Utilization of Western Coal Fly Ash in Construction of Highways in the Midwest

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16. Abstract

Coal burning utilities in the Midwest using sub-bituminous coal from Wyoming typically produce fly ash, which, because of its high calcium oxide content, may be classified as Class C fly ash. These ashes are characterized by their self-cementing property and, therefore, they can be used greatly improve soil strength. This research project focused upon the design, construction and environmental issues pertaining to utilization of Class C fly ash for soil stabilization. The compaction and strength development behaviors of clay soils stabilized with fly ash obtained from Kansas City Power and Light were investigated. Laboratory evaluations required to obtain efficient fly ash addition rates and compaction procedure were devised. In this report we present examples of laboratory evaluations for eight different clay soils. Four of these are natural clays obtained from the vicinity of Kansas City. The other four clays were prepared in the laboratory by blending a small proportion of bentonite with kaolinite. These laboratory clays have properties that are easily duplicated, and thus provide standard clays for evaluating efficacy of a particular ash. It is found that compaction delay is an important factor controlling soil stabilization. It is also found that the stabilization characteristics depend significantly upon soil plasticity. Finally, it is observed that long-term performance of fly ash stabilized soil depends upon the curing method and shrinkage crack development. Therefore, construction guidelines best suited for Class C fly ash soil stabilization are outlined. Environmental issues related to utilization of Class C fly ash for soil stabilization are also examined. The related federal and state regulations are presented. The leaching behavior and potential laboratory leaching tests for Class C fly ash are discussed. It is noted that, Class C fly ash, generally, leaches only very small quantities of contaminants of concern. Nevertheless, leaching behavior of each ash must be examined on a case-by-case basis in relation to the background water quality. Standards must be established for these leaching tests with respect to the leaching fluids that best represent the fluids in nature, such as, simulated groundwater or rainwater leachates. These issues are discussed in relation to the federal and state regulations.

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PREFACE

Coal burning utilities in the Midwest are increasingly using sub-bituminous coal from Wyoming. These utilities typically produce fly ash, which, because of its high calcium oxide content, may be classified as Class C fly ash. These ashes are characterized by their self-cementing property and, therefore, they can be used for soil improvement as cement surrogates. This report focuses upon the design, construction and environmental issues pertaining to utilization of Class C fly ash for soil stabilization. The report also gives a description of fly ash physical and chemical properties, with special consideration to high calcium Class C fly ash.

The compaction and strength development behavior of clay soils stabilized with fly ash are investigated. Laboratory evaluations required to obtain efficient fly ash addition rates and compaction procedure are discussed. Examples of laboratory evaluations are presented using eight clay soils. Four of these are natural clays obtained from the vicinity of Kansas City. The other four clays were prepared in the laboratory by blending a small proportion of bentonite with kaolinite. These laboratory clays have properties that are easily duplicated, and thus provide standard clays for evaluating efficacy of a particular ash. It is observed that compaction delay is an important factor controlling soil stabilization. It is also observed that the stabilization characteristics depend significantly upon soil plasticity. Data from the literature as well as laboratory tests performed in this work are presented to affirm these observations. It is also expected that long term performance of Class C fly ash depend upon the curing method and shrinkage crack development. Construction guidelines best suited for Class C fly ash soil stabilization are outlined.

Environmental issues related to utilization of Class C fly ash for soil stabilization are examined. The related federal and state regulations are presented. The leaching behavior and potential laboratory leaching tests for Class C fly ash are discussed. It is noted that, Class C fly ash, generally, leaches only very small quantities of contaminants of concern. Nevertheless, leaching behavior of each ash must be examined on a case-by-case basis in relation to the background water quality. Standards must be established for these leaching tests with respect to the leaching fluids that best represent the fluids in nature, such as, simulated groundwater or rainwater leachates. These issues are discussed in relation to the federal and state regulations.

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1. INTRODUCTION

Fly ash is a mineral by-product that typically results from coal combustion at electric power generating plants. It is one of the most voluminous of the industrial by-products. According to a compilation of production and use trends for coal combustion by-products by American Coal Ash Association (ACAA) released in 1994, almost 50 million metric tons of fly ash are produced in the United States every year. Without question, the disposal of fly ash presents a serious problem in terms of land use and potential environment pollution. Therefore, strong economical and environmental imperatives exist for effective use of fly ash. The ACAA study also reports that only about 24% of the fly ash is utilized in various beneficial applications, such as embankment or fill material, for stabilization of soil subgrades and aggregate road bases, in flowable fills for grouting of subsurface voids, for waste stabilization, as an additive in portland cement concrete, for manufacture of prefabricated structural and masonry units, in plasters, mortars, asphaltic and plastic compositions, and in ceramic products.

In spite of these many applications, the low-level of fly ash utilization may be attributed to a combination of the following three reasons:

(1) *Perception of non-uniformity of the by-product*: By their very nature coal combustion by-products have a variation in properties from plant to plant as well as within a single utility plant. In recent years, efforts have been made by the utilities to minimize the non- uniformity and ensure tight quality control. Nevertheless, due to historical reasons, perceptions persist regarding the non-uniformity of the by-product.

(2) *Inadequate design criteria and quality control guidelines for fly ash utilization*: Although studies on the use of by-products have been conducted, acceptable design criteria and quality control guidelines that address the local conditions in a manner useful to contractors are not

always available. Moreover, even if such criteria have been developed, many times the local contractors and state agencies are unaware of them.

(3) *Environmental concerns*: Coal combustion by-products could potentially contain hazardous, leachable trace metals. This has thwarted automatic permitting of fly ash in usages related to ground/roadbase modification.

This report examines the above issues as they relate to the design, construction and environmental impact pertaining to utilization of Class C fly ash for soil stabilization. The Class C fly ash is produced in voluminous quantities by the coal burning utilities in the Midwest, as a result of burning sub-bituminous coal from Wyoming. These ash, typically, have a high calcium oxide content and are characterized by their self-cementing property. Therefore, these Class C fly ash can be used for soil improvement as cement surrogates. The focus of the report is upon the behavior of Class C fly ash produced by the power plants of Kansas City Power and Light Company (KCPL).

The report is organized into five chapters including the introduction, which is given in chapter 1. Chapter 2 gives a description of fly ash physical and chemical properties, with special consideration to high calcium Class C fly ash produced by the Hawthorn and LaCygne plants of KCPL.

Chapter 3 discusses the compaction and strength development behavior of soils stabilized with Class C fly ash. Laboratory evaluations required to obtain efficient fly ash addition rates and compaction procedure are discussed. Examples of laboratory evaluations are presented using eight clay soils and Class C fly ash from Hawthorn and LaCygne plants of KCPL. Four of these are natural clays obtained from the vicinity Kansas City. The other four clays were prepared in the laboratory by blending a small proportion of bentonite with kaolinite. These laboratory clays have properties that are easily duplicated, and thus provide standard clays for evaluating efficacy of a particular ash. It is observed that compaction delay is an important factor controlling soil stabilization. It is also observed that the stabilization characteristics depend significantly upon soil plasticity. Data from the literature as well as laboratory tests performed in this work are presented to affirm these observations. It is also expected that long term performance of Class C fly ash will depend upon the curing method and shrinkage crack development. Construction guidelines best suited for Class C fly ash soil stabilization are also outlined.

Chapter 4 discusses the environmental issues related to utilization of Class C fly ash for soil stabilization. The related federal and state regulations are presented. The leaching behavior and potential laboratory leaching tests for Class C fly ash are discussed. It is noted that there is a lack of appropriate, standard laboratory leaching test protocol that incorporates the field conditions of stabilized soils. It is also noted that Class C fly ash, generally, and the two KCPL Class C fly ash in particular, leach very small quantities of contaminants of concern.

Finally, Chapter 5 reports the main conclusions and summary of this study.

2. FLY ASH CHARACTERISTICS

Fly ash is typically obtained as a by-product from electricity generating utilities that use pulverized coal powder consisting of 70 to 80% particles passing No. 200 sieve (75 mm). The non-combustible elements in powdered coal evaporate at high temperatures and combine to form a variety of complex inorganic compounds. Upon the cooling of exhaust gases, these compounds cool into fine spherical particles. These particles may be collected using a variety of methods such as mechanical collectors, electrostatic precipitators, fabric filters and wet scrubbers. The fly ash from KCPL, that this report focuses upon, are collected using electric precipitators.

2.1 Particle Morphology

Fly ash appears as a fine powdery material with mainly spherical glassy particles composed of silicon, aluminum and iron oxides. A small amount of irregular shaped particles are also present that consist of unburned coal remains and other minerals. Although fly ash is an extremely heterogeneous material, its particles can be classified into a few major types (Watt and Thorne 1965). The spherical particles are mainly glassy silica with calcium, magnesium, aluminum and iron. The spherical particles consist of glass bubbles (cenospheres), solid spheres, and cenospheres that are packed with smaller spheres (plerospheres). The irregular and angular particles are mainly crystalline materials such as quartz, unburned coal, hematite and sintered agglomerates. It has been observed that fly ash produced by burning western coals have a preponderance of plerospheres (Fisher et al. 1976, Carpenter et al. 1980).

Figures 1 through 3 show the SEM (Scanning Electron Microscope) micrographs for fly ash samples obtained from LaCygne and Hawthorn plants of KCPL. Both the LaCygne and the Hawthorn fly ash samples exhibited similar morphologies which also compare well with the morphologies of fly ash reported in the literature. A majority of the particles, for both these ash, are non-crystalline (glassy) with spherical or sub-spherical shapes. Some of the particles are broken open and some sintered into aggregates. A few plerospheres were could also be identified as shown in Figure 3a. Only a very few irregular and angular shaped crystalline particles, such as that in Figure 3b, could be identified.

2.2 Specific Gravity and Bulk Density

Due to a large variety of particle types and composition, the specific gravity or particle density of fly ash is expected to have large variations. The average density of solid fly ash phases measured by grinding ash to very fine powder has been found to be in the range 2.65 to 2.8 g/cm^3, while the unground average densities have been reported to be in the range 1.9 to 2.8 g/cm^3 (Helmuth 1987). The variation in the specific gravity is primarily due to the composition, especially the proportion of iron and carbon. In Table 1, typical specific gravity values are listed for a variety of fly ash along with the LaCygne and Hawthorn ash.

A review of the literature indicates that the bulk density of different fly ashes also varies over a large range, from 0.5 to 0.9 g/cm^3. The bulk density variation reflects the compaction conditions which are not same for the measurements in the literature. The bulk density of Hawthorn fly ash has been measured to be 0.75 g/cm^3 and of LaCygne fly ash to be 0.8 g/cm^3.

2.3 Grain Size

Fly ash grain sizes range from less than 1mm to greater than 1 mm. Several variables affect the grain size distribution and fineness of fly ashes, including, coal sources, combustion conditions, and ash collection systems. For a particular power plant, the variability of fly ash fineness depends primarily on the variations in operating loads. The grain sizes in fly ash are usually difficult to determine because of the properties of fly ash as well as the inadequacies of the measurement methods. For fly ashes, the grain sizes are typically specified in terms of: (I) fineness, (ii) specific surface, and (iii) cumulative grain size distribution curves.

Fineness is a measure of grain size that has implication upon the use of fly ash in the treatment of soils. Some measure of fineness is included in virtually all standard specifications regarding fly ash. Data in the literature suggests that fineness of fly ash is one of the most difficult properties to measure reliably. Even fly ash from a single source can have vastly different fineness values over both short and long time periods. The simplest and perhaps the most reliable measure of fineness is the amount either retained on or passing through a certain size sieve. ASTM C 618 specifies the fineness in terms of amount retained on No. 325 (45 mm) sieve, which should be no more than 34% by weight. Clearly, it would be useful to have complete information in form of cumulative grain size distribution curves which show the amount finer (or coarser) than any particular size over the entire range of sizes. Unfortunately, the grain size distributions for fly ash are not readily obtained.

Specific surface, defined as the total surface area per unit weight, is another indirect measure of particle sizes. Thus, the finer particles have higher specific surface areas. Several methods have been used to measure specific surface area of a powder material, namely, wet sieve, turbidimeter, air permeability, hydrometer, and microscope count methods. These methods may also be used to determine grain size distributions. Data in the literature shows large discrepancies between grain size distributions of fly ashes determined by different methods. Figure 4 gives a plot of typical variation in grain size distributions for fly ash based upon data in the literature. Since the densities, refractive indices, and resistivities of fly ash particles vary considerably, even modern automated sedimentation, laserlight scattering, or particle counter instruments cannot be yield highly accurate results for fly ash unless special procedures are used or corrections made.

2.4 Chemical Composition

Fly ash is composed of mineral matter contained in coal which melts at the high temperatures of the combustion chamber and upon rapid cooling forms tiny spherical particles. These particles are mainly comprised of silica and alumina glass. Other constituents present in fly ash are compounds of iron, magnesium, calcium, sulfur, alkalis and unburned carbon. The color of fly ash ranges from tan to gray depending on relative proportions of lime and carbon content (Minnick, 1959; NCHRP Synthesis Report 37, 1976; Manz, 1976: Roy, et. al. 1981; boles, 1986). Fly ash composition is affected widely by a lot of variables such as coal compositions, combustion conditions, and ash collection systems. Table 2 summarizes the chemical composition of various fly ash, based upon the data available in the literature.

Considering calcium oxide (CaO) content, fly ash are categorized as: (1) low (<10% CaO), (2) medium (10-20% CaO), and (3) high (>20% CaO) calcium fly ash. Furthermore, depending upon the relative amounts of the major chemical constituents, fly ash may be classified as Class C and Class F. Fly ash containing more than 50% but less than 70% of silicon, aluminum and iron oxides (SiO_2+Al_2O_3+Fe_2O_3) are classified as Class C. If the sum of these three oxides exceeds 70% then a fly ash is classified as Class F (ASTM C618_85, 1985). Thus the medium and high calcium fly ash are considered as Class C fly ash. As seen from Table 2, the combustion of Western coal (a sub-bituminous coal) typically produces a Class C fly ash. The two KCPL ash that are derived from Western coals may also be classified as Class C fly ash.

The chemical analysis of the KCPL ash indicates that the Hawthorn fly ash has more silica (SiO_2) and less CaO compared to the LaCygne fly ash. X-ray microanalysis given in Figures 5 and 6, of the samples imaged in Figures 1 and 2, show that the glassy fly ash particles are primarily composed of aluminum and calcium with minor amounts of silicon (Si), iron (Fe) and copper (Cu). This seems to indicate that most of the silica is in the form of crystalline quartz. The X-ray microanalysis also shows that the glassy particles of Hawthorn ash have a relatively smaller proportion of calcium than the LaCygne ash. It was also observed that the LaCygne sample has a trace amount of titanium (Ti) while the Hawthorn sample has a trace amount of chromium (Cr).

Class C fly ash, such as the Hawthorn and LaCygne ash, contains sufficient calcium and other compounds to induce a cementitious reaction in the presence of water. These self-cementing characteristics make these fly ash applicable to a wide range of construction applications as a cementing agent. Therefore, it is instructive to compare the oxide composition of fly ash with those of portland cement, natural cement and quick lime as shown in the ternary diagram in Figure 7. The LaCygne fly ash has chemical characteristics that are closest to the portland cement. As expected, the low calcium ash are predominantly composed to pozzolanic materials in form of oxides of silicon, aluminum and iron.

3. SOIL STABILIZATION USING CLASS C FLY ASH

Soil stabilization collectively describes the physical, chemical and biological methods, or combination of these methods, employed to alter soil properties. The different uses of soil puts different requirements of mechanical strength and resistance to environmental conditions. The term soil stabilization possesses a definite meaning only if the nature of the soil, the engineering requirements, and the environmental conditions are properly identified. Soil stabilization may include regional or mass soil densification, reinforcement, cementation, and control of drainage and volume stability of soil. The foundation or base soils may be manipulated with or without admixtures, to increase their load-carrying capacity and resistance to physical and chemical stress for the service life of the engineered facility. Properties of soil, such as, strength, stiffness, compressibility, permeability, workability, swelling potential, frost susceptibility, water sensitivity, and volume change tendency may be altered by the various soil stabilization methods. These methods can range from preparation of soil-aggregate and simple compaction, to application of admixtures, to thermal and electrokinetic methods.

Class C fly ash soil stabilization involves mixing pulverized soil, ash and water, and subsequently compacting the mix to a high density. Depending on the type of soils, class C fly ash soil stabilization occurs via different mechanism. The stabilization mechanism is of grave interest since Class C fly ash behaves like a mixture of cementitious and pozzolanic materials, i.e. a portion of ash hydrates like portland cement in presence of moisture, while the remainder is typically reactive aluminous-silliceous oxides like those found in pozzolans. This suggests that the Class C fly ash stabilization should be studied along the lines of soil-cement stabilization.

3.1 Applications of Class C Fly Ash Soil Stabilization

Class C fly ash may be used in a variety of soil stabilization applications, ranging from soil drying to production of high strength soil sub-grade.

3.1.1 Drying agent

One of the early applications of self-cementing fly ash was as a drying agent to facilitate soil compaction. Due to its hydration characteristics, the addition of Class C fly ash can provide an immediate drying effect and reduce the moisture contents to levels suitable for compaction. Application of fly ash can reduce moisture content in the soil by 10 to 20%. Thus the soil is available for final compaction in a short time.

3.1.2 Reduction of swell potential

Class C fly ash soil treatment can been used effectively to reduce shrink-swell potential of clay soils instead of the traditional lime treatment method. It is noteworthy that due to the lower calcium ion concentration, the effect to reducing the Atterberg Limits is less than that observed with lime stabilization. The additional flocculation of the clay minerals happens as a result of bonding of the soil particles by the cementitious products formed during hydration of the fly ash. It will contribute to the reduction of swell potential. So the fly ash may have the equal ability to reduce the Atterberg Limits as lime.

Literature laboratory tests show that fly ash treated soil will significantly reduce the swell potential comparing to the untreated materials.

3.1.3 Stabilization to increase shear strength and subgrade support capacity

Class C fly ash can be used in the construction of stabilized section that an increase in shear strength is needed. Such applications include stabilized base or subgrades for pavements, stabilization of backfill to reduce lateral earth pressure and stabilization of embankments to improve slope stability. Due to the rapid self-cementing properties, it is important to control the moisture content and compaction delay.

3.1.4 Stabilization of erodible soil

Class C fly ash can provide an enough array of cations which can enhance the flocculation of fine clay particles, therefore, the unstable clay soils can be stabilized effectively by cation exchange inside the soil structure. There are a lot of chemical methods that can be used to the purpose of stabilization of unstabilized soils. Such as cement and lime treatment. However, this traditional methods cannot be considered as cost effective. Therefore, the widely utilization of Class C fly ash as an effective soil stabilization agent is very attractive.

3.2 Design Issues

Class C fly ash behaves like a mixture of cementitious and pozzolanic materials, i.e. a portion of ash hydrates like portland cement in presence of moisture, while the remainder is, typically, reactive aluminous-silliceous oxides like those found in pozzolans. Considering the Class C fly ash behavior when exposed to moisture, there are several issues that must be thoroughly investigated to achieve proper soil stabilization. It is reasonable to expect that these design issues are similar to those for soil-cement stabilization. Among the issues of concern are: ash contents and water requirements, effect of compaction delay and procedure, strength development with time, curing methodology, and shrinkage cracking.

Fly ash content and water requirements depend upon ash characteristics as well as the type of soil to be stabilized. Laboratory tests using particular soil and fly ash are required to obtain the optimal ash content and water requirement for a required application. Since the hydration reactions for Class C fly ash are rapid, time delay is an important factor that influences the compaction control and procedure. In order to obtain optimal improvements in the properties of fly ash stabilized soils, such as increase in compressive strength, a high degree of compaction and short time delay from mix to compaction are required. Thorough pulverization of the soil and intimate mixing with the fly ash is also essential to ensure best stabilization results. Since hydration reaction can occur over a long period of time, long term strength gain is expected for soils stabilized with Class C fly ash.

However, in practice this gain is considered a “bonus,” and typically the benefits of long term strength gain are ignored. Consequently, very little attention has been paid to curing strategies for Class C fly ash stabilized soil. Finally, it is expected that for a soil stabilized with cementitious products, long-term shrinkage cracks may develop. These shrinkage cracks may be detrimental to the stabilized soil properties in the long term.

This work addresses some of these design issues as related to the use of Class C fly ash for stabilizing clay soils. As mentioned previously, both fly ash and soils exhibit large variation from source to source, therefore, each stabilization application must be examined individually. Nevertheless, general guidelines and testing procedure may be developed that appropriately address the aforementioned issues. In the subsequent sections, we present laboratory evaluation procedures and results, as well as construction guidelines for Class C fly ash soil stabilization, based upon case histories culled from the literature as well as laboratory test results obtained in this work. It is noted from the literature that Class C fly ash soil stabilization has been in the vast majority of cases applied to clay soils. Very little work has been reported for silty soils or sandy silts.

3.3 Laboratory Evaluation of Class C Fly Ash Soil Stabilization

The design issues for Class C fly ash soil stabilization may be addressed via laboratory experimentations. In this work, laboratory experiments were performed to study the changes in soil engineering properties with the addition of Class C fly ash as a stabilizing agent. Moisture-density relationships and unconfined compressive strengths were measured for eight types of clay soils blended with Class C fly ash. The fly ash used in these experiments was obtained from the Hawthorn and LaCygne plants of Kansas City Power and Light Company. The characteristics of these fly ash are tabulated in Table 1 and 2. The index properties and compaction characteristics of the soils used in this work are given in Table 3. The moisture-density relationships for soil-fly ash blends containing 0%, 10% and 20% fly ash by weight were measured. The stress-strain behavior of these soil-fly ash blends under unconfined compressive loading were also obtained for samples prepared with no delay, 2 hours delay and 4 hours delay between blend preparation and compaction. The samples for unconfined compression tests were compacted with moisture content in the range of ±7% around the optimum moisture content. The compacted samples were cured for seven days at 38 ^{o}C.

The lab clays in Table 3 were obtained by adding known amounts of bentonite to powdered calcium-kaolinite. Bentonite contents of 0, 2, 4 and 6 percent by weight were used for lab clays 1, 2, 3 and 4, respectively. Bentonite and kaolinite represent extremes of clay behavior in terms of clay activity in presence of moisture. While bentonite is a highly active clay composed mainly of very active sodium-montmorillonite, kaolinite is the least active of clay minerals. A study of the properties of known bentonite-kaolinite mixtures has been presented by Misra et al. (1996). In this work, these clay blends were used to provide clays whose properties can be controlled and repeated, a feat not easily attained for natural clays which typically have a large variation. The natural clays used in this study were obtained from areas in the vicinity of Kansas City.

3.3.1 Experimental Procedure

A few points must be carefully considered when utilizing the usual laboratory procedures for obtaining moisture-density relationships and unconfined compressive stress-strain behavior of soils treated with Class C fly ash. These particularly deal with the sample preparation, compaction procedure and time requirements, and curing procedure for samples for unconfined compression tests. The laboratory procedure used in this work for the moisture-density and unconfined compression tests is enumerated as follows:

1. The sample natural soils are ground up and passed through a No. 4 sieve. If necessary, the samples are then laid out in flat pans and allowed to room dry for two weeks, following which, the soil samples are powdered in a pulverizer. The use of powdered soil makes it easier to blend soil and fly ash, thus ensuring, that the fly ash is distributed evenly throughout

the soil sample. The soil-fly ash blends are prepared prior to the addition of water for subsequent testing.

2. Index property tests are performed on each soil in accordance with ASTM D4318.

3. Moisture-density relationship are measured via appropriate compaction test, such as, Standard Proctor tests (ASTM D698) performed upon natural soils C and D and Harvard miniature tests performed upon lab clays 1, 2, 3, 4, and natural soils A and B. These tests are performed on all the eight soils at 0%, 10% and 20% fly ash content. Moisture content of air-dried soils and lab clays is obtained before performing the compaction tests. This starting moisture content is used for calculating the amount of water to be added to each compaction specimen. The desired amount of fly ash, measured as percent of dry soil by weight, is then mixed thoroughly to produce a homogeneous soil-fly ash blend. Wetting of the sample soil is accomplished by spreading the soil-fly ash blend in a fairly large pan. The calculated amount of water is weighed and added very evenly over the surface. At first, only half of the required water is added to the soil-fly ash blend which is then mixed thoroughly into a homogeneous mix. The remaining half of the water is then added and mixing process repeated. The mixed soil-fly ash samples are placed in suitable sized plastic cups and covered in order to avoid evaporation. The samples are cured for a selected delay time of 0 hours, 2 hours and 4 hours. The soil-fly ash blends are then compacted in three layers using 25 blows per layer for both the Standard Proctor and Harvard miniature tests.

4. Unconfined compression test are performed on compacted soil-fly ash blend samples. The compaction moisture content is taken in a range of ±6% around the optimum moisture content corresponding to the maximum dry density. The moisture content is varied with the aim of ascertaining the optimum moisture content that corresponds to the maximum unconfined compressive strength. Usually, six different moisture content are used to make

the samples. One to three specimens are made for each soil-fly ash blend. These specimens are compacted in the same manner as the moisture-density samples and moisture samples are taken from the trimmings of these samples. The time between mixing of soil-fly ash blends and compaction is carefully monitored. Each specimen is then sealed in a suitable size plastic (Ziploc) bag and placed in an oven at 38 ^{o}C (100 ^{o}F) immediately after compaction. These specimens are cured in the oven for seven days and subsequently tested for unconfined compressive strength. The unconfined compressive strength test were performed using a triaxial test apparatus as per ASTM D2850-87. The stress-strain relationships are recorded by computer using an automatic data acquisition system. The moisture content of the cured samples were also measured for comparison with the compaction moisture content.

3.3.2 Maximum dry density and optimum moisture content

The results obtained from the Harvard miniature compaction tests on soil-fly ash blends are plotted in Figures 8 and 9 for natural soils A and B containing 10% and 20% fly ash from KCPL's LaCygne plant. The results of the compaction tests are summarized in Tables 4 and 5. Two series of compaction tests were performed for soil B under similar conditions. As seen from Figure 9, the results almost coincide, indicating minimal operator error and the ability to obtain repeatable results, which is very important for obtaining reliable information from compaction tests.

It is quite apparent that the addition of fly ash to soil changes its compaction characteristics, although the general compaction behavior is same as that of typical fine-grained soils. The soil-fly ash blends typically have a different maximum dry density and optimum moisture content. In addition these blends exhibit dependence of compaction behavior upon the delay between blend preparation and compaction. Moreover, the change in compaction characteristics depend upon the soil type. The soil-fly ash blends using soil A, which is described as silty clay, have a lower optimum moisture content than those using soil B, which is described as clayey silt. In contrast, the maximum dry density for soil B-fly ash blends is found to be higher than that for soil A-fly ash blends.

Figures 8 and 9 also show that compaction delay can have serious impact upon the moisture-density relationship of clays stabilized with Class C fly ash. It is observed that the maximum dry density, generally, occurs at a lower optimum moisture content for the case of no delay. When a compaction delay happens, the optimum moisture content typically increases by about 1 to 4 percent. The results also show that upon delay, the compaction is difficult and the maximum dry density achieved is 5 to 10 percent lower. The decrease in the maximum dry density and the increase in optimum moisture contents, upon delay, is attributable to the self-cementing nature of Class C fly ash. Upon exposure to moisture, even for very short times, Class C fly ash quickly hydrates to form partial cementitious structure. Although the complete process of hydration takes a long time to complete, the major action seems to occur in the first few hours. Therefore, the delayed blends need more moisture as lubricant to avoid the friction between the surfaces of cementitious structures.

The maximum dry density as well as the optimum moisture content significantly depend upon the ash content as depicted in Figures 10 and 11. A higher maximum dry density is obtained by increasing the fly ash content under the condition of no delay. However, the dry density increase diminishes with the increase in fly ash content beyond certain fly ash content, typically around 10%. Above this fly ash content the dry density shows a only a small increase and, for some soils, even a slight decrease as seen in Figure 10. Upon compaction delay, as shown in Figure 10, the maximum dry density decreases dramatically for all the natural soils-fly ash blends.

On the other hand, the optimum moisture content decreases with fly ash content for the condition of no compaction delay as shown in Figure 11. However, as in the case of maximum dry density, the optimum moisture content has only a slight decrease and, for some soils, even an increase beyond ash content of ~10%. Upon compaction delay, the optimum moisture content increases for all soil types tested as seen from Figure 11.

3.3.3 Stress-strain behavior of stabilized soil

Unconfined stress-strain behavior of the various soil-fly ash blends compacted at different moisture contents were measured in a triaxial machine as described in a previous section with a loading rate of 0.5 mm per minute. The results of these tests are given in Figures 12 through 15 for natural soils A and B. The stress-strain behaviors are plotted for a given fly ash content for samples compacted at various moisture contents and cured for 7 days. The moisture contents measured at the end of compression tests for the cured samples are noted on the figures. It is noteworthy that the moisture contents of the cured samples are within 5% of their compaction moisture content, which indicates a very small loss in moisture during the curing process.

As seen from Figures 12 through 15, the addition of Class C fly ash to soil, generally, results in a stiffer and stronger material. A comparison of stress-strain curves in Figure 12a and 12b shows that upon addition of 10% fly ash the stabilized soil becomes stiffer, stronger and more brittle at all compaction moisture contents. It is noted that the untreated soil is very brittle at moisture contents below the optimum moisture content of 16% for soil A. Above the optimum moisture content, the stress-strain behavior is quite ductile (plastic) as seen in Figure 12a. On the other hand, the behavior of stabilized soil is quite different in that it is very brittle even at moisture contents above the optimum moisture content of 15% for soil A-10% fly ash blend compacted with no delay as seen in Figure 12b. Similar brittle behavior is exhibited by soil A-10% fly ash blends compacted at 2 hour and 4 hour delays. Only at very high moisture contents does the behavior tends to be ductile (plastic). It is also remarkable that samples prepared with delayed compaction always have a lower strength than the samples prepared with no delay. However, no definite trends are observed with respect to the stiffness of these samples. Nevertheless, the stiffness of all treated samples are greater than the untreated samples. Similar behavior is observed for soil B as seen from Figures 14 and 15.

Comparison of Figures 12 and 13 indicates, that soil A treated with 20% fly ash is generally more brittle than with 10 % fly ash. The strength and stiffness are also generally higher for samples with more fly ash. Similar behavior is observed for soil B as seen from Figures 14 and 15.

3.3.4 Unconfined compressive strength

The unconfined compressive strength is often taken to be the parameter by which the mechanical characteristics of a subgrade is judged. In Figure 16 and 17, the unconfined compressive strength, obtained as the highest axial stress point from stress-strain curves in Figures 12 through 15, is plotted against the moisture content of the cured sample. Interestingly, the unconfined compressive strength shows a strong dependence on moisture content. The strength increases up to a certain moisture content and then decreases, such that an optimum moisture content, corresponding to the maximum unconfined compressive strength for the soil-fly ash blend, may be defined. These optimum moisture contents are tabulated in Tables 4 and 5 along with the maximum unconfined compressive strengths for the various soil-fly ash blends. It may be recalled that there is only a negligible difference between the cured moisture contents and the compaction moisture contents for these samples. Therefore, it is noteworthy that the optimum moisture content corresponding to the maximum compressive strength is generally 3 to 4 percent smaller than the compaction optimum moisture content corresponding to maximum dry density. Thus, stronger soil-fly ash blends are obtained by compacting on the drier side of (at moisture contents lower than) the compaction optimum moisture content.

Fly ash content has a significant influence on the strengths of soil-fly ash blends. The effect of fly ash content on strength gain is depicted in Figure 18, which gives a plot of the maximum unconfined compressive strength versus fly ash content. For soil A, the unconfined strength increases almost linearly with fly ash content up to 20%. For soil B, on the other hand, the strength increase is not always linear. While a strength gain of almost 3 times is attained by adding 10% fly ash under no delay conditions, the addition of another 10% increases the strength by only 1.17 times. This result seems to indicate that for clayey soils, the maximum stabilization benefits are realized with fly ash content around 10%, while for silty soils, maximum stabilization benefits may be realized with fly ash contents even exceeding 20%. Further testing, with intermediate fly ash contents and particular soil, may be required to clearly resolve the optimal ash content for efficient stabilization.

As seen from Figure 18, compaction delay time is also a major factor that influences the stabilization potential of Class C fly ash. The 10% and 20% fly ash-soil A blends prepared at compaction delays lost 38% and 50% potential strength, respectively, compared with samples compacted at no delay. For Soil A, compaction delay times of 2 hours and 4 hours produced almost same results. For Soil B, on the other hand, a 2-hour compaction delay resulted in a loss of 40 %, while a 4-hour delay resulted in a loss of 50% potential strength. In spite of these difference in behavior of the two soils, it is important to note that a compaction delay of 2 hours results in a considerable loss of potential strength and any further delay is likely to produce additional loss in potential strength.

The compactibility and strength gain for soil-fly ash blends are related in an interesting way as depicted in Figure 19, which gives a map of the maximum unconfined compressive strength, maximum dry density and optimum moisture content for various compaction delay times with increasing fly ash content. It is noticed that for no compaction delay considerable strength gain may be achieved with only a small increase in densification and a small decrease in water requirement as shown in Figure 19 by filled and hollow circles for soils A and B, respectively. Upon compaction delay, however, it is difficult to compact the soil-fly ash blend even with increased moisture contents. In addition the strength gain is also fairly low as shown by filled and hollow squares and triangles in Figure 19.

3.3.5 Relationship of plasticity index and strength gain characteristics

The unconfined strength of fly ash stabilized clay normalized by the unconfined strength of unstabilized clay is plotted against the plasticity index in Figure 20. The results obtained from the tests performed in our work suggests that the stabilized fat clays have a lower strength gain than the stabilized lean clays as illustrated by hollow squares in Figure 20. It is believed that for lean clays, the cementitious ingredients of Class C fly ash act primarily to cement the less active clay and silt particles. While for fat clays, which contain more active clay minerals, some of the cementitious ingredients will be used for altering the clay physico-chemical characteristics. However, contrary results have been reported by Ferguson (1993), wherein clays with high plasticity index show a greater strength gain than the clays with lower plasticity index as shown by the filled squares in Figure 20.

3.3.6 Long term strength development and degradation

Since hydration reaction can occur over a long period of time, long term strength gain is expected for soils stabilized with Class C fly ash. It is also expected that for a soil stabilized with cementitious products, long-term shrinkage cracks may develop. These shrinkage cracks may be detrimental to the stabilized soil properties in the long term. Little data exists in the literature regarding this long-term behavior.

3.4 Construction Guidelines

To obtain the best results of Class C fly ash soil stabilization, clear and consistent construction guidelines must be followed. Based upon the information culled from case studies and specification developed by various agencies (Sharp 1993, AASHTO, ASTM, EPRI), an outline of construction guidelines are presented hereafter. It is noted that the Class C fly ash treated soil must comprise of a uniform fly ash and soil mixture with no loose or segregated areas. It should have uniform density and moisture content. The surface of the treated soil should be smooth. A detailed construction sequence must be specified along with the proper amounts of Class C fly ash and water requirements to obtain effective soil stabilization.

3.4.1 Preparation of subgrade

Any unsuitable soil or other material, for example, organic soils, debris etc., must be removed and replaced with suitable soil, if necessary. The subgrade must be suitable to enable in-place fly ash treatment, i.e. the subgrade should be firm and have enough stability to support the construction equipment. If the subgrade is not suitable, some engineering improvement must be performed to correct the situation.

3.4.2 Application of Class C fly ash

The fly ash must be spread by an approved spreader or by bag distribution at the rates shown on the plans. It is generally recommended that a motor grader be not used to spread the fly ash. It is critical that the fly ash be distributed uniformly on the site. The scattering of fly ash by wind must be restricted to a minimum and the use of fly ash on a windy day should be avoided.

The initial mixing upon the addition of fly ash is best accomplished dry or with a minimum water to prevent the fly ash from balling-up. For the final mixing, the soil-fly ash blend may be sprinkled until the designed moisture content has been obtained. The final moisture content of the mix before compaction should be within +2% to -4% of the optimum moisture content. If the natural moisture content of the soil be above the specified range, soil must be aerated before the addition of the fly ash.

3.4.3 In-situ mixing of soil-fly ash blend

The soil and fly ash must be thoroughly mixed by a specified engineering equipment. Care must be taken to ensure that the final mixture is homogeneous, of uniform color and friability, and without clods and lumps. The amount of water required to achieve the specified moisture content of the mixture should be added using a spreader after the initial mixing of soil and fly ash. It is good practice to add the water in installments by passing the spreader over the site several times.

If the soil-fly ash mixture includes clods, a reduction is clod size may be accomplished via one or a combination of the following techniques: raking, blading, disking, harrowing, scarifying or the use of other approved pulverization methods. The soil-fly ash blend should be such that when tested at the field moisture condition or dry by laboratory sieves, 100% must pass 1-3/4 inch sieve and a minimum of 60% must pass No. 4 sieve.

3.4.4 Compaction of soil-fly ash blend

The soil-fly ash blend must be compacted at or near the optimum moisture content. Compaction should commence immediately after the addition of water to the blend and it must be completed within 2 hours. It is also recommended that laboratory test be conducted to determine the permitable time lapse for every specific project.

The soil-fly ash mix should be compacted in layers to the specified density. All unsatisfied section which are too wet, too dry or insufficiently treated must be improved. The improvement may be accomplished by loosening the affected areas, adding or removing material as required and reshaping and recompacting by sprinkling and rolling to meet the requirements. The final surface of the course should be smooth, without undulations and ruts.

Guidelines detailed in ASTM D1557 may be followed for specifying the compaction criterion. On completion of a section, sample tests must be made by the supervising engineer. If the sample fails to meet the density requirements, the engineer may require the area to be reworked as necessary to meet the requirements. Some times the construction method may be altered to satisfy the requirements. In any case, blading must be terminated within 2 hours after blending of the fly ash with soil. If for some reason, the soil-fly ash blend loses the required stability and density, it should be reprocessed. Reprocessing should follow same construction guidelines as the initial stabilization including the method of fly ash addition.

3.4.5 Finishing, curing and preparation for surfacing

For certain applications, the fly ash stabilized soil needs to be finished for further construction, such as, for sub-base etc. It has been noticed that the compaction of certain fly ash stabilized soils results in the formation of horizontal shear planes, which, consequently, produces thin platy structures in the upper compacted layers. In these conditions, light scarification with a spike-toothed harrow, weeder, or nail drag is recommended. The loosened material may be, subsequently, moistened and recompacted with a pneumatic-tire roller of sufficient weight.

The surface of the compacted fly ash stabilized subgrade material should be kept moist during the initial curing period. Typically, the curing time depends upon the rate of strength development of the soil-fly ash mix. A bituminous seal coat can be applied to seal-in the moisture or the subgrade can be continually moistened using a water truck to prevent drying of the surface. Generally, the curing period should be extended until base course strength development has achieved design value. Otherwise, heavy construction vehicles should be kept off of the stabilized subgrade material.

4. ENVIRONMENTAL ISSUES

Since Class C fly ash is produced as a waste by-product of coal combustion, it is considered to be a potential pollutant. Fly ash from certain types of coals have been known to leach substantial amounts of trace metals that may be considered hazardous (see for example Garcez and Tittlebaum 1984, Atalay and Laguros 1990). Almost all fly ash are expected to contain trace amounts of several heavy metals. The degree of leaching of heavy metals is an important factor of concern with regards to environmental problems. It is also noteworthy that the leaching quality of ash may change when is added to soil. It is expected that the change in leaching quality will depend upon the soil type, with clay soils having the most impact.

In the subsequent sections, we consider the environmental regulations as well the polluting potential of Class C fly ash, especially in the context of its application as a soil stabilizing agent.

4.1 Regulatory Background

Fly ash has been applied to construction applications even before the formation of U.S. Environmental Protection Agency (EPA). Nevertheless, in recent years, the environmental impact of fly ash has been a topic of much discussion and debate among the regulatory agencies.

4.1.1 Federal regulations

At the federal level, the two environmental statutes under which fly ash utilization may be regulated are: (1) the Resource Conservation and Recovery Act (RCRA) and, (2) the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). Pursuant to Bevill amendment of 1980, the EPA conducted a study of the environmental impact of coal combustion by-products. Subsequently a regulatory determination of wastes from coal combustion by electric utilities was issued by the EPA (Federal Register 1993). The EPA report found the utilization of coal combustion by-products to have limited risk and the regulation of these materials under Subtitle C of RCRA unwarranted. The EPA report encouraged the beneficial use of coal combustion wastes.

Although fly ash is considered to be non-hazardous under RCRA, it may still be regulated by the Superfund liability provisions of CERCLA. This is because the EPA considers these provisions to be applicable for both disposal as well as recycling of wastes and by-products. In recent years, CERCLA recycling amendments have been proposed. These amendments are based upon EPA regulatory determination (Federal Register 1993). However, the environmental liability aspect has been one of the important factor inhibiting increased utilization of fly ash as identified in the U.S. Department of Energy (DOE) report to the U.S. Congress on the barriers to use of coal combustion by-products (DOE 1994).

4.1.2 State agency regulations

The state agencies, have normally exercised local oversight on regulations governing fly ash utilization. Herein, we describe the regulations in selected mid-western states regarding the use of Class C fly ash for soil stabilization.

<u>State of Kansas</u>: The regulatory agency is the Kansas Department of Health and Environment. The department has no regulations with regards to the utilization of Class C fly ash as a soil stabilization agent.

<u>State of Missouri</u>: In the state of Missouri, the concerned regulatory agency is the Division of Environmental Quality in the Department of Natural Resources. The Solid Waste Management Program of the Division of Environmental Quality is currently engaged in drafting regulations under 10 CSR 80-2.020, that deal with permits for fly ash usage. Section 9 of 10 CSR 80-2.020, describes the various conditions under which permit exemption may be granted for utilization of Class C fly ash in road base, structure fills, and soil stabilization. The following exemption specifically applies to utilization of Class C fly ash for soil stabilization:

> *“The beneficial use of type C fly ash for soil amendment will be allowed if the total mixture of soil and ash will not exceed six inches. The beneficial use of type C fly ash for soil stabilization will be allowed provided the fill area is less than five acres in size and the maximum depth of ash will not exceed two feet. General exemptions will be issued on an annual basis and the applicant must apply to renew the exemption at least 30 days prior to the exemptions expiration.”*

For the use of ash in amounts greater than specified above, permit or exemption is needed from Missouri Clean Water Commission. The following statute governing permit exemption is contained in 10 CSR 20-6.015:

> *“(A) De minimis exemption. Persons may apply to the department for an exemption as a de minimis source for operations that will not discharge or will have a negligible environmental impact. The department shall make a determination on a case-by-case basis. This determination shall consider the potential for releases to surface water and groundwater of contaminants in concentrations exceeding background water quality levels or limitations in the water quality standards rule under 10 CSR 20 Chapter 7, whichever is more stringent. Testing of total and leachable concentrations of pollutants as compared to background levels in soils and/or wastes of the state shall be submitted as determined necessary by the department.”*

4.2 Laboratory Methods for Leaching Behavior of Fly Ash

A number of laboratory tests have been developed for evaluating the leaching behavior of solids, which may be applied to study fly ash. These tests may be classified into two main categories: (1) batch leaching method, and (2) column leaching method.

4.2.1 Batch leaching method

Batch leaching test methods include single batch extraction method and sequential batch extraction methods. For both of these, single or sequential, batch methods a variety of leachant or extraction fluid with varying pH may be utilized. Typical leachant include water and buffered acidic extraction fluids.

In these extraction methods, a representative sample of the waste is pulverized into a fine powder. A known weight of the powdered solid waste is then combined with the leachant in a 20:1 liquid to solid ratio. The mixture is, typically, agitated for 18± hours using an end-over-end agitator. A tolerance of anywhere from 0.25 to 2 hours is allowed for agitation time. The resulting mixture is then filtered through a filter paper and the filtrate used to analyze the leachate for contaminants of concern. In the single batch extraction method this procedure is performed once, while in the sequential method, the waste residue on the filter paper is combined again with the leachant and the extraction procedure repeated several times (typically, 10 times). The detailed description of these test procedures are contained in the following ASTM and EPA test standards:

(1) Standard test method for single batch extraction method for wastes (ASTM D5233-92).
(2) Standard test method for sequential batch extraction of waste with acidic extraction (ASTM D5284-93).
(3) Standard test method for sequential batch extraction of waste with water (ASTM D4793-93).
(4) Standard test method for shake extraction of solid waste with water (ASTM D3987-85).
(5) Toxicity characteristic leaching procedure (EPA Method 1311, TCLP).

It is noteworthy that ASTM D5233-92 and the EPA TCLP test procedure are almost identical.

4.2.2 Column leaching method

In column leaching tests, an aqueous extraction fluid (for example, distilled water) is passed through waste materials of known mass in a saturated up-flow mode. An analysis of the column effluent then provides the required information on the leaching characteristics of waste under the conditions used in the test.

In this extraction method, a representative sample of the waste is prepared taking into account factors such as curing, moisture content and density. The waste material is packed into a column ensuring that a uniform density is achieved throughout the column length. In order to replicate the physical and chemical state representative of the waste as it undergoes leaching in the field, curing for sufficient duration under appropriate conditions may be carried out. The column is then connected with the effluent structure containing distilled water at a certain pH value and the waste allowed to saturate under a back-pressure. Subsequently, an up-flow regime is established by appropriately controlling the hydraulic gradient. Typically, in the column leaching experiments the flow rate is maintained at a certain value. A detailed description of the column leaching test procedure is contained in the following ASTM test standard:

(1) Standard test method for leaching solid waste in a column apparatus (ASTM D4874-89).

4.2.3 Leachant or extraction agent

A variety of leachant have been developed and suggested for the laboratory leaching experiments described above. For the batch extraction tests, such as the EPA TCLP test, two types of leachants have been specified with the view of simulating leaching behavior in a landfill under conditions of co-disposal. The first type is a buffered acidic leachant prepared with 5.7 ml of galcial acetic acid per liter of distilled deionized water. The pH of this leachant is adjusted to 4.93±0.05 by addition of 64.3 ml of 1N sodium hydroxide solution. The second type of leachant is an acetic acid solution prepared by diluting 5.7 ml of glacial acetic acid to a volume of 1 liter with distilled deionized water such that the pH of the leachant is 2.88±0.05.

The acidic leachant are not always considered appropriate, although they have been widely adopted by state agencies for evaluating the leaching behavior of a wide variety of solid materials.

Quite clearly, these leachant are not appropriate for evaluation of the leaching behavior of fly ash, especially when considering its utilization as a soil stabilization agent. For these conditions, the synthetic groundwater leaching procedure (SGLP) along the lines of ASTM D3987-85, has been suggested as the more appropriate alternative. The SGLP procedure follows a similar protocol as the EPA TCLP test, except it uses a leachant whose chemistry is designed to replicate the actual field leaching conditions. For fly ash utilized as soil stabilization agent, the most likely source of water would be rainwater. Hence, in this case rainwater or distilled deionized water may be utilized as the leachant.

4.3 Leaching behavior of fly ash

A large number of factors affect the leaching behavior of fly ash. Among these, the most significant are considered to be leachant chemistry, leaching method, prior exposure to water and utilization method. To investigate the effect of leachant on the leaching behavior, Hassett (1994) performed single batch extraction tests on fly ash using the two EPA TCLP leachants as well as distilled deionized water leachant. Wasay (1992) has reported results for both single batch and column leaching tests using leachants of differing pH values. Gareez and Tittlebaum (1984) studied the leaching behavior of Class C fly ash and stabilized soil using a synthetic acid rain leachant and sequential batch extraction with 24-hour agitation and 4 extractions. Field scale case studies have also been reported on leaching behavior of fly ash utilized for road construction (EPRI 1995).

Although only limited studies are available in the literature, these are nevertheless instructive from the viewpoint of assessing the suitability of the leaching tests as well as the potential pollutant capacity of Class C fly ash.

4.3.1 Effect of leachant

The data reported in the literature suggests that the leachant pH may be the primary factor that affects the fly ash leaching behavior. Data presented by Wasay (1992) and Hassett (1994) shows that low pH, acidic leachants, generally, leach a higher quantity of heavy metals, such as, cadmium, chromium, lead and zinc. However, this trend is not always true for arsenic and selenium. While the data by Hassett (1994) shows that a less acidic leachant extracted a higher quantity of arsenic and selenium, the data by Wasay (1992) shows an exactly opposite trend. Barium and antimony also exhibit unusual pH dependence. Barium concentrations are controlled by the solubility of available sulfates. At low pH, more calcium sulfate dissolves providing the necessary sulfate to reduce barium concentrations (Hassett 1994). Further, since antimony mostly occurs in sulfate form, its concentration also decreases with pH. Thus, acidic leachant may not always extract higher amounts of contaminants of concern.

4.3.2 Effect of leaching method

In addition to the leachant chemistry, the leaching behavior is influenced by the following physical parameters that control the exposure of fly ash to the leachant: (1) the length of exposure of fly ash particle to the leachant, (2) leachant concentration, (3) the volume ratio of the leachant and fly ash. Among the standard leaching tests, the column leaching test has the lowest volume ratio of the leachant and fly ash. Further, although the exposure time in column test depends upon the flow-rate, it is very likely that the length of exposure of fly ash particle to leachant will be lowest for the column test. Therefore, it is expected that for a given leachant chemistry and concentration, the column test will produce the lowest leaching concentrations of all the test protocols. Test results by Wasay (1992), using both single batch and column methods, seem to confirm this expectation, Although, it is difficult to reach a definite conclusion as the leachant pH was 5 for the column test and 6 for the batch tests. It is nevertheless noteworthy, that the column leaching method more closely resembles the leaching method in the field than the batch leaching methods. The batch leaching methods, at best, represent the worst case scenario. Among the batch leaching test, the sequential test is expected to produce higher total leaching concentrations in comparison to the single batch leaching test.

4.3.3 Effect of exposure to water

Fly ash, especially, the Class C type, has the propensity to form hydrated compounds whose compositions are quite different from the chemical compounds in the fly ash that has not been exposed to water. These hydration reactions can occur over a long period of time and depend upon the availability of calcium and reactive silicates, aluminates or alumino-silicates. The hydration reactions have been known to decrease the concentrations of contaminants such as borates, chromates, selenates, and vanadates that tend to exist as oxyanions (Hassett et al. 1990). Since the hydration reactions occur over time, it is likely that the leaching behavior of fly ash exposed to moisture would be a function of time. Results presented by Hassett (1994) for long term leaching test of fly ash exposed to water using a distilled-deionized water leachate shows diminished concentrations of cadmium and lead with exposure. The concentrations of barium, chromium and selenium did not show any appreciable change, while arsenic concentrations increased with exposure. It is noted that the fly ash tested by Hassett contains very low levels of calcium. In low calcium ash, the hydration reactions are expected to be inhibited.

4.3.4 Effect of utilization method

The leaching behavior of fly ash utilized for soil stabilization will also be affected by the soil characteristics. Among the most significant soil characteristics are its permeability and cation exchange capacity (CEC). The permeability of the stabilized soil is important from the viewpoint of exposure time of fly ash particle to the leachant. The cation exchange capacity of a soil is its ability of exchange cations of smaller charge and larger size with those of greater charge and smaller size. These cations of greater charge are then held on to the soil particle surface. For a given soil, only the clay portions have the cation exchange ability. Also, the CEC differs for the various clay minerals. Thus certain types of soils have the ability to adsorb some of the contaminants of concern. Data reported by Garcez and Tittlebaum (1984) indicates lower concentrations of arsenic, lead and zinc in the leachate from a sandy loamy soil stabilized with 30% Class C fly ash. A sandy loam soil has a relatively small CEC, therefore, the larger and lower charged cations of trace elements are likely to remain leachable. However in clayey soils these are likely to immobilized as well. Indirect evidence of this immobility is available from field studies conducted on the leaching characteristics of Class C fly ash stabilized roadbeds (EPRI 1995).

Leaching characteristics of an 8" thick fly ash road base course constructed in Pine Bluff, Arkansas using Class C fly ash from Arkansas Power and Light White Bluff plant shows that the maximum migration depth for most contaminants was 3 feet. The 3 feet depth also corresponded with an increase in soil clay content. Leaching characteristics of a recycled asphalt roadbase stabilized with 15% Class C fly ash from KPL Jeffries Plant shows a more dramatic decrease in contaminant migration with depth. It is noteworthy that the soils underlying the stabilized bed are described as clay or clay loam. Most importantly, for both these field studies using Class C fly ash, the contaminant concentrations were much below the RCRA standards.

4.3.5 Leaching potential of KCPL ash

Data available in the literature shows that Class C fly ash derived from Wyoming coal, generally, leaches only very small quantities of contaminants of concern (Garcez and Tittlebaum 1984, EPRI 1995). Nevertheless, leaching behavior of each fly ash must be examined on a case-by-case basis in relation to the background water quality. These leaching tests must be standardized with respect to the leaching fluids that best represent the fluids in nature, such as, simulated groundwater or rainwater leachates. In absence of these standards, the TCLP test provides a method for evaluating the leaching potential of a fly ash. Therefore, in this report, the leaching behaviors of the two KCPL ash (the Hawthorn and the LaCygne ash) are examined based upon the TCLP test results. As shown in Table 6 and Figure 21, none of contaminants of concern exceed the RCRA standards. From discussions in the above sections, it is quite likely that the extracted concentrations of the various contaminants are highest in the TCLP test. Thus in most cases these TCLP numbers represent the worst case scenario and may be used to judge the leaching potential of the fly ash. Quite clearly, the two KCPL fly ash leach very low quantities of most contaminants of concern.

5. SUMMARY AND CONCLUSIONS

This report presents the findings of a study conducted on issues related to the design, construction and environmental impact pertaining to utilization of KCPL Class C fly ash for soil stabilization. Burning sub-bituminous coal from Wyoming produces the Class C fly ash in voluminous quantities. These ashes, typically, have a high calcium oxide content and are characterized by their self cementing property. Therefore, these Class C fly ashes are particularly suited for use as soil improvement agents.

Literature review and test results show that the physical and chemical properties of high calcium Class C fly ash produced by the Hawthorn and LaCygne plants of KCPL are similar to those of other Class C fly ash. Scanning electron microscopy, X-ray microanalysis and chemical composition studies show that the two KCPL fly ashes are primarily made of spherical and sub-spherical glassy particles composed of amorphous oxides of aluminum and silicon combined with calcium. X-ray microanalysis and the chemical composition studies also show that the LaCygne ash has a relatively larger proportion of calcium than the Hawthorn ash. Both the fly ashes have similar bulk densities between 0.75 and 0.8 g/cm^3, with the LaCygne ash, generally, occurring on the denser side. A statistical analysis of the data measured on ash sampled at various times shows that the two ashes have fairly uniform physical and chemical properties.

For the most effective use of a fly ash as a soil stabilizing agent, a complete knowledge of its physical and chemical characteristics is necessary. Literature review and the tests performed in this report suggest that the self-cementing, Class C fly ash is an effective clay stabilization agent. Appropriate laboratory evaluations required to obtain efficient fly ash addition rates and compaction procedure are described in this report. Examples of laboratory evaluations are presented using eight clay soils and Class C fly ash from Hawthorn and LaCygne plants of KCPL. Four of these are natural clays obtained from the vicinity Kansas City. The other four clays were prepared in the laboratory by blending a small proportion of bentonite with kaolinite. These laboratory clays have properties that are easily duplicated, and thus provide standard clays for evaluating efficacy of a particular ash.

The soil-fly ash blends prepared using the two KCPL fly ashes exhibited up to three times strength gain when compacted without delay after blend preparation. It was observed that a two-hour delay between blend preparation and compaction resulted in up to 60% loss in strength gain. Therefore, the rapid hydration characteristics of Class C fly ash must be considered during the design of soil-fly ash blends and development of construction procedures. Construction controls on moisture contents, mixing procedures and time delay between fly ash mixing and mixture compaction must be specified. Construction guidelines' best suited for Class C fly ash soil stabilization are outlined in the report.

It is also observed that the stabilization characteristics depend significantly upon soil plasticity. Data from the literature and the laboratory tests performed in this work are presented to affirm these observations. At present, it seems that the hydration chemistry of Class C fly ash and its variation with ash composition is not well understood. An important unknown is the form of the calcium in the various Class C fly ashes, which also governs the physico-chemical interaction between clay minerals and fly ash. The physico-chemical interaction has implication on the effectiveness of Class C fly ash in stabilizing highly plastic clay soils. The results obtained in this report suggest that lean clay with less active clay mineral have a greater strength gain than fat clays that have more active clay minerals. Finally, it is also expected that the long term performance of Class C fly ash stabilized soil, will depend upon the curing method and shrinkage crack development. At present, very little information is available on the long-term performance of these stabilized soils.

The federal and state regulations, related to the environmental concerns of utilization of Class C fly ash for soil stabilization, are reviewed. The present regulations are not uniform across the states and seem to discourage Class C fly ash utilization in some cases. With these issues in mind the leaching behavior and potential laboratory leaching tests for Class C fly ash are discussed. It is noted that there is a lack of appropriate, standard laboratory leaching test protocol that incorporates the field conditions of stabilized soils. It is also noted that Class C fly ashes, generally, and the two KCPL Class C fly ashes in particular, leach very small quantities of contaminants of concern. Although it is clear that only very small amounts of trace elements are likely to be mobilized from Class C fly ash applied to soil stabilization, the eventual fate of these can only be predicted on a case-by-case basis considering the complete ecosystem at the site of application.

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Table 1. Physical characteristics of fly ash.

Component	Class F fly ash[+]		Class C fly ash[+]				Typical Western[+] coal ash (estimated)		Hawthorn[1]		LaCygne[2]	
	< 10% CaO		10-20% CaO		>20% CaO							
	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
MC	0.11	0.14	0.1	0.0	0.06	0.06	0.059	0.055	0.091	0.018	0.076	0.025
LOI	2.6	2.4	0.5	0.7	0.33	0.35	0.37	0.108	0.316	0.104	0.341	0.147
Fineness	23	9	20	7	15	4.9	14	3.4	15.82	1.057	12.28	1.540
Specific gravity	2.19	0.36	2.4	0.14	2.61	0.10	2.6	0.05	2.598	0.027	2.571	0.033

MC---moisture content.
LOI---loss on ignition.
[1]-------based upon 13 samples collected between February 1996 and Jun 1996.
[2]-------based upon 18 samples collected between February 1996 and Jun 1996.
[+]-------data from McCarthy et al. 1989.

Table 2. Chemical composition of fly ash.

Component	Class F fly ash[+]		Class C fly ash[+]				Typical Western[+] coal ash (estimated)		Hawthorn[1]		LaCygne[2]	
	< 10% CaO		10-20% CaO		>20% CaO							
	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
SiO_2	52.2	9.6	48.5	4.8	36.9	4.7	35.1	1.52	34.29	2.46	34.09	2.13
Al_2O_3	22.8	5.4	19.6	3.6	17.6	2.7	17.6	0.45	23.23	0.75	22.67	0.98
Fe_2O_3	7.5	4.3	6.2	2.1	6.2	1.1	5.8	0.35	5.41	0.30	5.86	0.41
Sum	82.8	13.1	74.3	4.4	60.7	5.2	58.5	1.62	62.92	2.06	61.67	1.78
SO_3	0.6	0.5	1.3	0.8	2.9	1.8	3.1	0.45	1.46	0.20	1.70	0.20
CaO	4.9	2.9	15.2	2.5	25.2	2.8	25.9	0.79	25.13	1.29	26.70	1.36
AA	0.8	0.9	1.0	0.9	5.1	1.0	2.2	0.45	1.40	0.06	1.38	0.05

Sum---$SiO_2 + Al_2O_3 + Fe_2O_3$.
AA----available alkaline.
[1]-------based upon 13 samples collected between February 1996 and Jun 1996.
[2]-------based upon 18 samples collected between February 1996 and Jun 1996.
[+]-------data from McCarthy et al. 1989.

Table 3. Index properties and compaction characteristics of clays used in this study.

	Lab clay1	Lab clay2	Lab clay3	Lab clay4	Natural Soil A	Natural Soil B	Natural Soil C	Natural Soil D
Liquid Limit (%)	58	70	74	85	39	57	46	60
Plastic Limit (%)	37	33	34	36	23	29	22	21
Plasticity Index (%)	21	37	40	49	16	28	24	39
Optimum Moisture Content (%)	29.8	32.3	25.9	28.6	19.0	20.7	20.5	23.5
Maximum Dry Density (kN/m^3)	14.2	13.3	13.2	13.9	16.2	16.5	16.0	14.9

Table 4. Summary of laboratory test results for soil A.

Fly Ash Content	Delay Time (hr.)	Optimum Moisture Content (%)	Maximum Dry Density (kN/m)	Optimum Moisture Content (%)	Maximum Unconfined Compressive Strength (kPa)
0%		19	16.2	16.0	425
10%	0	17	16.51	15.0	870
	2	20	15.93	17.0	550
	4	20	15.7	16.5	530
20%	0	18.5	16.37	14.5	1230
	2	20	15.65	19.3	640
	4	22	15.48	19.0	610

Table 5. Summary of laboratory test results for soil B.

Fly Ash Content	Delay Time (hr.)	Optimum Moisture Content (%)	Maximum Dry Density (kN/m)	Optimum Moisture Content (%)	Maximum Unconfined Compressive Strength (kPa)
0%		20.7	16.5	15.0	475
10%	0	19.4	16.4	18.0	1200
	2	22.0	15.44	17.2	725
	4	22.0	15.3	18.0	600
20%	0	19.5	16.25	17.5	1400
	2	23.0	15.15	21.0	870
	4	23.5	15.1	20.0	740

Table 6. Leaching characteristics of fly ash.

Element	Literature data (mg/l)		Hawthorn fly ash (mg/l)		LaCygne fly ash (mg/l)		DWS Standards (mg/l)	RCRA Standards (mg/l)
	Subbituminous fly ash	30% fly ash stabilized soil	Sampled 01/15/94	Sampled 02/06/95	Sampled 01/15/94	Sampled 02/03/95		
lead	0.54	0.14	<0.05	<0.05	<0.05	<0.05	0.05	5.0
Chromium	NA	NA	0.06	0.02	0.09	0.18	0.05	5.0
Cadmium	0.01	0.43	<0.01	<0.01	<0.01	<0.01	0.01	1.0
Barium	NA	NA	0.25	0.39	0.76	0.50	1.0	100
Silver	NA	NA	<0.03	<0.02	<0.03	<0.02	0.05	5.0
Selenium	NA	NA	0.077	0.08	0.224	0.19	0.01	5.0
Arsenic	1.20	0.24	0.010	<0.01	0.048	0.12	0.05	5.0
Mercury	NA	NA	0.002	<0.005	<0.0002	<0.005	0.002	0.2

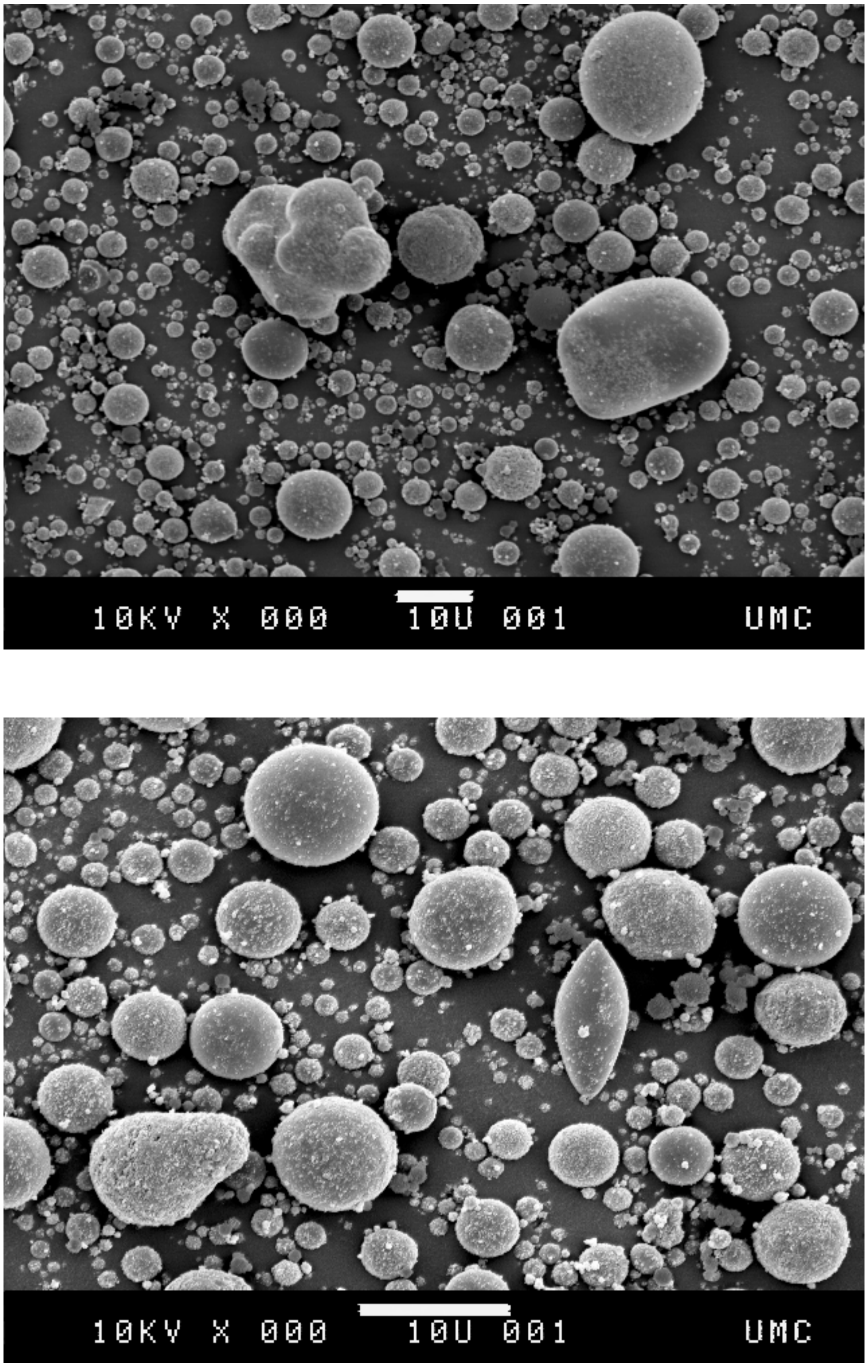


Figure 1. Scanning electron micrograph of LaCygne fly ash.

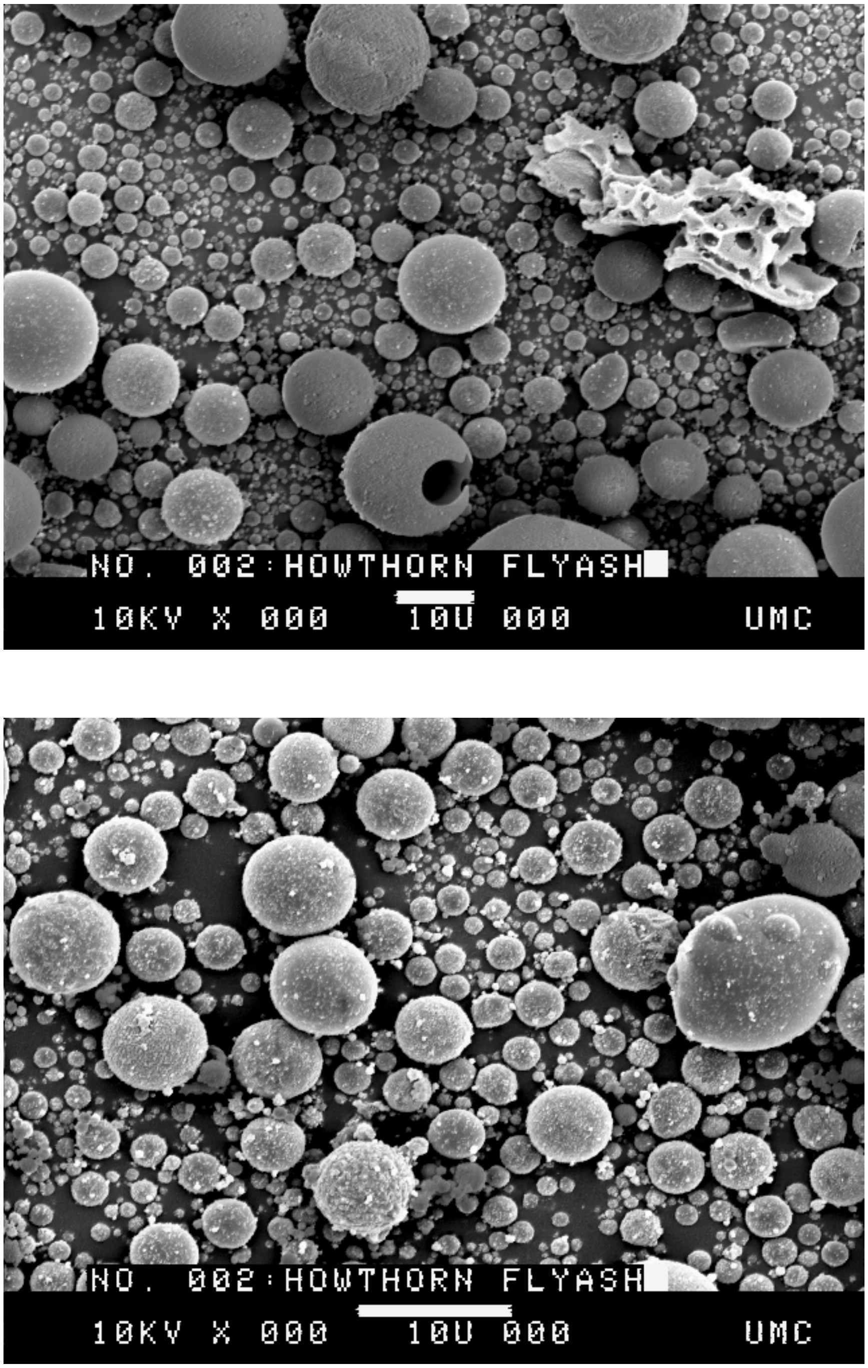
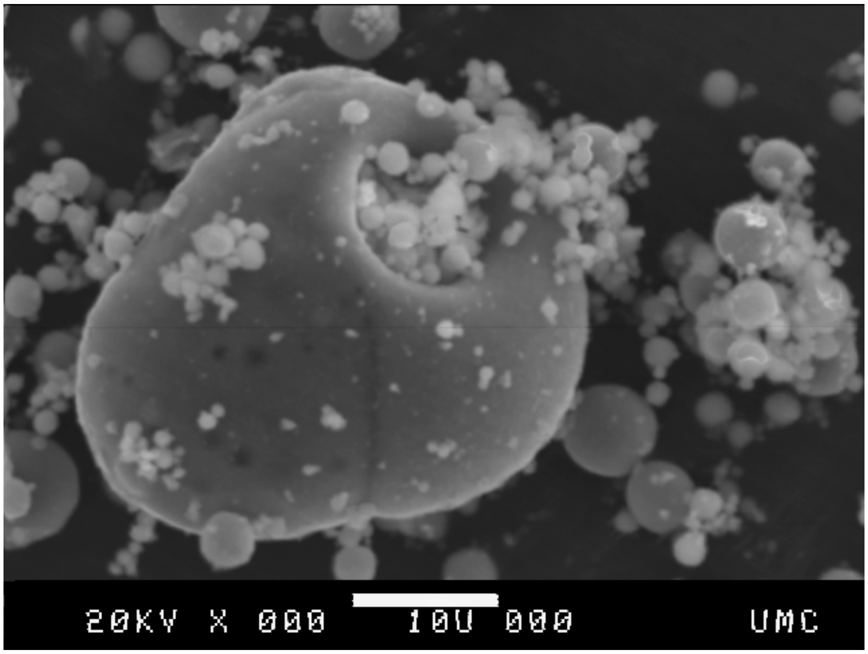
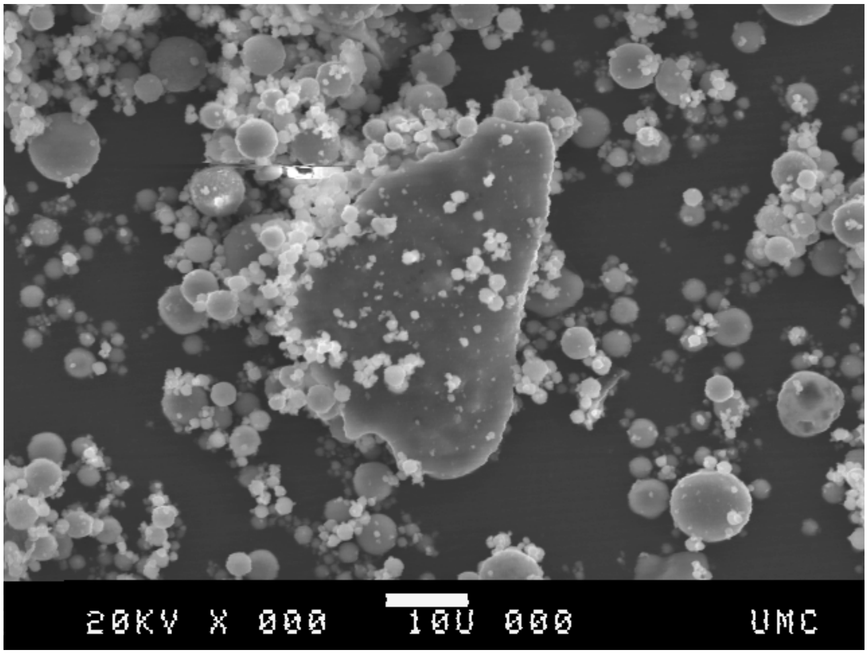


Figure 2. Scanning electron micrograph of Hawthorn fly ash.



(a)



(b)

Figure 3. Scanning electron micrograph showing: (a) a plerosphere, and (b) an angular shaped crystalline particle.

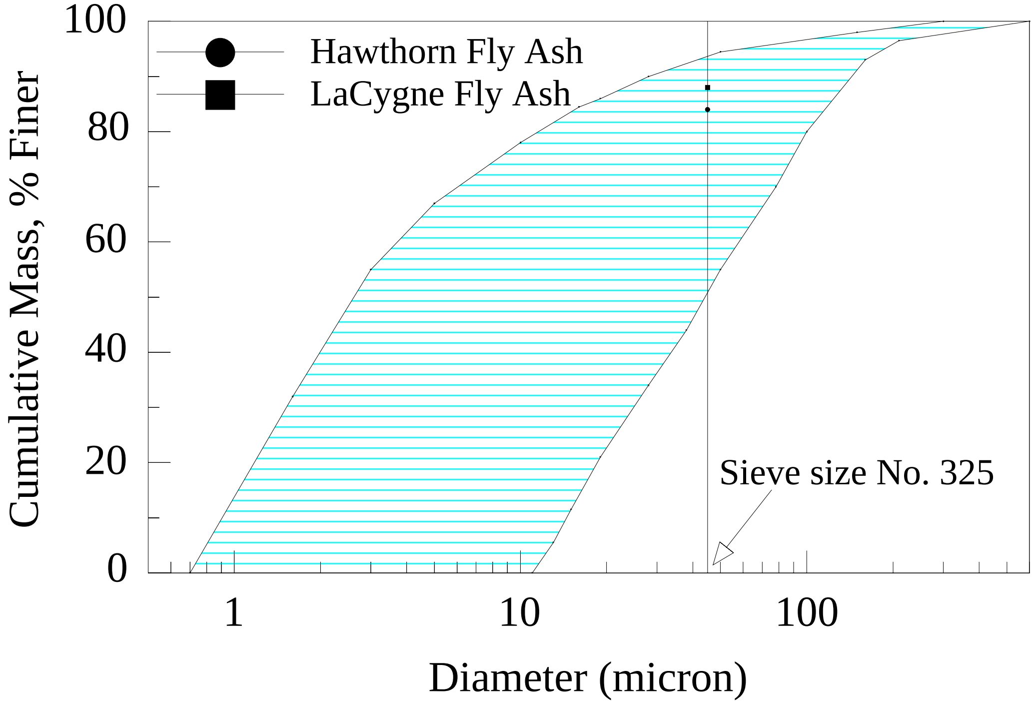
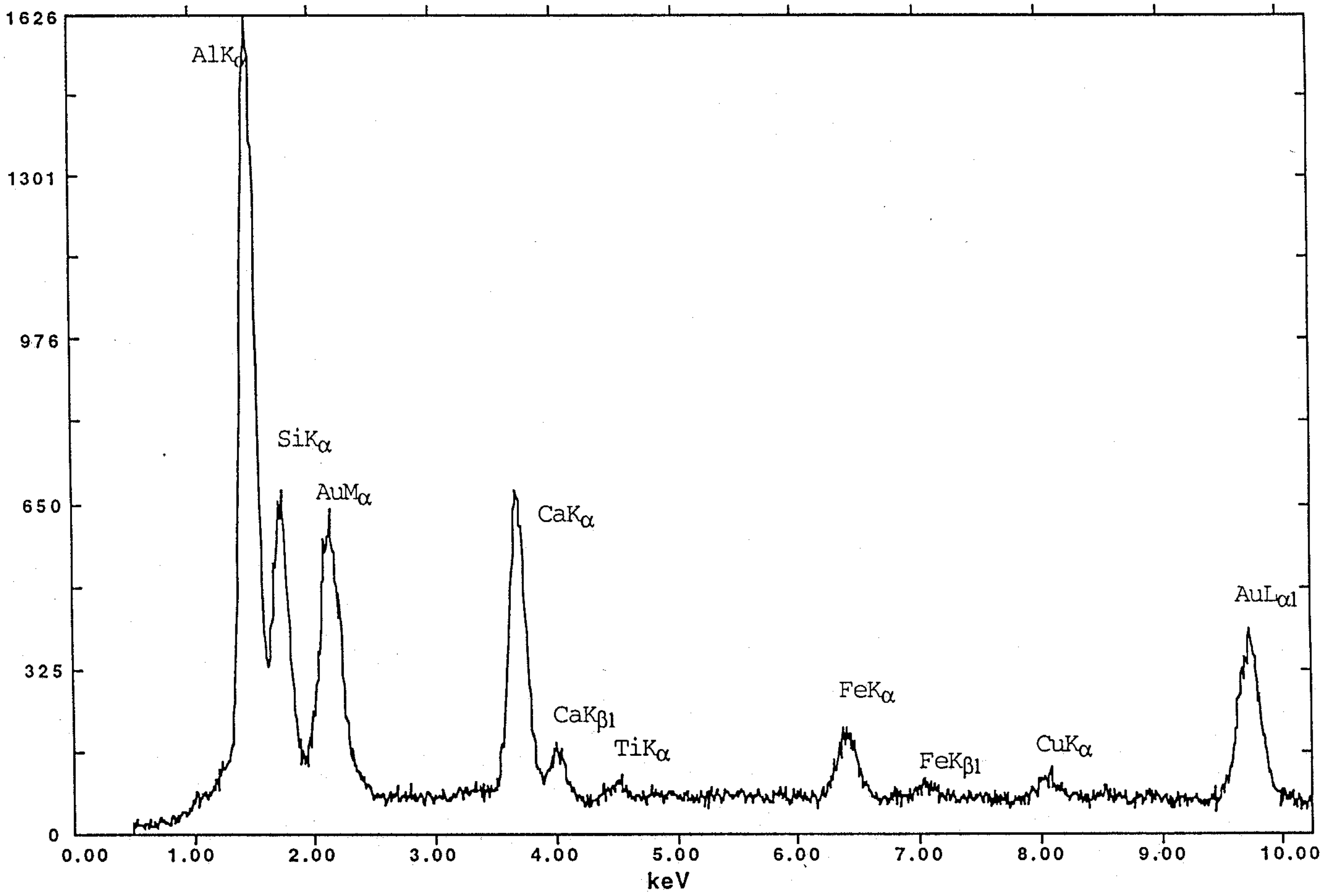


Figure 4. Grain size distribution range for fly ash.



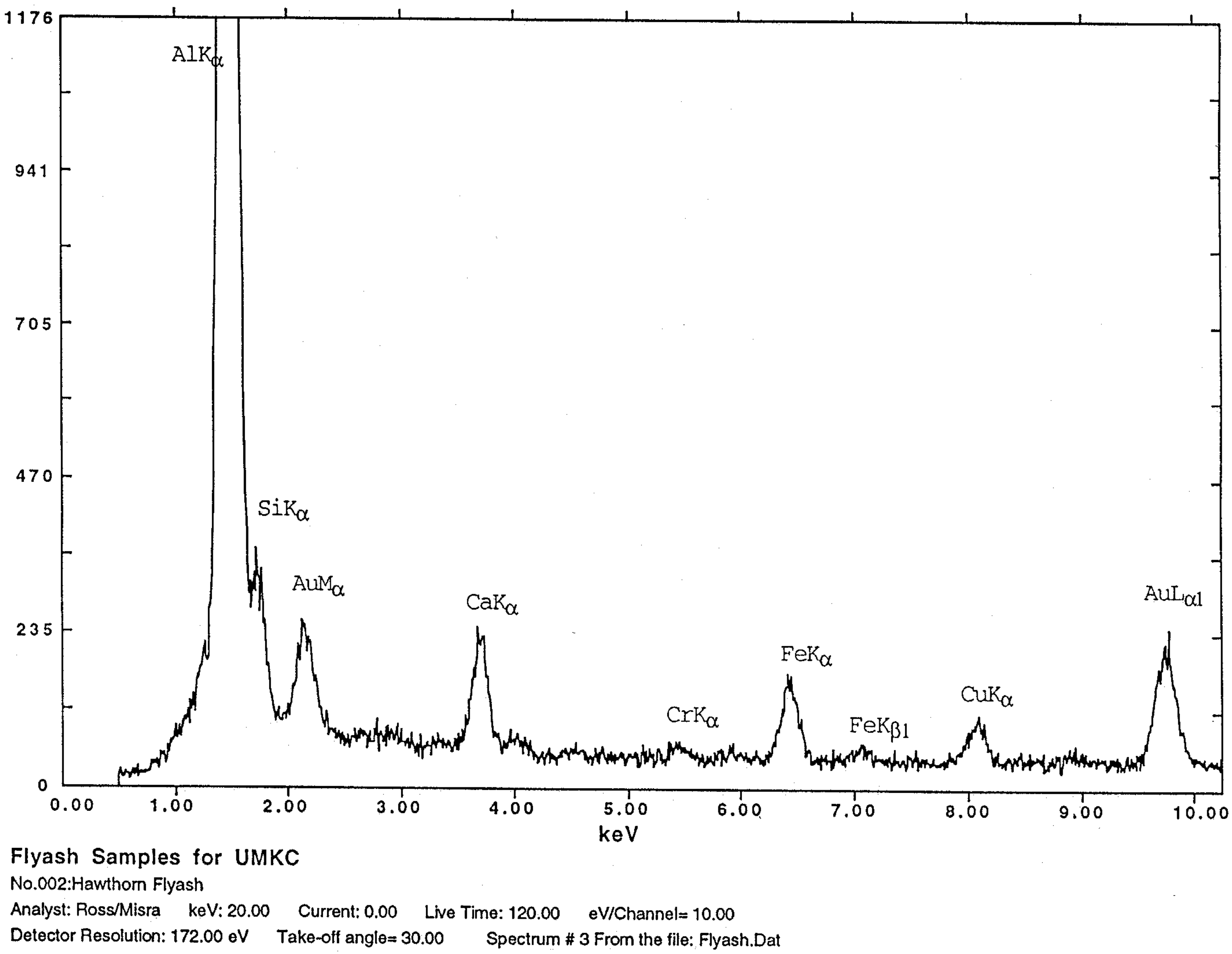
Flyash Samples for UMKC

No.001;LaCygne Flyash

Analyst: Ross/Misra keV: 20.00 Current: 0.00 Live Time: 120.00 eV/Channel= 10.00

Detector Resolution: 172.00 eV Take-off angle= 30.00 Spectrum # 1 From the file: Flyash.Dat

Figure 5. X-ray micro analysis of LaCygne fly ash.



Flyash Samples for UMKC

No.002:Hawthorn Flyash

Analyst: Ross/Misra keV: 20.00 Current: 0.00 Live Time: 120.00 eV/Channel= 10.00

Detector Resolution: 172.00 eV Take-off angle= 30.00 Spectrum # 3 From the file: Flyash.Dat

Figure 6. X-ray micro analysis of Hawthorn fly ash.

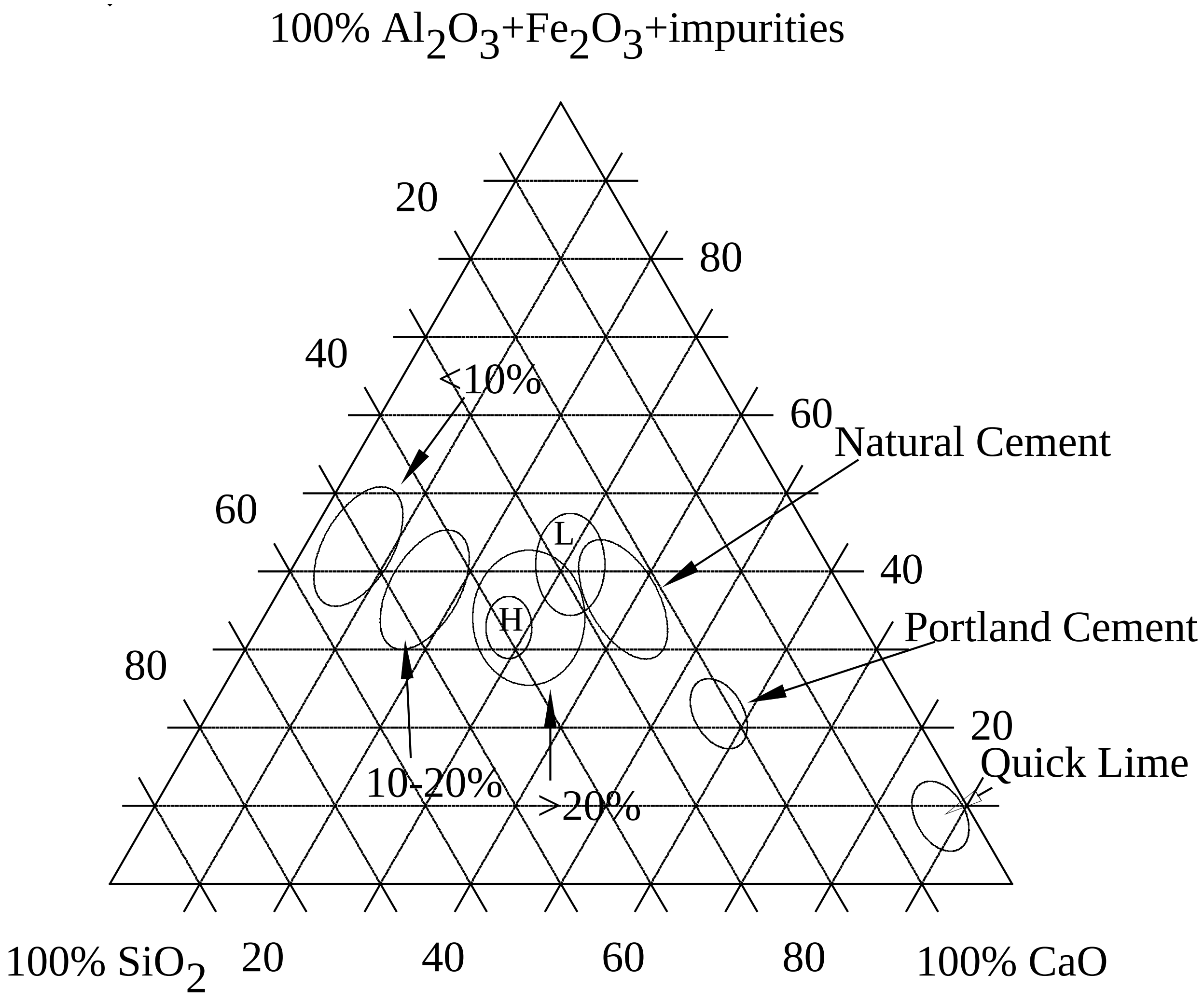
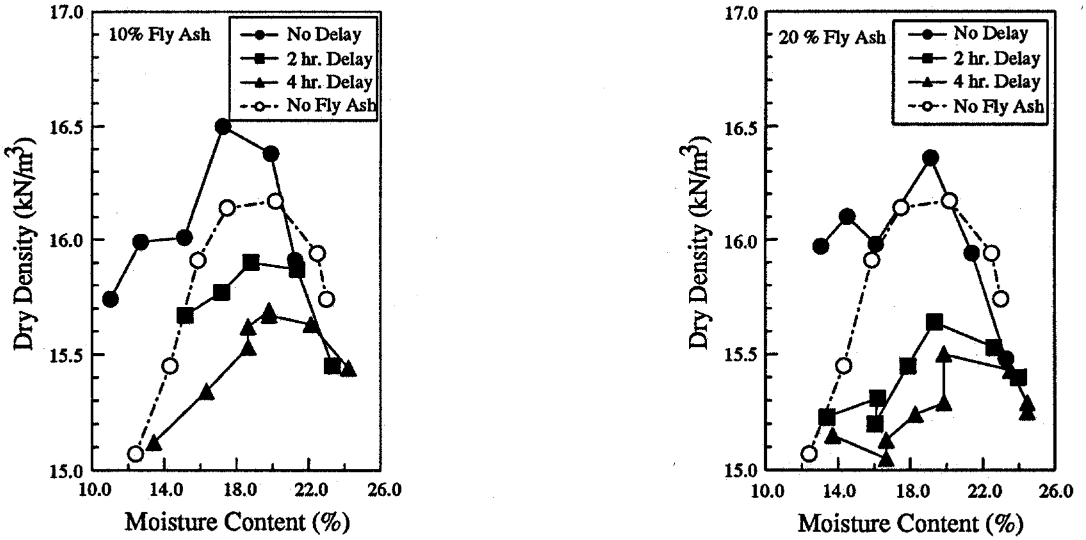


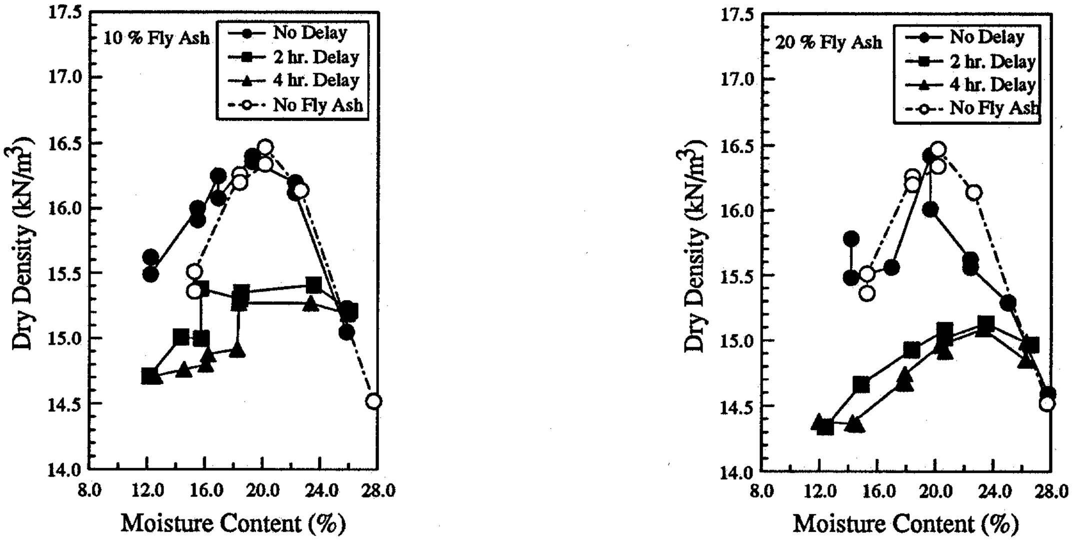
Figure 7. Ternary diagram of oxide composition of fly ash.



(a) 10% fly ash

(b) 20% fly ash

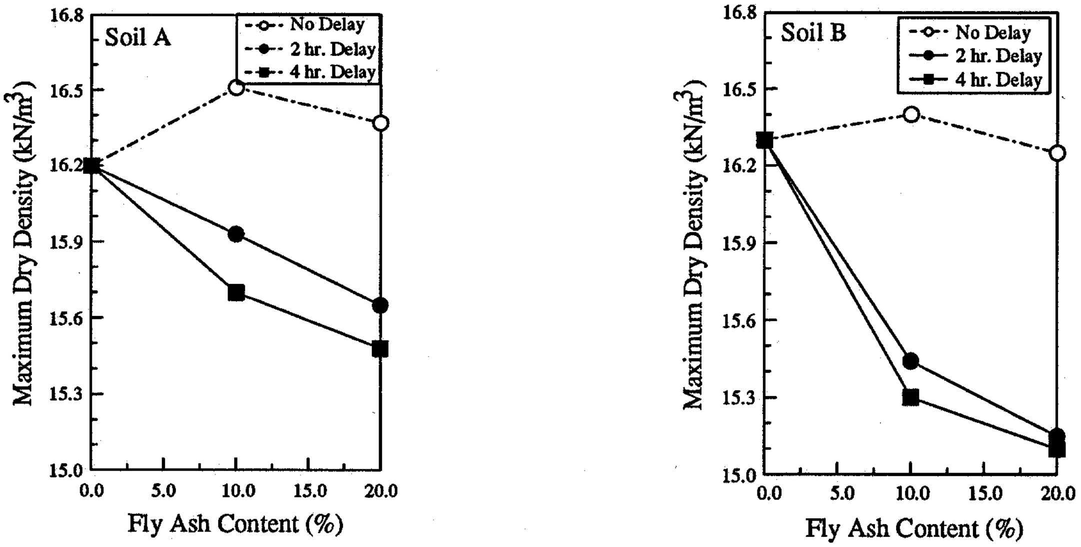
Figure 8. **Dry density versus moisture content at different delay times for soil A.**



(a) 10% fly ash

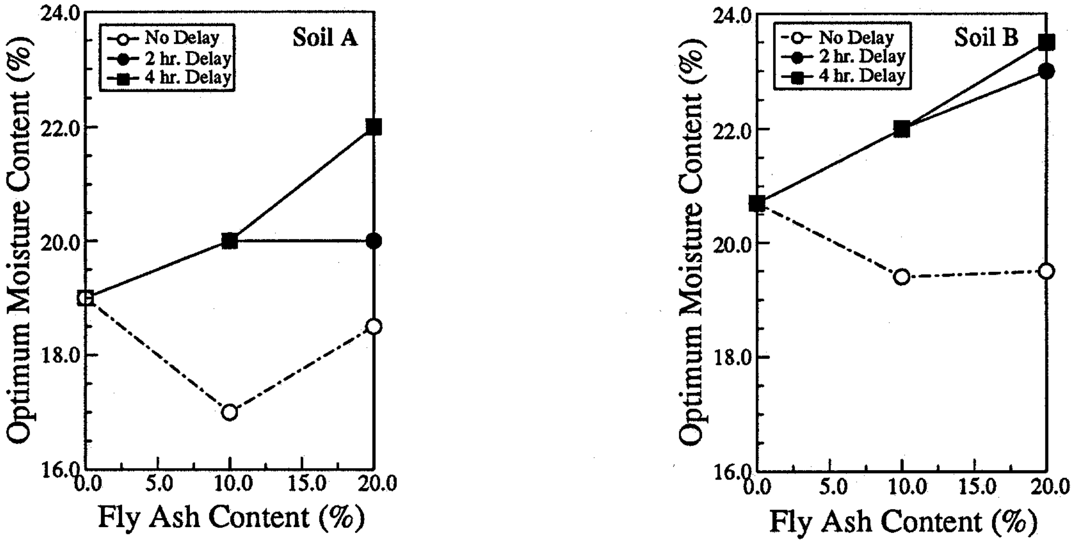
(b) 20% fly ash

Figure 9. **Dry density versus moisture content at different delay times for soil B.**



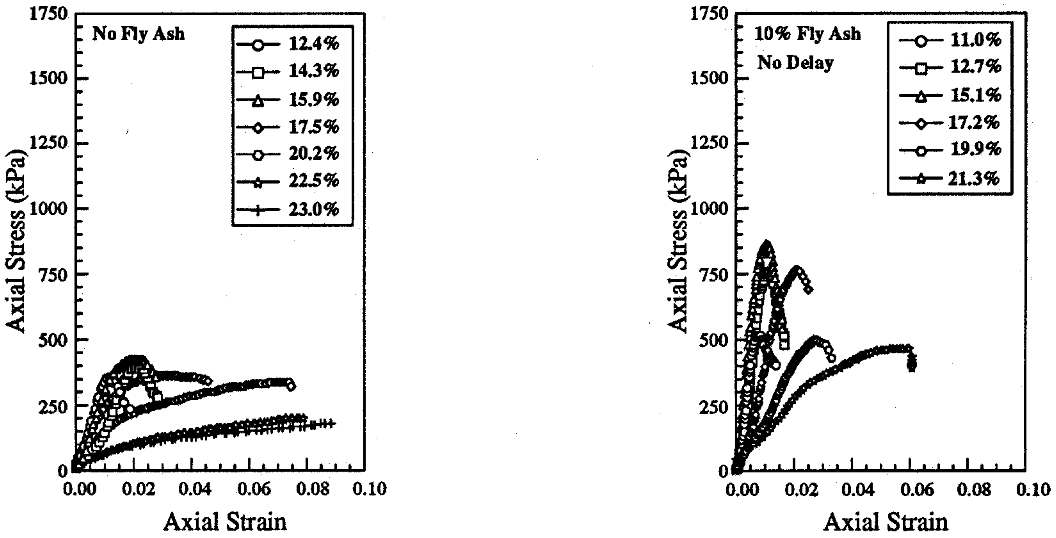
(a) Soil A (b) Soil B

Figure 10. **Maximum dry density versus fly ash content at different delay times.**



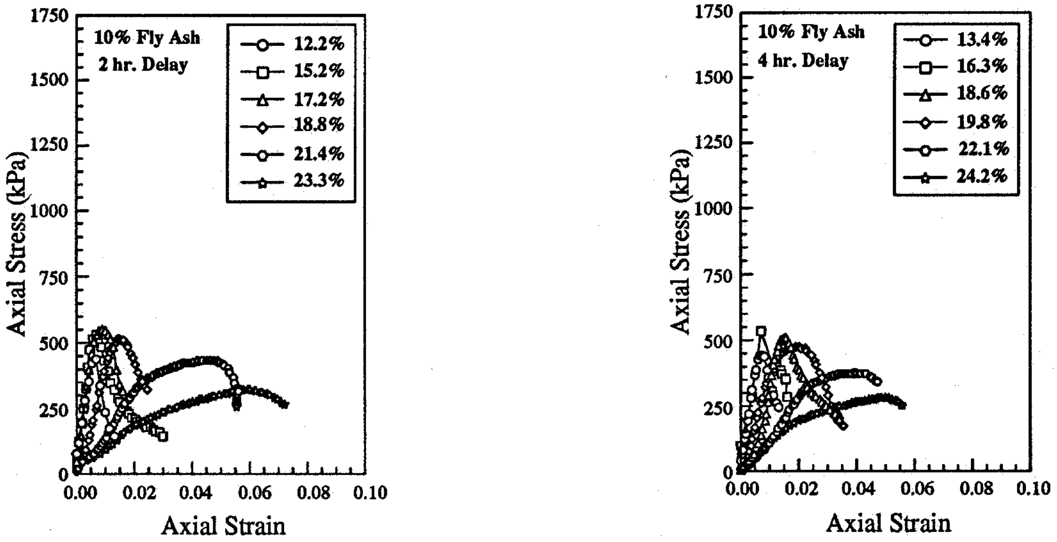
(a) Soil A (b) Soil B

Figure 11. **Optimum moisture content versus fly ash content at different delay times for soils A and B.**



(a) No fly ash

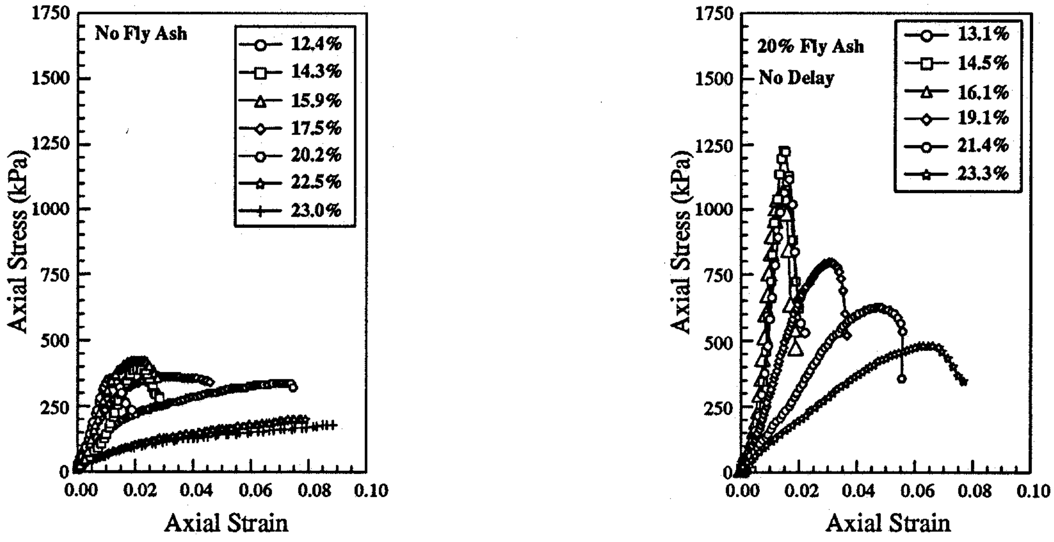
(b) 10% fly ash, no delay



(c) 10% fly ash, 2 hr. delay

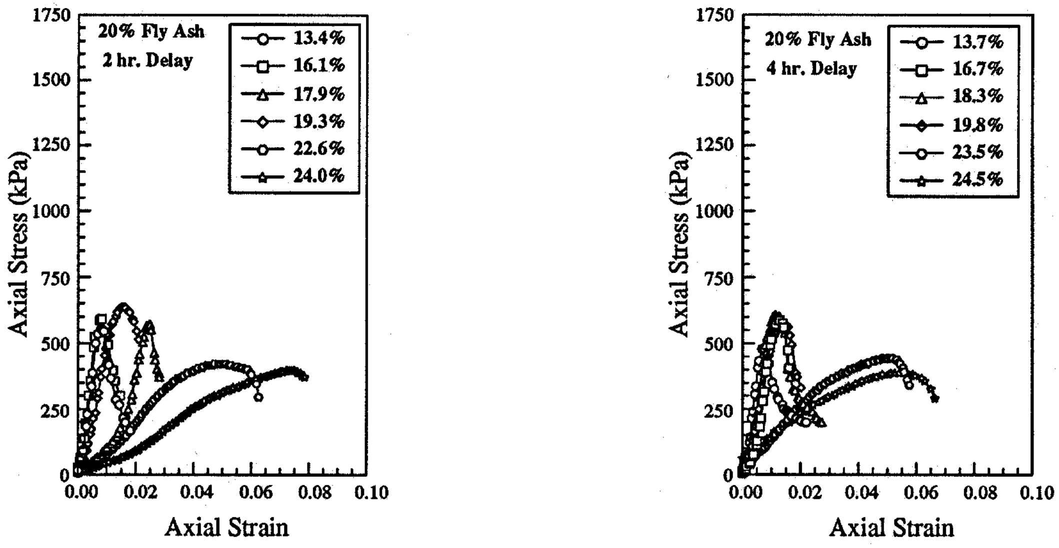
(d) 10% fly ash, 4 hr. delay

Figure 12. **Axial stress versus axial strain at various compaction moisture contents for soil A stabilized with 10% fly ash.**



(a) No fly ash

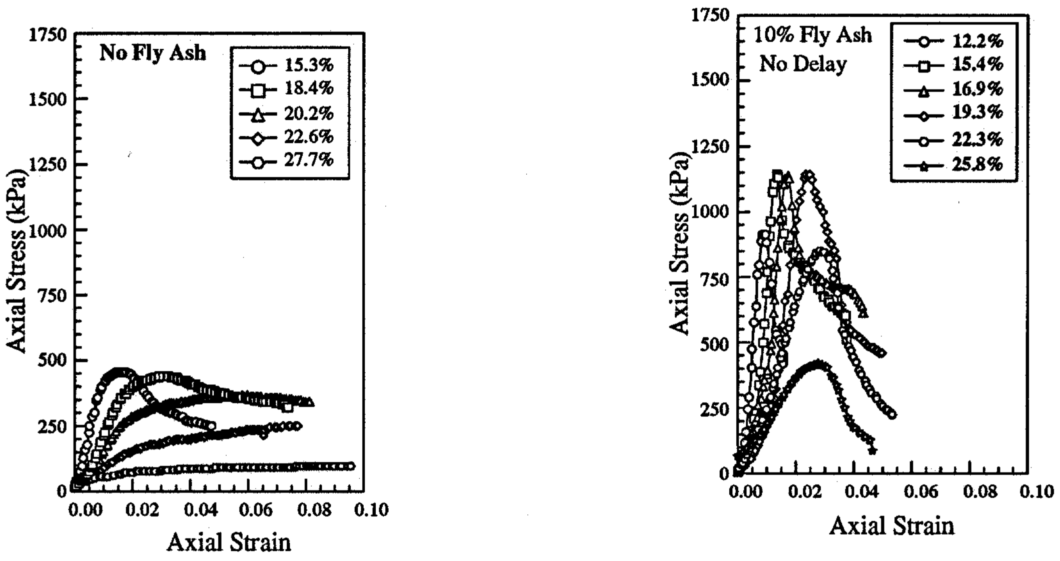
(b) 20% fly ash, no delay



(c) 20% fly ash, 2 hr. delay

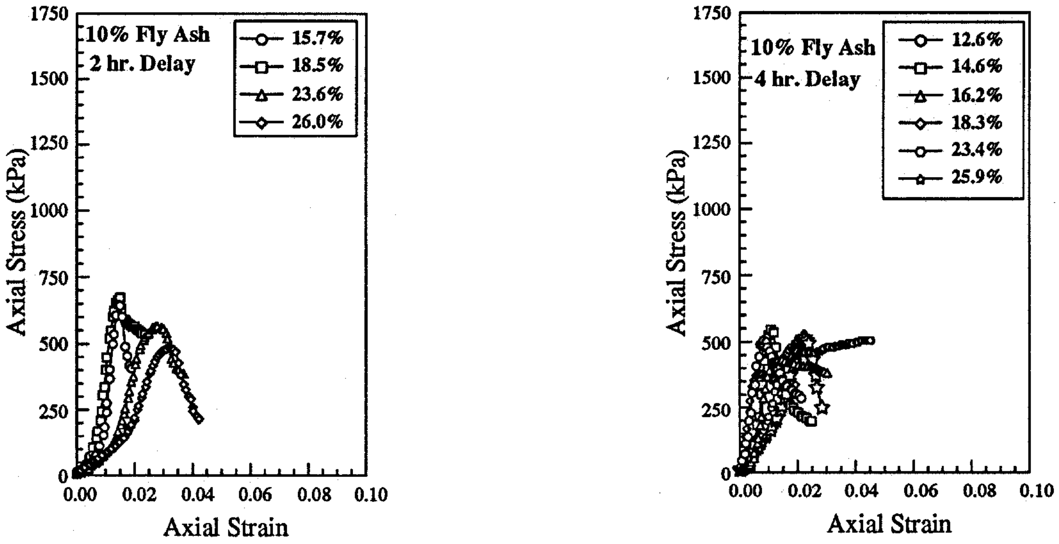
(d) 20% fly ash, 4 hr. delay

Figure 13. Axial stress versus axial strain at various compaction moisture contents for soil A stabilized with 20% fly ash.



(a) No fly ash

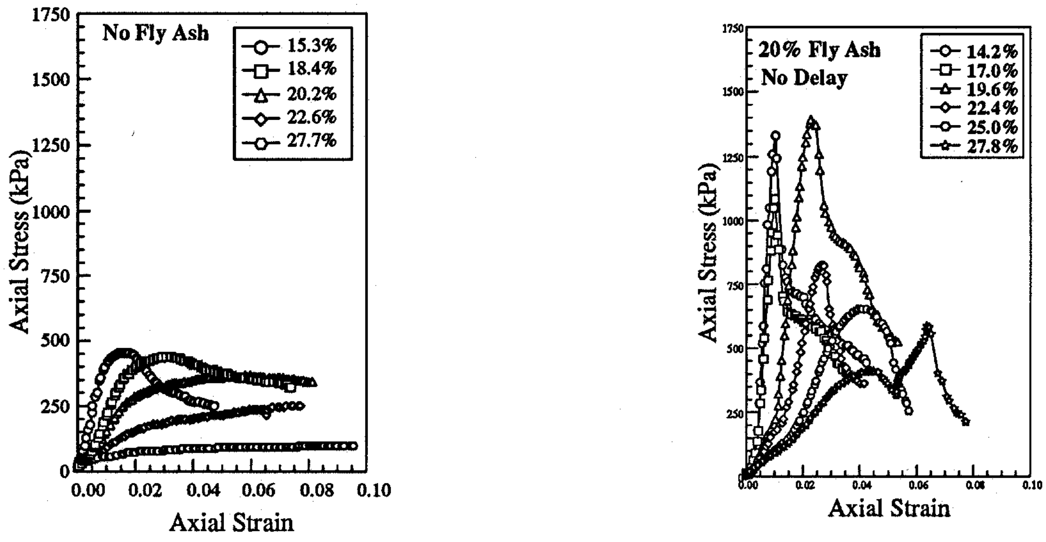
(b) 10% fly ash, no delay



(c) 10% fly ash, 2 hr. delay

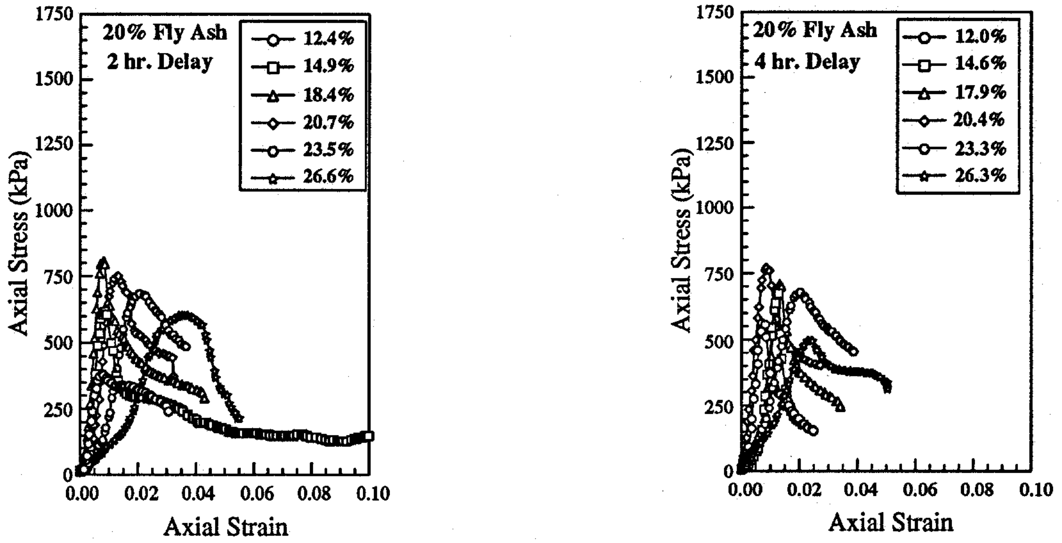
(d) 10% fly ash, 4 hr. delay

Figure 14. Axial stress versus axial strain at various compaction moisture contents for soil B stabilized with 10% fly ash.



(a) No fly ash

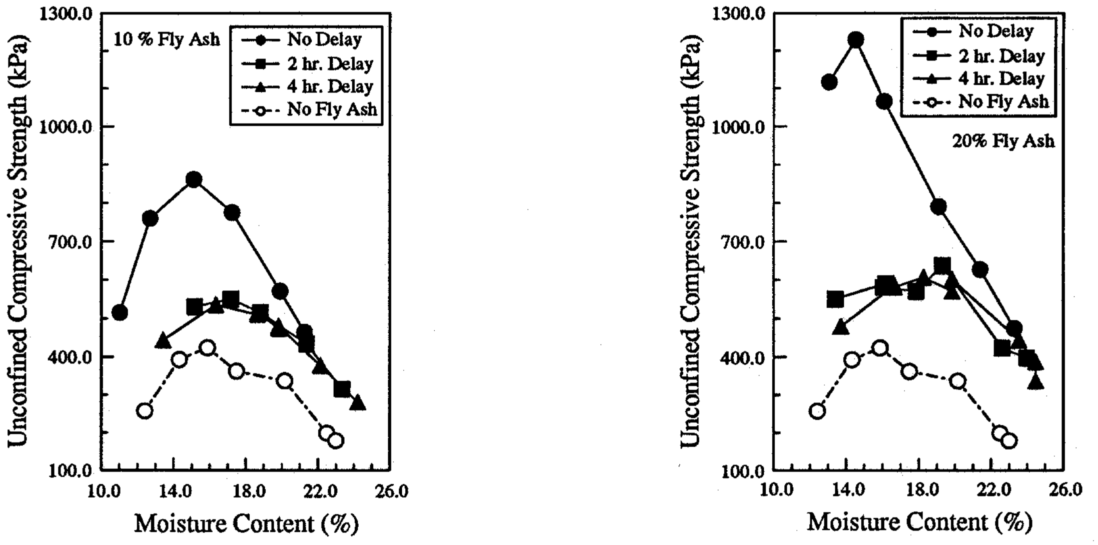
(b) 20% fly ash, no delay



(c) 20% fly ash, 2 hr. delay

(d) 20% fly ash, 4 hr. delay

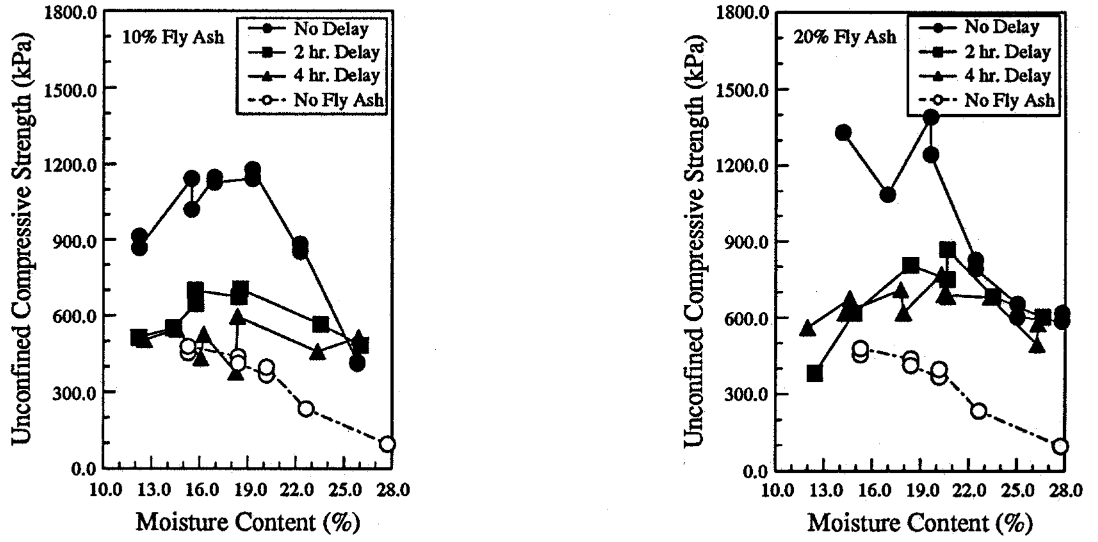
Figure 15. Axial stress versus axial strain at various compaction moisture contents for soil B stabilized with 20% fly ash.



(a) 10% fly ash

(b) 20% fly ash

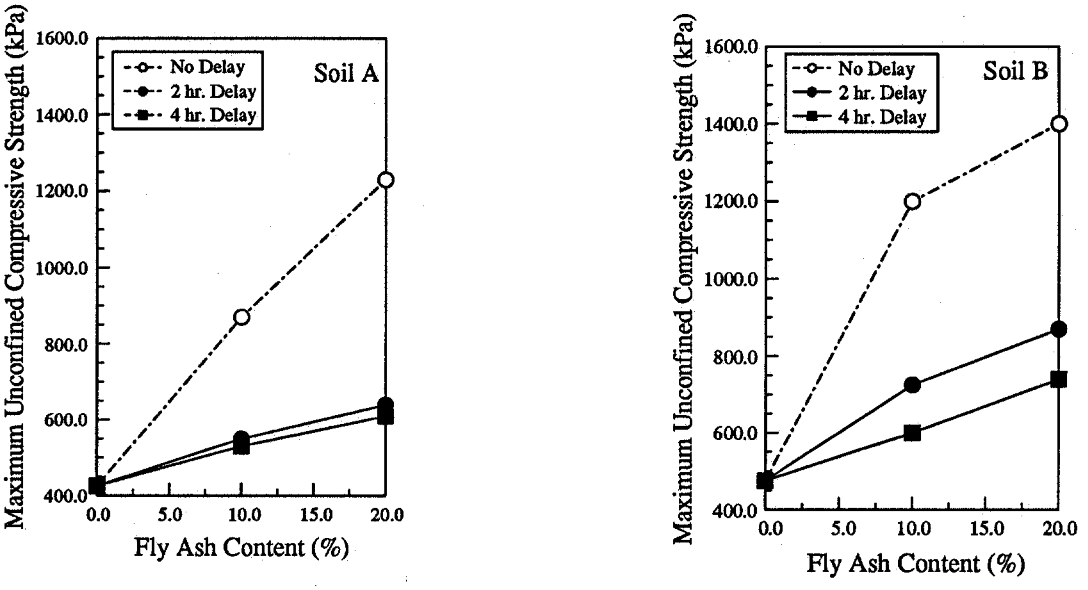
Figure 16. Unconfined compressive strength versus moisture content at different delay times for soil A.



(a) 10% fly ash

(b) 20% fly ash

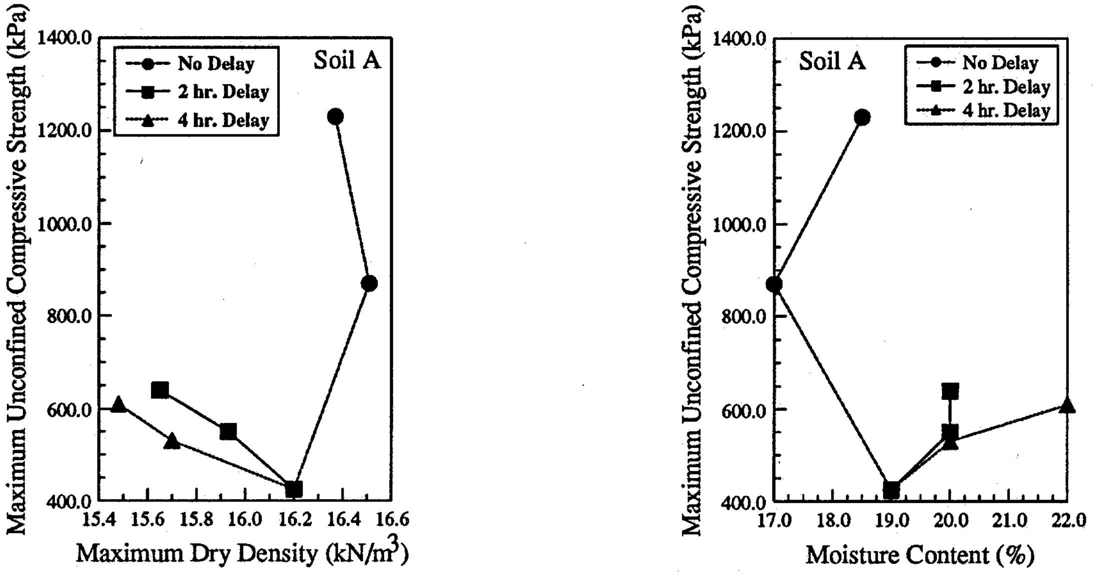
Figure 17. Unconfined compressive strength versus moisture content at different delay times for soil B.



(a) Soil A

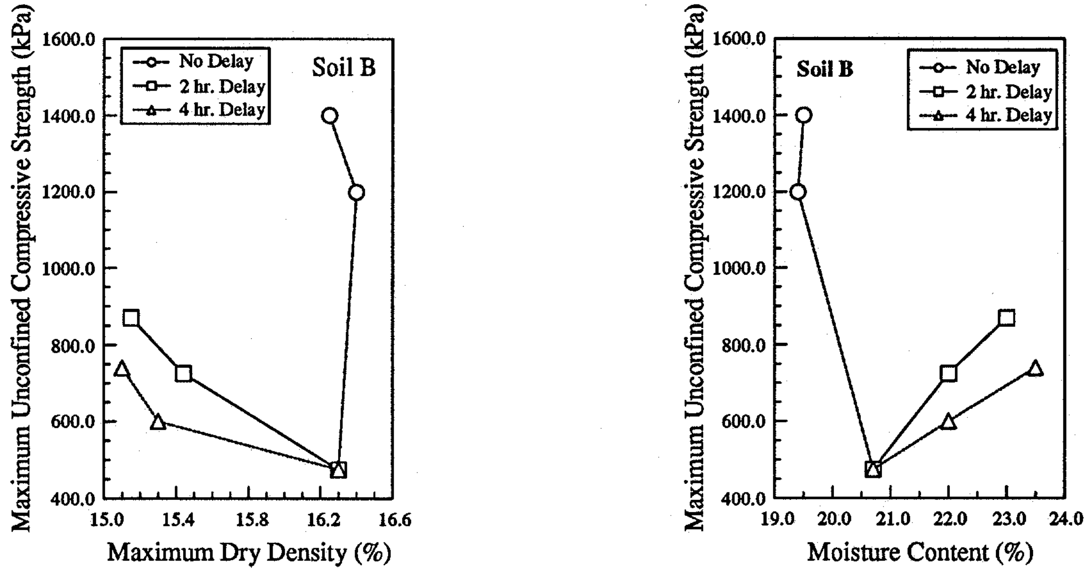
(b) Soil B

Figure 18. **Maximum unconfined compressive strength versus fly ash content at different delay times.**



(a) Soil A

(b) Soil A



(c) Soil B

(d) Soil B

Figure 19. **Maximum unconfined compressive strength versus maximum dry density and optimum moisture content at various fly ash contents for soils A and B.**

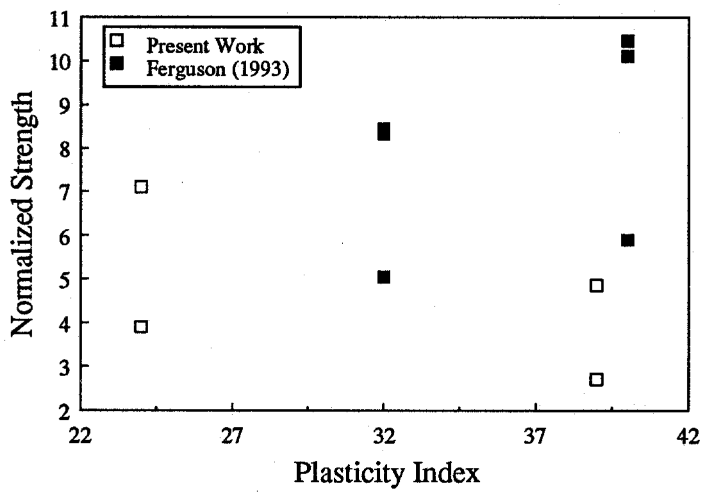


Figure 20. Relationship of clay plasticity index and strength gain characteristics.

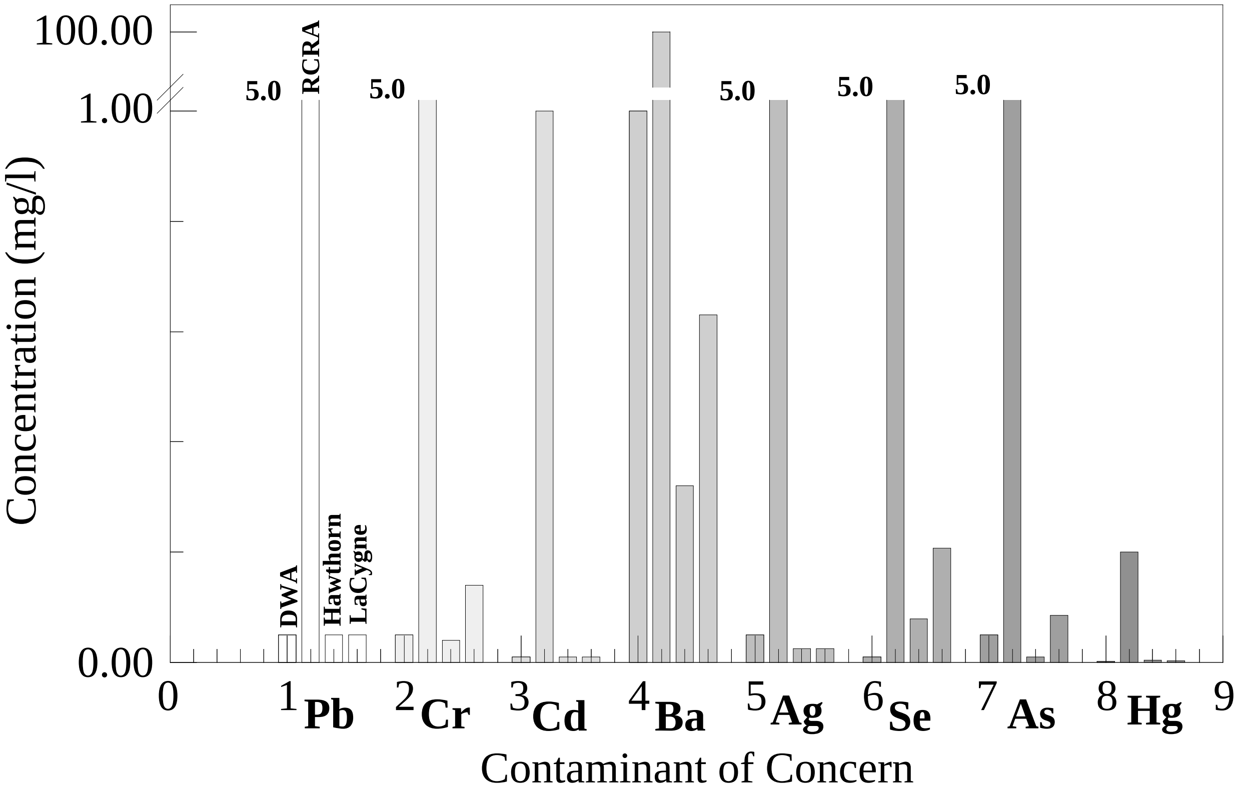


Figure 21. Leaching behavior of Hawthorn and LaCygne Class C fly ash.