Troxell, Davis and Kelly[2] the term phase denotes a homogenous, physically distinct portion of matter in a heterogenous system, separated from other phases by a distinct physical boundary.

Dicalcium silicate (β-C_2S) and tricalcium silicate (C_3S) are two phases or compounds which make up approximately 75 percent of an ordinary portland cement. The remainder of portland cement is comprised of two phases or compounds known as tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF).

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*Superscript numbers in parentheses refer to those entries in the List of References.

Hydration Processes

When portland cement is combined with water the four basic phases or compounds that constitute portland cement undergo hydration. Hydration is the process resulting from attraction of a positive or negative ion for the charged poles of the water molecule. Hydration of the four basic phases of portland cement is the mechanism responsible for the cementitious action in soil cement and portland cement concrete.

The reaction of the calcium silicates with water results in the formation of calcium hydroxide and a calcium silicate hydrate gel, which is a cementitious crystal formation. This cementitious reaction product is sometimes called a tobermorite gel because of its resemblance to the rare but natural mineral known as tobermorite. The reaction product is also denoted as C-S-H gel. The C-S-H term, according to Lea,[3] is preferrable because the gels formed in the hydration of C_3S and βC_2S show only a few of the x-ray diffraction peaks of well crystallized tobermorites.

During any stage of hydration the calcium silicate compounds will comprise the major portion of the cement paste. However, hydration of the majority of the calcium silicate compounds will take place after the "setting" period has occurred.

Lea[3] has stated that the initial hydration products of C_3S and βC_2S have a composition close to $C_3S \cdot$aqueous and $C_2S \cdot$aqueous, but within a matter of hours these change to a calcium silicate hydrate gel (CSH) with a $CaO \cdot SiO_2$ ratio of approximately one to five.

The final composition of this gel has a ratio of $CaO \cdot SiO_2$ which varies from one to five to one to eight. The actual ratio depends upon type cement, water-cement ratio, and hydration temperature.

It has also been determined that the complete hydration of tricalcium silicate releases 40 percent calcium hydroxide by weight while the complete hydration of dicalcium silicate releases about 18 percent calcium hydroxide by weight. Calcium hydroxide has been found to be a significant factor in the resistance of cement to potentially deleterious agents.

Tricalcium aluminate reacts very rapidly with the addition of water. It is well established that the hydration of tricalcium aluminate yields an end product with the formula $3CaO \cdot Al_2O_3 \cdot 6H_2O$ which indicates that tricalcium aluminate is hydrated by combining with only six molecules of water. The entire hydration of tricalcium aluminate is much more complicated. According to Czernin[4] knowledge of hydration products of the aluminate compounds in cement clinker is much less detailed than the silicate compounds.

Czernin[4] found that tricalcium aluminate initially forms a water rich hydrate with an additional molecule of lime: $4CaO \cdot Al_2O_3 \cdot 14H_2O$. This compound is metastable and in time releases one molecule of lime which produces tricalcium aluminate hydrate. The extent to which this transformation occurs and the time involved remains a point of hypothesis and controversy.

The fourth major phase of portland cement is known as the ferrite phase. Several compounds such as C_6AF_2, C_2F and C_6A_2F are potential components of the ferrite phase. However, tetracalcium aluminoferrite (C_4AF) is the compound which most commonly typifies the ferrite phase. The variable composition of this phase is influenced primarily by the ratio of alumina to iron. Increases in the iron oxide content of cements

cause an increase in the tetracalcium aluminoferrite, C_4AF composition rather than tricalcium aluminate. Tetracalcium aluminoferrite, C_4AF has setting properties that are somewhat slower than tricalcium aluminate, C_3A. Lea[3] has stated that the substitution of tetracalcium aluminoferrite C_4AF for tricalcium aluminate C_3A decreases the heat of hydration as well as increasing resistance to seawater deterioration.

The explanation concerning the hydration of the ferrite phase varies somewhat with different researchers.[1,3,4] However, most researchers agree that the hydration reactions of the ferrite phase are analogous to the reactions of the aluminate phase.[3,4] Czernin[4] has suggested that the end product of tetracalcium aluminoferrite C_4AF hydration might be represented as $C_3AH_6 + C_3FH_6$.

Control of Hydration Reactions

Calcium hydroxide and the oxides of gypsum also play an important role in the hydration of cement.

Gypsum is added to cement clinker in order to control the rapid reaction of tricalcium aluminate which could cause flash setting. Gypsum combines with tricalcium aluminate, C_3A to form a relatively insoluble sulpho-aluminate coating on the tricalcium aluminate, C_3A phases to slow the reaction. Calcium aluminate trisulphate hydrate and a calcium aluminate monosulphate are the only two forms of sulpho-aluminates present in hydrated cements. The calcium aluminate trisulphate hydrate is also known as the mineral ettringite Taylor 1964.[1]

According to Taylor[1] the monosulphate crystallizes as hexagonal plates similar in appearance to hexagonal calcium aluminum hydrates. The trisulphate forms readily in water and forms needle like crystals.

Calcium hydroxide in portland cement has also been found to effectively retard the hydration of tricalcium aluminate. Taylor[1] has documented research performed by Parker and Forsen that showed calcium hydroxide to be more effective than calcium sulphate as a retarder. Forsens' results indicate that the combination of calcium hydroxide and calcium sulphate was more effective than calcium hydroxide alone.

The actual retarding mechanism of calcium hydroxide in combination with gypsum is not completely understood. Taylor[1] has proposed that calcium hydroxide augments the retarding action of gypsum by forming a protective coating around the trisulphate form of the calcium sulpho-aluminate.

Internal Deterioration

Although small amounts of gypsum are imperative in the prevention of flash set of cement, large amounts of gypsum can be deleterious to a cement mix. Large amounts of gypsum cause the formation of the calcium sulpho-aluminate to proceed after setting and hardening which results in expansion. Large expansions after setting are common causes of deterioration in soil cement and portland cement concrete. Cements that undergo large expansions after setting are termed unsound. In order to prevent unsoundness or large volume expansions after setting it is very important that gypsum be added in an amount that will completely combine with the cement during the setting or hardening period.

An excess lime content above that which can be combined with the acidic oxides of the cement mix is also a cause of unsoundness.

According to Lea[3] free lime may develop from an overlimed mix, inadequate burning, or insufficiently fine grinding and mixing of the raw material fed into the kiln during the cement manufacturing process.

G. E. Bessey,[5] found that unsoundness occurs when free CaO is in excess of 2 percent. However, Bessey[5] has also indicated that cements with a total free lime content as high as 5 percent are quite sound when it is mainly present as calcium hydroxide and the actual free CaO content is below 2 percent.

An excessive proportion of magnesia can also create unsoundness in cement mixes. Unsoundness due to magnesia is the result of magnesia crystallizing to periclase. The small crystals of periclase tend to hydrate quickly without causing any problems, whereas the larger periclase crystals hydrate slower causing excessive internal pressures. In order to offset the adverse effects of MgO (magnesia) rapid cooling of the clinker has been suggested.[3]

Clinker that is cooled quickly results in smaller periclase crystals which readily hydrate before any unsoundness problems can develop.

The Setting and Hardening Process

An understanding of the setting and hardening process of cement is also important to the control of the quality of soil cement and portland cement concrete.

Before an explanation of the setting and hardening process of cement is provided it is necessary to describe the physical structure of the essential ingredient of soil cement and portland cement concrete, the cement paste. The fresh cement paste can be described as being composed of a mixture of cement grains and water, while the hardened paste can be described as being composed of solid reaction products and pores penetrable by water.

The major portion of the hydration products within a body of cement paste is called a cement gel. According to Troxell, Davis and Kelly,[2] a cement gel is a two-component, dispersed system of which the solid phase is of colloidal dimensions. The cement gel is also often described as a dense though porous substance.

The area required to fill all the space within the boundary of the cement paste is usually more than the cement gel can accommodate. The space not filled is referred to as capillary space. Taylor[1] has stated that a hardened cement paste is composed of cement gel, capillary space, and a residue of unreacted cement. Pores within the gel are referred to as gel pores.

The setting and hardening process of cement has been outlined by many researchers. According to Lea[3] and Czernin[4] rapid reactions begin to occur as soon as water is mixed with cement. These reactions result in a supersaturated solution from which a gel-like mass of crystals precipitates. Troxell, Davis and Kelly[2] have stated that after formation of the initial layer of gel, some reaction products precipitate in the space made available by dissolution of cement particles and some are formed outside the growing layer of gel as constituent molecules migrate through the porous gel structure. According to Taylor[1] the rate of reaction slows to a low level after five minutes. During the next forty to one hundred and twenty minutes the paste remains plastic. This period is sometimes referred to as the dormant period. The cement paste shrinks slightly while still in this plastic state because there is a contraction in the entire system.

Taylor[1] has described another period that takes place after the dormant period in which relatively rapid chemical reactions take place for about three hours. During this period the paste begins to loose its plasticity and passes through two arbitrarily defined degrees of firmness known as initial set and final set. Once the mass becomes rigid a small expansion sets in for the gel mass deposits around the cement grains causing them to swell and exert an outward pressure. With time the gel mass increases in quantity and spreads into the intergranular spaces.[3]

After final set, which commonly occurs at approximately six hours after mixing the rate of chemical reactions begin to slow until all the cement is consumed or until one or more of the conditions for the reaction is not possible.

Cementation

Completion of the setting and hardening of the cement paste is responsible for the cementation of aggregate in concrete and the cementation of soil grains in soil cement. However, the mechanism by which an admixture of cement can strengthen a large mass of soil has not been defined.

Ingles and Metcalf[6] have suggested that hydrated cement forms either strong nucleii scattered throughout the soil mass, or else a skeleton of hydrated cement develops throughout the voids that restrains the entire soil mass.

Handy[7] has suggested that cementation is the combination of mechanical bonding of cement to rough mineral grains as well as the chemical bonding between cement and mineral surfaces. According to

Handy[7] chemical bonding becomes more important as the soil becomes finer as a result of smoother textures and higher surface areas.

Several researchers[8,9] have described a supplementary soil cementation in clay soils which is due to the chemical bonding of calcium hydroxide and silica. Hydrating cement produces a high pH which enables some of the silica held on clay particles to enter into solution. Calcium hydroxide is produced as a result of the hydration of the calcium silicates. The combination of calcium hydroxide with silica results in the formation of calcium silicate hydrate gels that are very similar to the CSH gels produced from cement hydration. Gilliott[8] has suggested that the compounds produced from the bonding of calcium hydroxide and silica connect with the structure of the cement reaction products to provide additional strength. The chemical reaction of calcium hydroxide with silica is also the basic principle of lime soil stabilization.

III. SOIL LIME REACTION MECHANISMS

For many years soil stabilization has been achieved with quicklime, CaO, calcium hydroxide or slaked lime, $Ca(OH)_2$ and dolomitic limes. Quicklimes, CaO are formed when limestone is heated to a temperature high enough to drive off carbon dioxide. Calcium hydroxide or slaked lime is formed when CaO reacts with water. The process is heat producing and is known as slaking.

Although lime treatment has been practiced since ancient times the actual reaction mechanisms that take place between the soil and lime are not completely understood.

Before a discussion of the soil lime reaction mechanisms is undertaken it is important to clarify what is meant by lime treatment. For many years lime treatment has been used synonymously with lime stabilization. However, lime stabilization along with lime modification should be considered as two aspects of lime treatment which are controlled by the percentage of lime added to the soil.

Lime modification is considered to be the level of lime treatment which affects the consistency limits or physical limits of cohesive soils as a result of the addition of low percentages of lime.

Lime stabilization concerns the strength gains in cohesive soils resulting from the addition of larger percentages of lime.

In order to provide a detailed explanation of the lime modification-stabilization idea, a discussion of the reaction mechanisms involved in each phase of lime treatment is necessary. Four reaction mechanisms are frequently presented to account for the phenomena that results when lime is added to cohesive soils. These reaction mechanisms include cation exchange, flocculation, carbonation, and pozzolanic reactions.

Marks and Halliburton[10] provided support for the lime modification-stabilization idea on the basis that certain of these reaction mechanisms that control modification may or may not control the stabilization process.

Lime Modification Processes

Davidson and Hilt[11] among others, believe that cation exchange and ion crowding are the two mechanisms responsible for the phenomenon of lime modification. Ions of Ca^{++} penetrate the ionic atmosphere of clay particles in an attempt to reach the net negative charge along the surface of the

clay particles. As a result of this attraction other cations such as K+, H+ and N+ that are already on the surface of the clay particles are replaced by the divalent calcium ions. The continuation of these cation exchange reactions increases the pH of the system. The increase in pH as well as the saturation of the system with Ca^{++} ions, results in an "ion crowding."[12] This ion crowding is thought to be a compression of the ionic atmosphere of the clay particles. As the ionic atmosphere of the clay particles becomes more compressed the electrical charge that keeps the particles apart is overcome and the particles aggregate or become flocculated.[11]

The capacity a soil has for cation exchange is significantly influenced by the amount and types of clay minerals in the soil and the presence of organic matter. Research conducted by Eades, Nichols and Grim[13] indicated that soil with a greater percentage of fines (material passing the #200 sieve) needs more Ca^{++} to satisfy the cation exchange capacity and have free lime left for further reaction. Consideration must also be given to the clay minerals comprising the soil because all clay minerals do not have the same exchange capacity. Organic compounds frequently have a high exchange capacity and are believed to compete with the clay minerals for the available calcium ions. Dumbleton[14] suggested that an organic precipitate surrounds the lime particles and isolates them from further reaction with the clay minerals.

Cation exchange and flocculation have been rejected as adequate explanations of the phenomena that occurs when lime is added to clay soils. Cation exchange was rejected as a mechanism of modification on the basis that calcium saturated montmorillonitic soils of the southwestern United

States must be stabilized before they are able to perform satisfactorily as subgrade materials. Flocculation was rejected on the premise that many soils of the southeastern United States are flocculated in nature yet they are not stable and do respond to lime treatment.[15]

Marks and Halliburton[10] have contested the rejection of cation exchange presented by Diamond and Kinter by explaining that ion activity does not cease with Ca^{++} saturation since cation exchange capacity increases with concentration and with an increase in the pH of the system.[15] Marks and Halliburton[10] also suggest that lime treatment does increase Ca^{++} concentration and pH of the system, thus allowing cation exchange to take place. Consequently, cation exchange cannot be disclaimed as a mechanism controlling lime treatment.

Marks and Halliburton[10] agreed with Diamond and Kinter that flocculation is not solely responsible for lime-soil modification. Claire and Crutchley[16] have indicated that compression of the ionic atmosphere around clay particles may be achieved even in flocculated suspensions. Therefore, further compression of the ionic atmosphere along with other reaction mechanisms may be very influential in lime treatment, especially modification.

Previous research in the field of lime-soil stabilization has shown that small percentages of lime mixed with clayey soils increases workability, whereas larger percentages contribute to strength increases. From this many researchers believed that the soil has an affinity it must satisfy before any cementing compounds are formed Harrison and Hilt.[11]

Marks and Halliburton[10] have described the lime fixation point as the percentage of lime which causes a maximum compression of the ionic

atmosphere of the clay particle and a completion of cation exchange reactions.

The lime fixation point can be regarded as the dividing point between the phases of lime modification and lime stabilization. Percentages of lime above the lime fixation point contribute more significantly to strength gains rather than workability.

Stabilization Processes

The mechanisms most commonly presented in literature as being responsible for soil strength gains are pozzolanic reactions and carbonation.

Pozzolanic Reactions

Pozzolanic reactions begin as soon as Ca^{++} ions suspersaturate the system. A pozzolan is defined as a siliceous or siliceous and aluminous material, which in itself possesses little or no cementing value, but will in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties, American Society for Testing Materials.[17]

Many clays contain enough siliceous and aluminous material to react with the Ca^{++} ions that supersaturate the system.

The high pH that the addition of lime creates results in the solution of silica from quartz crystals and clay minerals.

The major source of the silica and alumina is from the mineral allophane. Allophane has a random arrangement of silicon in tetrahedral coordination and metallic ions (such as alumina) in octahedral coordination without any symmetry.[18]

The cementitious compounds that form as a result of pozzolanic reactions have been identified by x-ray diffraction studies as tetra-calcium aluminate and calcium silicates which are the same type minerals produced during the hydration of cement. The tetra-calcium aluminate hydrates produce fast low strength bonds between soil particles. Calcium silicate hydrates, which resemble the mineral tobermorite, produce higher and prolonged strength gains.

Cementation

The other reaction mechanism which has been frequently mentioned in the literature on soil-lime stabilization is carbonation. The carbonation process can be summarized as the reaction of lime with carbon dioxide to form calcium carbonate which exerts a cementing action that bonds soil particles.

Recent research performed by Eades, Nichols and Grim[13] has failed to provide conclusive evidence as to the importance of carbonation in the development of significant strength gains that lime-soil mixtures have produced.

IV. SUMMARY

In conclusion, it should be understood that lime stabilization as well as cement stabilization depends upon the formation of calcium silicates to provide the soil with substantial strength gains. Pozzolanic reactions are responsible for the formation of the calcium silicates during lime stabilization whereas cement hydration is responsible for the formation of calcium silicates during cement stabilization.

CHAPTER III

MATERIALS AND TEST PROCEDURES

I. INTRODUCTION

The purpose of this chapter is to provide a description of the chemical additive (stack dust), soils, sample preparation and test procedures used in this study.

A chemical analysis of the stack dust as well as a description of the physical properties of the two soils utilized in this study were essential in evaluation of reactivity between the additive and soils. Sample preparation and test procedures are also important in a study of this nature since chemical reactions between additive and soil are time dependent.

II. CHEMICAL ADDITIVE

The chemical additive used throughout this study was obtained from the stock pile at the Ideal Cement plant in Knoxville, Tennessee. This material is collected by dust precipitators in the kiln stacks of the plant.

The chemical composition of stack dust is variable depending upon the production process and quality of limestone being used in the cement production. However, several previous chemical analyses of the stack dust indicated the material had potential as a soil stabilization additive. These analyses revealed that the stack dust contained calcium in both the

oxide and hydroxide form. Presence of high percentages of lime in the stack dust indicated a stabilization potential relative to cohesive soils. As a result of the origin of the material, the stack dust obviously had a comprehensive analysis similar to portland cement which would make its use as a stabilization additive for low to non-cohesive soils quite feasible.

Comparison of the composition of the stack dust to that of Type I portland cement is presented in Table I. Major compounds of both the stack dust and portland cement appear to be within relatively close agreement. However, special attention should be directed to the sulphur trioxide (SO_3) content of the stack dust. The SO_3 content of the stack dust is somewhat higher than a normal Type I portland cement can accommodate without the possibility of harmful expansion upon hydration. Sieve analyses conducted on the stack dust, reveal that this material is considerably coarser than allowable for Type I portland cement under ASTM specifications. Coarseness of the stack dust may be a result of some hydration which has occurred in the stockpile.

III. SELECTED SOILS

In order to evaluate the stabilization potential of the stack dust for a broader range of soil types than is normally treated with either portland cement or lime, both a sandy silt and clayey soil was selected for treatment. The sandy silt soil selected was obtained from the flood plain of the French Broad River near the head of the Tennessee River east of Knoxville, Tennessee. This material is a micaceous alluvial silt of very low plasticity. This material represents typical alluvial soils occurring in flood plains throughout the East Tennessee area.

TABLE I

CHEMICAL ANALYSIS OF STACK DUST AND PORTLAND CEMENT

Compounds	Stack Dust	Portland Cement
SiO_2	13.34	21.00
Al_2O_3	6.22	6.00
Fe_2O_3	2.70	2.35
CaO	39.93	63.62
SO_3	8.06	2.13
Loss on ignition	23.38	1.37
Na_2O	0.43	0.12
K_2O	6.15	0.94
Mg_2O	0.96	2.58

The clayey soil selected for treatment in this study was obtained from a depth of approximately twenty feet in a borrow pit in West Knoxville. This material is moderately plastic residual clay weathered from limestone bedrock. This material often contains relatively high percentages of chert fragments.

Physical properties of both the sandy silt and clayey soil are presented in Table II. Grain size distribution curves for the two selected soils are presented in Figure 1.

TABLE II

PHYSICAL PROPERTIES OF SOILS

Test	Sandy Silt	Clay
LL	25	46
PL	20	23
PI	5	23
G_s	2.69	2.76
Classification (Unified)	SM	CL

IV. SAMPLE PREPARATION

Subsequent to procurement of bulk samples of each selected soil, the samples were allowed to air dry to a moisture content of 2 to 3 percent moisture.

After air drying the soils were reduced to minus No. 40 sieve material by mechanical abrasion in a small ball mill. The grinding and

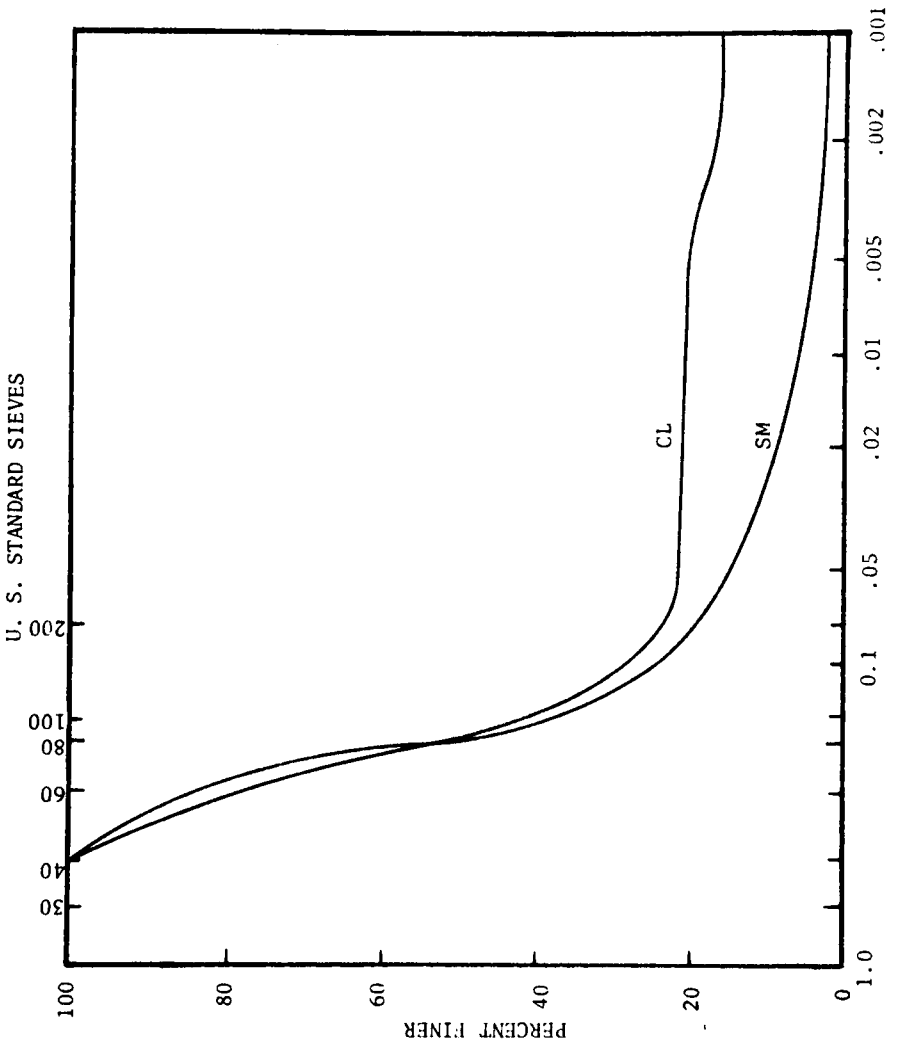


Figure 1. Grain Size Distribution of Selected Soils.

sieving processes were repeated until approximately seventy pounds of each soil had been accumulated.

Each mixture of soil and additive also underwent a standard procedure in preparation for compaction tests and sample production for unconfined compression tests. The initial step in the preparation of each soil mixture was to weigh the desired quantity of soil and stack dust to the nearest 0.1 gram. The percentage of stack dust for the mixture was determined by the dry weight of the soil. The dry soil and chemical additive were then combined and mixed until the mixture appeared to be thoroughly blended.

After blending the soil and additive in the dry condition, the mixture was spread over a large mixing pan in a uniform layer of approximately a one inch thickness. The desired amount of moisture was then evenly distributed over the soil mixture. When the desired moisture content had not yet been determined only enough water was added to produce a moisture content near the plastic limit of the mixture.

After moisture was added the soil mixture was sealed with wax paper and allowed to cure for one hour. The curing period was initiated to enable moisture to migrate as evenly as possible throughout the soil mixture and to allow sufficient time for hydration reactions to begin. At the end of the hour the soil mixture was weighed to determine if any moisture had been lost. If there was a loss of moisture enough water was added to regain the desired moisture content.

The moist soil was then blended by hand in a moisture room so as to prevent any further moisture loss. The sample production for compressive strength tests was also conducted in the moisture room to insure that the

samples were compacted at the optimum moisture content. As a further precaution against moisture loss the soil mixture was covered with wax paper during the molding of each sample.

V. TEST PROCEDURES

Standard Proctor moisture-density relationships were established for all mixtures after preparation procedures previously described. During the mixture preparation sufficient moisture was added to insure that after the curing period points on the dry side of optimum moisture content could be obtained on the Standard Proctor curve.

Equipment utilized to produce Standard Proctor moisture-density relationships included a Harvard Miniature mold and a specially designed impact compaction hammer. The drop-hammer was designed by Dr. B. Dan Marks for soil stabilization research and instruction at the University of Tennessee. The hammer was scaled in such proportions as to produce the same compactive effort as the full scale Standard Proctor hammer.

Soil samples to be used for unconfined compression tests also underwent the standard preparation procedures. These samples were molded at optimum moisture contents as determined from Standard Proctor moisture-density relationships.

Approximately twenty samples were molded from each soil mixture with the Harvard Miniature mold and the impact compaction hammer. Each sample was individually wrapped with plastic and coated with wax to prevent any loss of moisture.

Three test samples from each mixture were tested in unconfined compression after three hours of curing. The remaining samples were stored in a 70°F. moisture room at a relative humidity of 100 percent.

A test schedule was adopted which required three samples of each soil mixture to be tested after 3, 7, 14, 21, 28 and 60 days.

CHAPTER IV

DISCUSSION OF RESULTS

I. INTRODUCTION

The primary objective of this study was to determine the soil stabilization potential of stack dust collected during the production of portland cement. Accomplishment of this objective was through a laboratory program developed for determining the effect of stack dust treatment on the physical and engineering characteristics of two distinctively different soil types.

Physical properties of particular importance in this study were consistency limits, compacted unit weights and optimum moisture contents. The behavior of these properties upon chemical treatment are major indicators in evaluation of the stabilization potential of an additive.

The unconfined compression test of compacted and cured specimens has become a standard procedure for evaluation of strength gain in chemically stabilized soils. Consequently, the unconfined compression test was utilized in this study to evaluate the stabilization potential of the portland cement stack dust. The twenty-eight day unconfined compressive strength is most often utilized as an indicator of strength gain; however, intermediate compressive strengths do produce information relative to rate of strength gain and strength versus curing relationships.

II. PHYSICAL PROPERTIES

Atterberg limits conducted in accordance with ASTM D423-66 revealed that the addition of from 4 to 10 percent stack dust to the selected soils had little or no effect on the consistency limits of these materials.

Although the addition of lime does cause reduction of plasticity in soils, results of Atterberg limits tests are not surprising since treatment of clayey soils with portland cement does not significantly reduce the plasticity of clay.

Since the plasticity of the sandy silt was very low initially any reduction in plasticity of this soil could only be academic and would not reflect any significant physical property change.

From evaluation of the results of the Atterberg limits tests it appears that portland cement stack dust is not a suitable modification additive for clayey soils. This assertion is made because no appreciable improvement in the workability of the clayey soil was observed after stack dust treatment.

Analysis of Standard Proctor moisture-density relationships for the sandy silt material revealed that increased percentages of stack dust produced a reduction of compacted unit dry weight. Although maximum unit dry weights were reduced with the addition of stack dust, a loss of only three pounds per cubic foot was realized between the untreated soil and the mixture containing 10 percent stack dust. As the percentage of stack dust increased, decreasing unit dry weights were accompanied by increasing optimum moisture contents. Figure 2 illustrates the effect of stack dust treatment on the moisture-density relationships of the sandy silt.

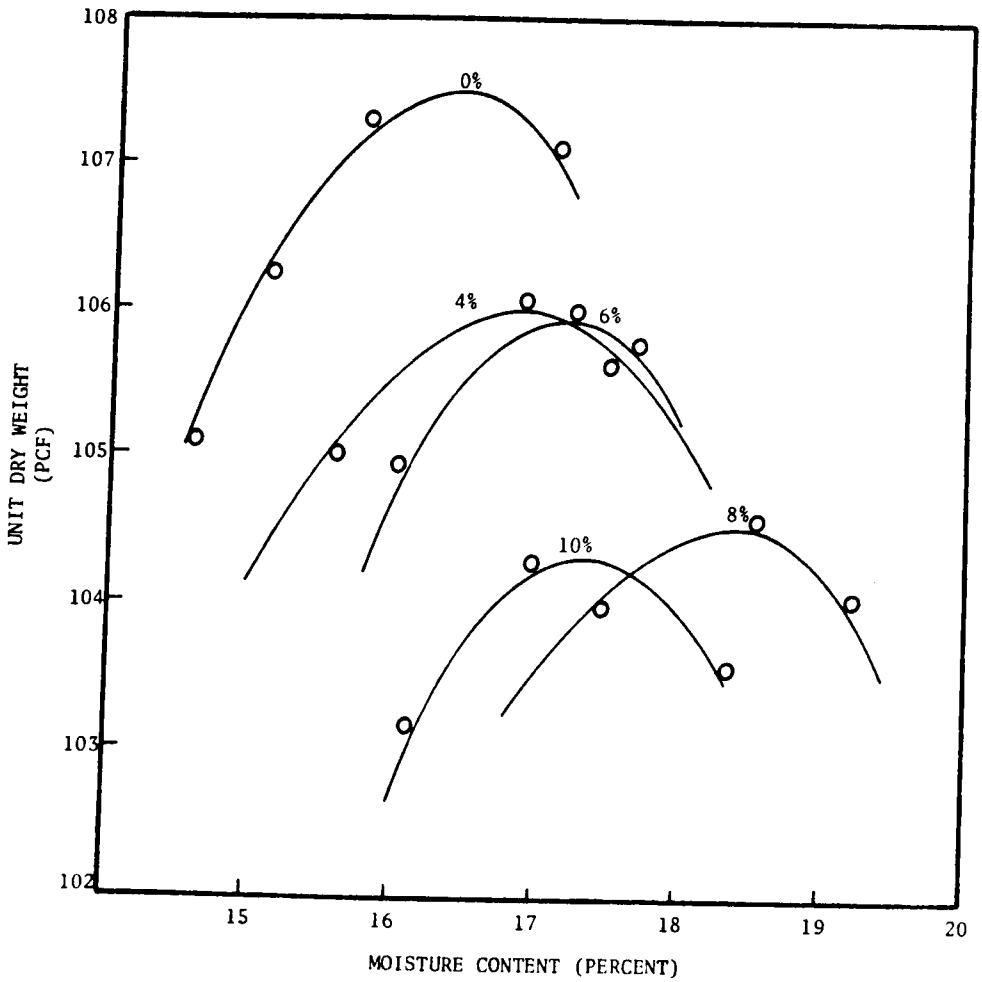


Figure 2. Moisture Density Relationships for SM Soil Mixtures with Varying Percentages of Stack Dust.

Analysis of Standard Proctor moisture-density relationships of the clayey material were similar to those of the sandy silt material in that increased percentages of stack dust produced a reduction of maximum unit dry weight. As in the case of the silty clay, the maximum unit dry weight was reduced by approximately three pounds per cubic foot between the untreated soil and the mixture containing 10 percent stack dust. As the stack dust percentage increased, the decrease of unit dry weight was accompanied with an increase in the optimum moisture content. Figure 3 illustrates the effect of stack dust treatment on the moisture-density relationships for the clayey type soil.

III. STRENGTH PROPERTIES OF SELECTED SOILS

Results of the unconfined compression tests conducted on the sandy silt soil mixtures indicated that increased percentages of stack dust additive produced increased rates of strength gain and greater ultimate compressive strengths. Figure 4 represents unconfined compressive strengths versus curing time for all stack dust percentages.

Inspection of Figure 4 reveals that a noticeable reduction in compressive strength was obtained after sixty days of curing for mixtures containing 4, 6 and 8 percent stack dust additive. This type behavior may be attributable to the high SO_3 (sulphur trioxide) content of the stack dust. Cement specifications normally designate the maximum allowable amount of SO_3 in portland cement as approximately 5 percent. However, the stack dust additive used in this study was composed of over 8 percent SO_3. Upon hydration sulphur trioxide forms calcium sulphoaluminate compounds. Excessive amounts of SO_3 result in the formation of the calcium

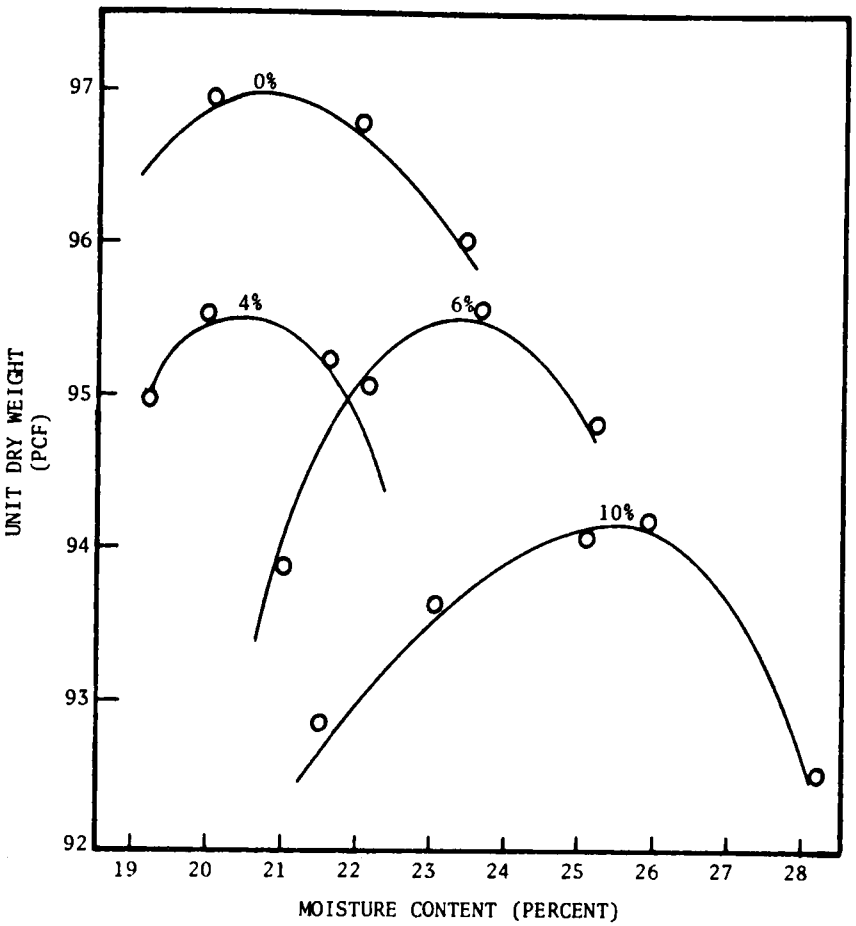


Figure 3. Moisture Density Relationships for CL Soil Mixtures with Varying Percentages of Stack Dust.

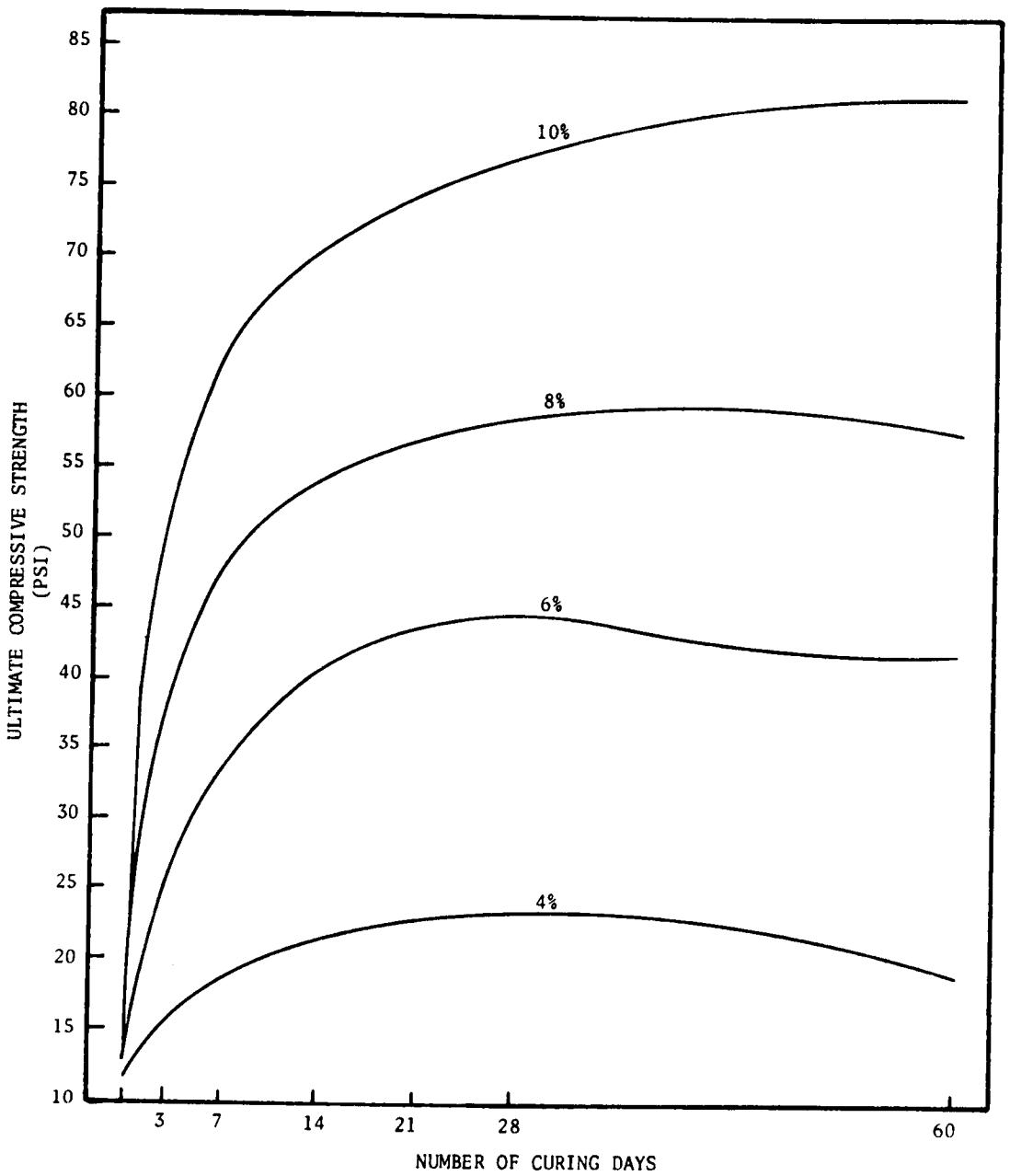


Figure 4. Qu Versus Curing Time for SM Soil Mixtures with Varying Percentages of Stack Dust.

sulphoaluminates after setting and hardening. If sulphoaluminates continue forming after the hardening stage volume changes result which often cause deterioration of concrete and soil cement.

The strength deterioration observed in the sandy silt soil mixtures may very well be attributed to volume changes caused from the formation of sulphoaluminates. Further inspection of Figure 4 indicates the deterioration process was prolonged with increasing percentages of stack dust additive. The decrease in strength did not begin as quickly in the 8 percent mixture as in the 4 and 6 percent soil mixtures.

The curve representing the 10 percent stack dust soil mixture did not show any signs of strength deterioration which would tend to substantiate the idea that an increase in the percentage of stack dust prolongs the period before strength deterioration.

Relationship between twenty-eight day strengths and percent stack dust in the sandy silt is very similar to that which would be obtained from soil cement specimens. Figure 5 illustrates the linearity of the twenty-eight day compressive strength versus percent additive relationship. This type relationship is that which would normally be produced with cement-treated materials.

Compressive strength test results obtained from clay mixtures were similar to those obtained from the sandy silt soil mixtures. The twenty-eight day compressive strengths versus percent additive relationship for the clayey soil mixtures was essentially linear as in the case of the sandy silt mixtures. Twenty-eight day compressive strengths versus percent additive for the clayey soil are shown in Figure 6.

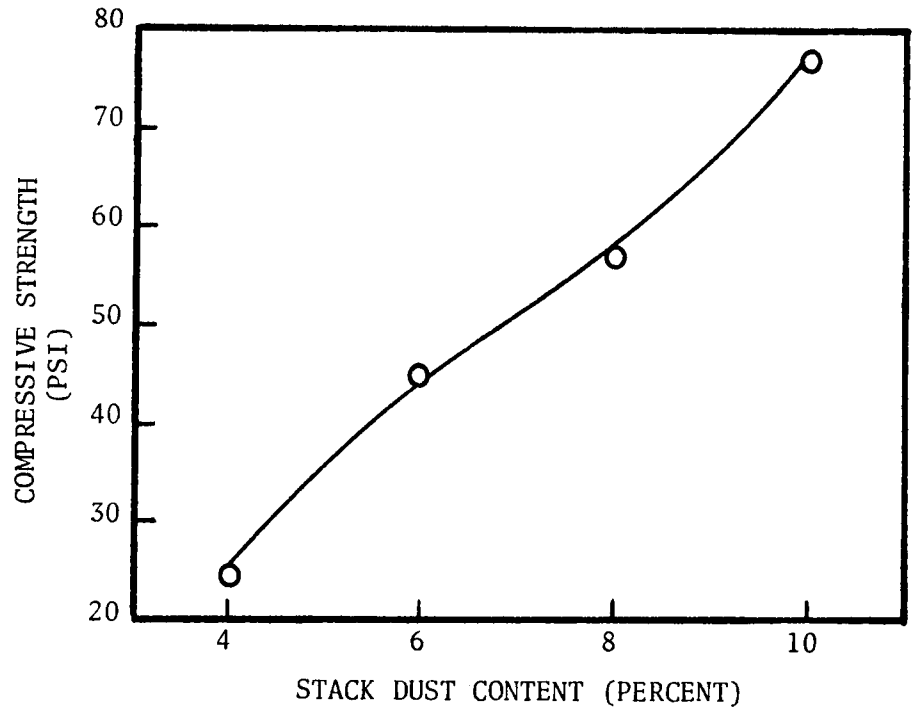


Figure 5. Twenty-eight Day Strength Versus Stack Dust Content in SM Soil Mixtures.

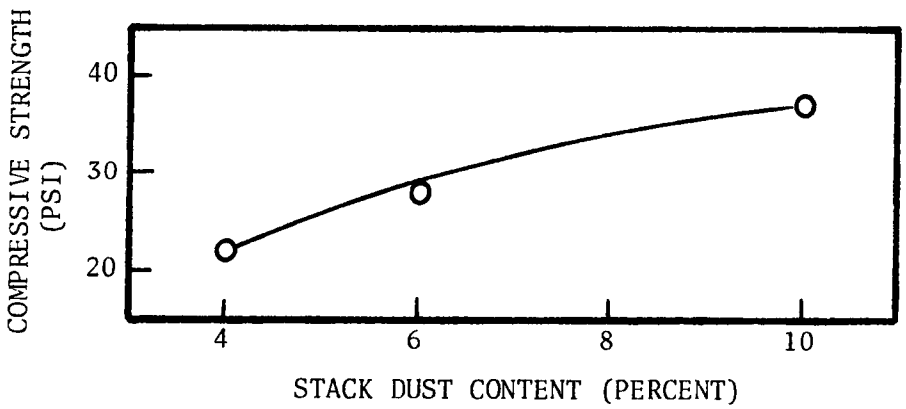


Figure 6. Twenty-eight Day Strength Versus Stack Dust Content in CL Soil Mixtures.

Analysis of compressive strengths versus curing time shown in Figure 7, reveals that increased percentages of additives produced increased ultimate compressive strength; however, the rate of strength gain in clayey mixtures was not significantly affected by increased additive percentages.

The clayey soil mixtures also underwent strength deterioration similar to that experienced by the sandy silt mixtures. As more stack dust was added to the soil mixtures the period before deterioration was extended. The compressive strength of the 6 percent clayey soil mixtures did not begin to deteriorate as quickly as the 4 percent clayey soil mixture. The 10 percent clayey soil mixture exhibited the same type behavior as the 10 percent sandy silt soil mixture in that no strength deterioration was visible after sixty days. This would again indicate that the more stack dust added to the soil prolongs the period before deterioration.

IV. SUMMARY

Results of the laboratory tests performed in this study indicate that the stack dust influences soil in a manner similar to that of portland cement rather than lime. This assertion was based in part on the fact that the sandy silt type soil underwent more significant strength gains after stack dust treatment than the clayey type soil. Linear relationships between compressive strength and percent additive exhibited by both soils is indicative of the behavior of cement stabilized soils. However, some long term strength loss was obtained in specimens of both soils. The sample of stack dust utilized in this study possessed an excessive amount of SO_3 as compared to portland cement. This excessive amount of SO_3

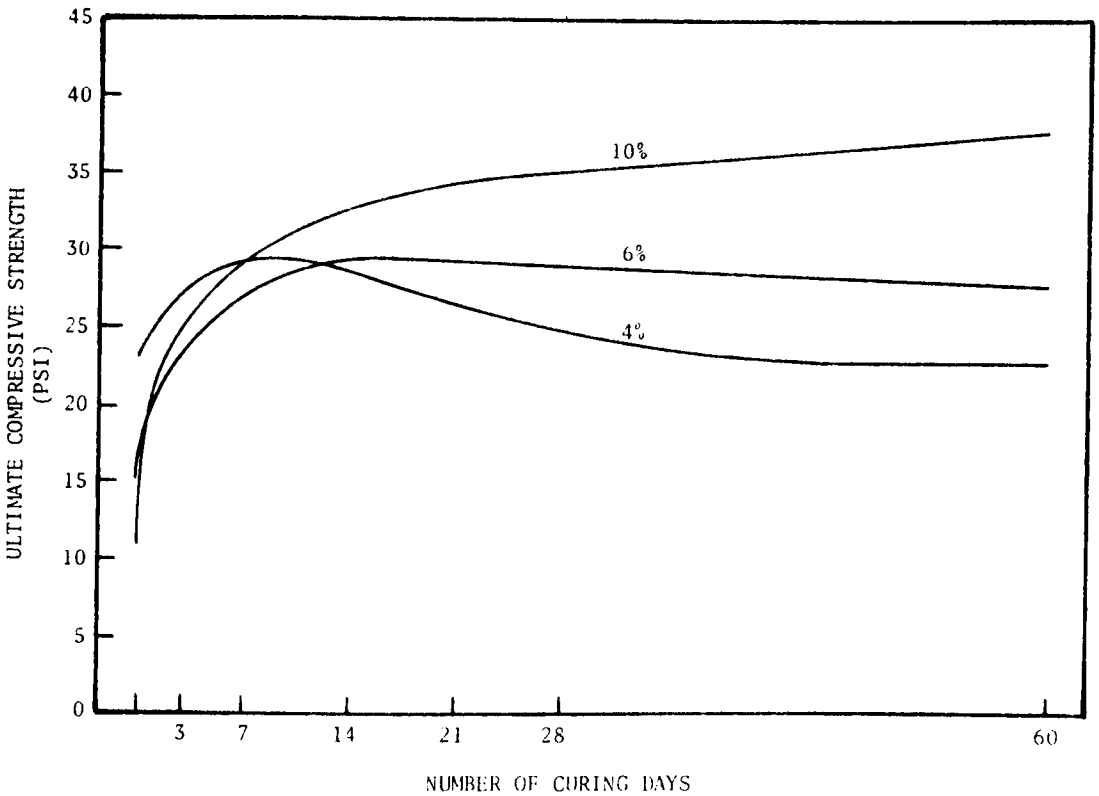


Figure 7. Qu Versus Curing Time for CL Soil Mixtures with Varying Percentages of Stack Dust.

could be responsible for the observed strength loss. Results of this study do indicate that stack dust deserves some attention as an economical additive for soil stabilization.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

I. CONCLUSIONS

Based upon results of the laboratory investigation of the stabilization potential of portland cement stack dust, the following conclusions were drawn.

1. Addition of stack dust to the selected soils did not cause significant alteration in the consistency limits of these materials. Consequently, portland cement stack dust did not significantly improve workability of either soil.
2. Addition of portland cement stack dust to the selected soils did produce some reduction in compacted unit dry weight and some increase in optimum moisture content; however, these changes in moisture-density relationships were not considered significant relative to stabilization potential of the additive.
3. Addition of portland cement stack dust to the selected soils produced a linear twenty-eight day compressive strength versus percent additive relationship similar to that developed by cement-treated soil. However, the sandy silt soil responded more favorably to stack dust treatment than did the clayey soil.
4. Addition of portland cement stack dust to the selected soils did produce significant strength gains; however, strength

losses which may be contributed to high sulfate content do occur over long periods, especially with low additive percentages.

5. Strength losses in stabilized soils may prevent the utilization of this additive on high quality stabilization projects; however, it is most acceptable for stabilization on low volume rural expedient road construction.

II. RECOMMENDATIONS

Based upon results and conclusions developed from this study, the following recommendations are presented.

1. Portland cement stack dust can be utilized as a soil stabilization additive for low quality, low volume roads and streets.
2. If portland cement stack dust is utilized for subgrade stabilization, a flexible pavement structure should be utilized to prevent possible sulphate reaction causing portland cement concrete slab deterioration.
3. Research should also be conducted to investigate the potential of stack dust as an additive for slope stabilization and erosion control.
4. Further evaluation of the stabilization potential of stack dust should be conducted relative to other soil types.
5. Strength losses should be investigated over longer time periods to ascertain the amount of deterioration.
6. The variability of the chemical composition of stack dust should be investigated relative to the stabilization potential.

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VITA

Jo Kendall House was born in Tullahoma, Tennessee on October 8, 1951. He attended elementary schools in Tullahoma and graduated from Tullahoma High School in 1969. In September of the same year he entered the University of Tennessee at Martin in the College of Liberal Arts. In September 1970, he transferred to the University of Tennessee at Knoxville, where in March 1974 he received a Bachelor of Science degree in Geology. He then worked three months with the Tennessee Department of Conservation at Nashville. In September of the same year he accepted a research assistantship from the Civil Engineering Department at the University of Tennessee at Knoxville. In the summer of 1976 he completed all requirements for a Master of Science degree in Civil Engineering. He is a member of the honor society Sigma Gamma Epsilon and is an associate member of the American Society of Engineers.