STABILIZATION OF ORGANIC SOILS USING FLY ASH

by

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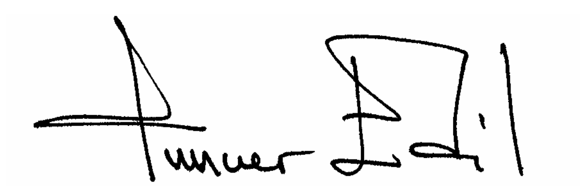

Signature Date

Tuncer B. Edil, Professor

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CHAPTER 1

EXECUTIVE SUMMARY

1.1 INTRODUCTION

Wet organic soils typically are weak and highly compressible, making construction of roads over organic soils problematic. Current approaches for road construction of over organic soils includes (i) removal of the organic soil to a sufficient depth and replacement with a crushed rock (so called "cut-and-replace" method), (ii) improving the engineering properties of organic soils through preloading, and (iii) chemical stabilization. The cut-and-replace method can be costly and time consuming and preloading is often impractical because of the relatively long time required. In contrast, chemical stabilization can be conducted rapidly at a low cost and therefore is becoming a popular method to improve the mechanical properties of organic soils.

Chemical stabilization of soft soils involves blending a binder (e.g., cement, lime, or fly ash or combinations thereof) with the soil in sufficient quantities to increase the strength and stiffness to acceptable levels. Fly ash, a by product of coal combustion that is produced in vast quantities, is a binder of significant interest because many fly ashes are available at low cost. Past research has shown that many fly ashes are effective for stabilizing soft inorganic soils, but little is known about their effectiveness for stabilizing soft organic soils. The objectives of this study were (i) to determine if fly ashes can stabilize organic soils and, if so, (ii) to quantify the improvement in the unconfined compressive strength and resilient modulus of the organic soil as admixed with fly ash and (iii) to investigate potentially important factors affecting the stabilization process such as fly ash and soil characteristics, fly ash percentage in the mixture, and water content.

1.2. MATERIALS AND METHODS

Three soils (Markey, Lawson, and Theresa) and six fly ashes were used in the study. The Markey soil represents a highly organic soil (loss on ignition, or LOI, of 27%) whereas the Theresa represents a low plasticity organic clay (LOI = 5%) and Lawson represents a high plasticity organic clay (LOI = 6%). The fly ashes were obtained from Midwestern power plants and have a broad range of organic carbon contents (0.5% to 49%) and composition. Type 1 Portland cement and Boardman silt were also used to simulate a highly reactive binder (cement) and a non-reactive binder (silt).

Specimens were prepared at optimum water content (a control condition) and very wet of optimum water content (~10% wet of optimum water content, a typical condition for soils in the upper Midwestern US) with fly ash percentages (dry weight) of 10%, 20%, and 30%. Soil-fly ash mixtures were allowed to sit for 2 hr prior to compaction to simulate the delay between blending and compaction that commonly occurs in the field. After compaction, the specimens were sealed and cured in a 100% humidity room for one week.

Unconfined compression (UC) tests and resilient modulus (Mr) tests were conducted on compacted soil-fly ash mixtures as well as the soils alone. The UC tests were conducted according to ASTM D 5102 at a strain rate of 0.21%/minute. The resilient modulus tests were conducted according to AASHTO T 292-91 with the loading sequence for cohesive soils and the conditioning and confining stresses were set at 21 kPa. Operative resilient moduli corresponding to a deviator stress of 21 kPa are reported herein. Tests were also conducted to determine the chemical composition of the fly ashes, pH and index properties of each soil, and pH of the soil-fly ash mixtures.

1.3. MAJOR FINDINGS

1.3.1 Effect on Strength and Modulus

UC strengths of soil-binder mixtures prepared with Lawson soil are shown in Figure 1.1 for optimum and very wet of optimum water contents and fly ash contents of 10, 20, and 30%. Addition of fly ash or cement increases the strength of the Lawson soil significantly. Blending with fly ash increased the strength of the Theresa soil a comparable amount. However, the level of strength improvement was much less for the Markey soil due to its very high organic content.

Resilient modulus of all three soils at very wet of optimum could not be measured because the soils were too soft to withstand the conditioning stress. Addition of fly ash increased the stiffness of the soils to the measurable range for soil fly-ash mixtures prepared with slightly organic soils, Lawson and Theresa, and in some cases very high resilient moduli were obtained (up to 100 MPa for the Lawson soil in the very wet condition). Resilient moduli of the soil-fly ash mixtures prepared with Lawson soil are shown in Figure 1.2. Similar resilient moduli were obtained for mixtures prepared with the Theresa soil. However, as with the UC tests, less improvements in the resilient moduli were obtained with the Markey soil (not more than 30 MPa).

Unconfined compression and resilient modulus tests were conducted with Boardman silt as a binder to distinguish between the effects of chemical binding (cements, cementitous fly ashes) and reduction in water content by adding dry solid (silt). Comparison of strengths and resilient moduli obtained using fly ash, silt, or cement (Figs. 1.1 and 1.2) show that cementing has an important role in stabilization. Depending on the test condition (water content, binder content), the increase in strength or resilient modulus obtained with a fly ash admixture ranged from no different than that obtained using non-cementing silt (e.g., UC strength for Lawson soil blended with 30% Boardman silt vs. 30% Presque Isle ash very wet of optimum water content) to appreciably greater than that obtained with silt (e.g., UC strength for Lawson soil blended with 30% Boardman silt vs. 30% Columbia ash very wet of optimum water content). In addition, the highest strengths were obtained using Portland cement, which is expected to be most effective in cementing. Conditions affecting cementing also appear important. For example, some mixtures (e.g., UC strength for Lawson blended with 10% Dewey or 10% Stanton fly) had higher strengths when the water content was very wet of optimum water content rather than at optimum water content (i.e., the opposite of what was expected).

1.3.2 Influence of Fly Ash and Soil Properties

Statistical and graphical analyses indicated that CaO content and CaO/SiO_2 (or $CaO/(Al_2O_3 + SiO_2)$) ratio of the fly ash are significant factors contributing to increasing the UC strength and resilient modulus of organic soil-fly ash mixtures (see Figures 1.2 and 1.3). For the inorganic clays, strength and stiffness of the soil-fly ash mixtures increase as the CaO content and CaO/SiO_2 ratio increase. Based on Figures 1.2 and 1.3, fly ashes should have at least 10% CaO and a CaO/SiO_2 greater than 0.5 to stabilize organic clays. The highest level of stabilization is obtained with at least 20% fly ash and a CaO/SiO_2 ratio between 0.5 and 0.8. These criteria are not applicable to the highly organic Markey soil, which was not greatly affected by adding fly ash. In contrast, no relationship was found between strength or stiffness and loss on ignition (LOI), fineness, or pH of the fly ash. Thus, factors considered important when using fly ash in Portland cement concrete applications appear not to be important for soil stabilization.

The effect of organic content (OC) of the soil on strength and stiffness of fly ash-stabilized organic soils is illustrated in Figure 1.4. Both strength and stiffness of the soil-fly ash mixtures decrease as the OC increases. The effect of soil pH and plasticity index (PI) on strength and stiffness were also investigated, but the effects of

OC, PI, and pH could not be differentiated due to the limited number of soils in the analysis. More research on the effect of soil composition on the strength and stiffness of stabilized organic soils is still necessary. In contrast to other studies, no correspondence was observed between strength or stiffness and pH of the soil-fly ash mixtures

A regression model for predicting UC strength of organic soil-fly ash mixtures was developed. This regression equation is

$$\begin{aligned} q_{u-treated} &= -319.559 + 794.663(CaO/SiO_2) - 572.833(CaO/SiO_2)^2 \\ &-125673(e^{-OC}) + 6.01475(FAperc) + 25.3824(q_{u-untreated}) - 32.727(pH_{mixture}) \end{aligned} \quad (1.1)$$

where CaO/SiO_2= CaO/SiO_2 ratio of the fly ash, OC= organic content of the soil, FAperc= fly ash percentage in the mixture, $q_{u\text{-}untreated}$= untreated unconfined compressive strength of the soil, $q_{u\text{-}treated}$= unconfined compressive strength of the stabilized soil. CaO content of fly ash was not included in the regression model because CaO content is highly correlated with CaO/SiO_2 ratio. The regression has an R^2 = 0.71%.

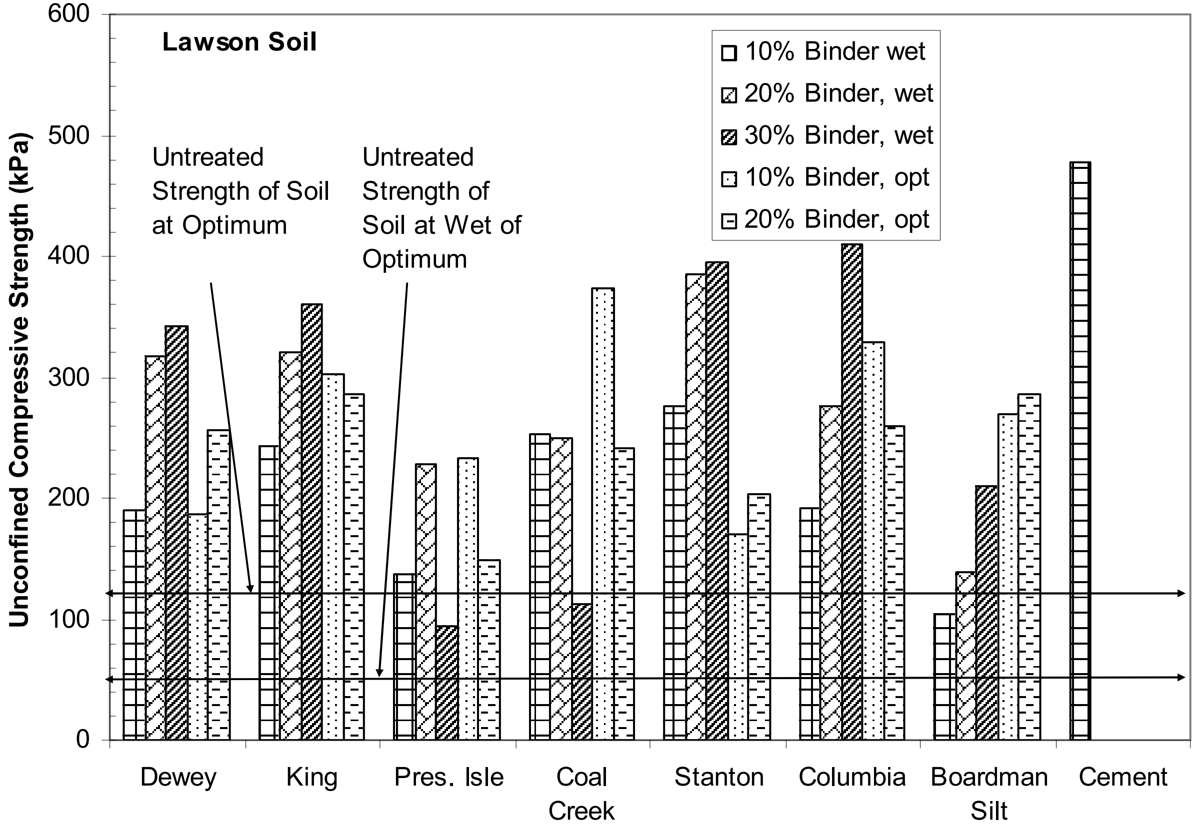


Figure 1.1 Variation of UC strength of soil-binder mixture as a function of binder type and percentage, and water content, wet=wet of optimum and opt= optimum water content

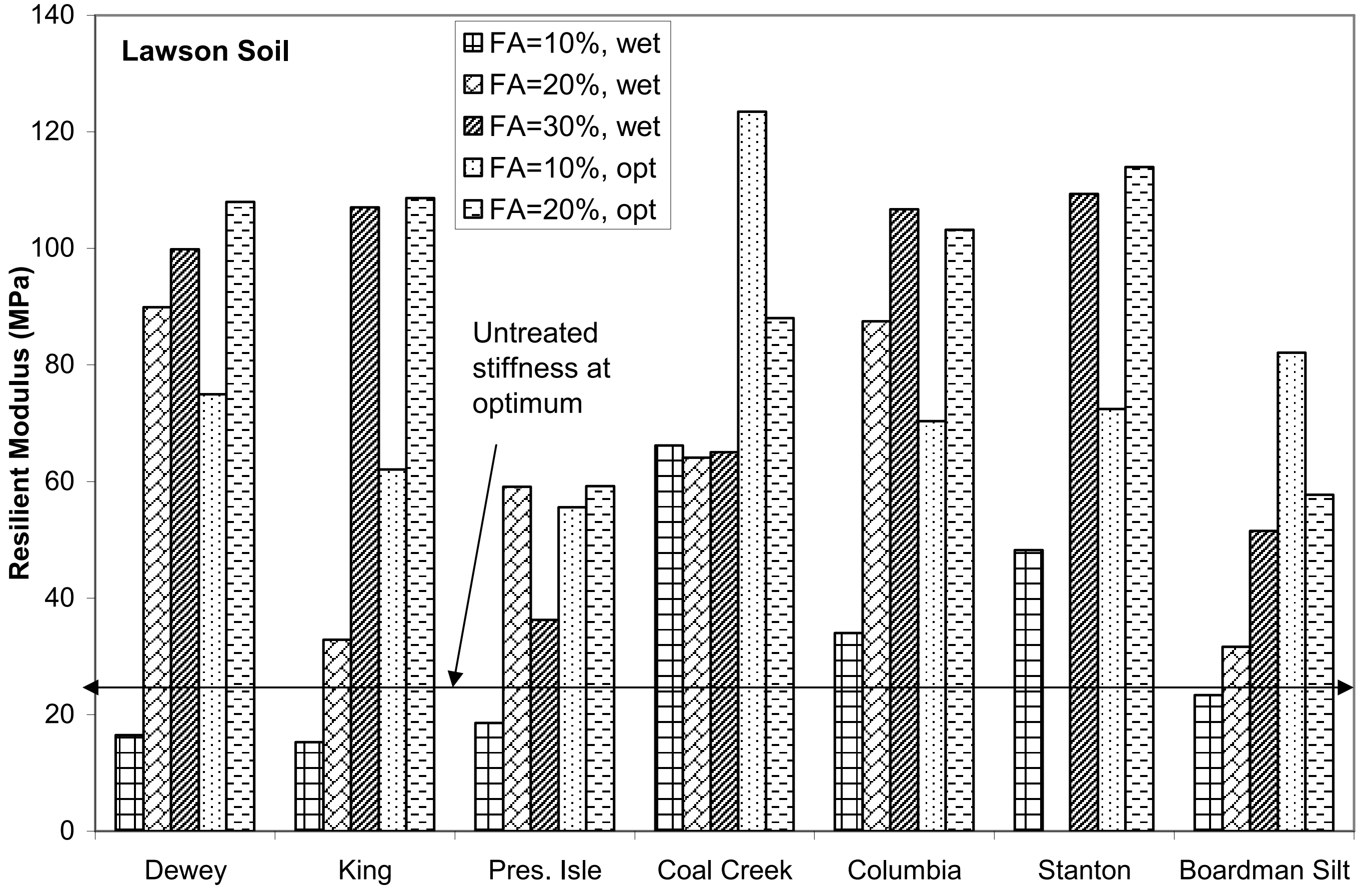


Figure 1.2 Variation of resilient modulus of soil-binder mixture as a function of binder type and percentage, and water content, wet=wet of optimum, opt=optimum water content

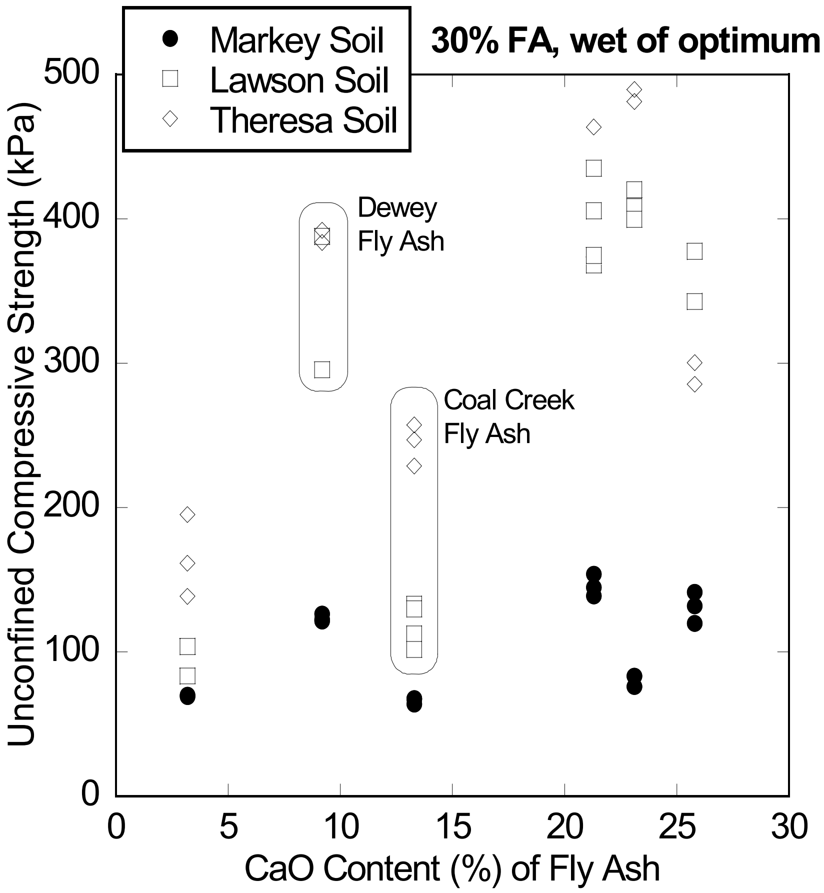


Figure 1.3. Unconfined compressive strength of organic soil-fly ash mixtures as a function of CaO content of the fly ash.

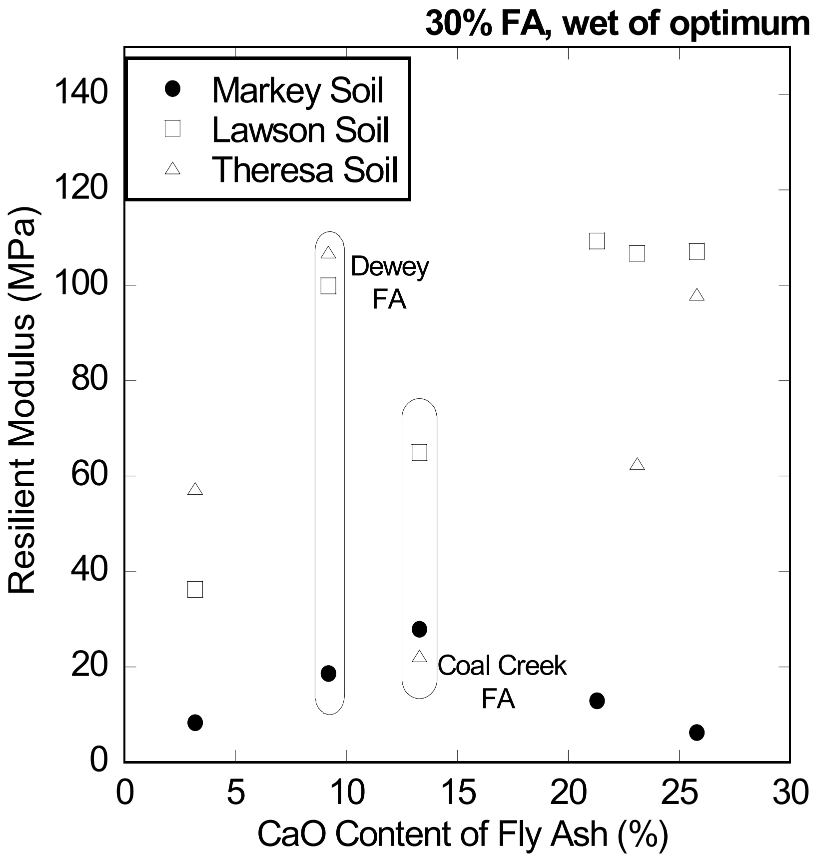
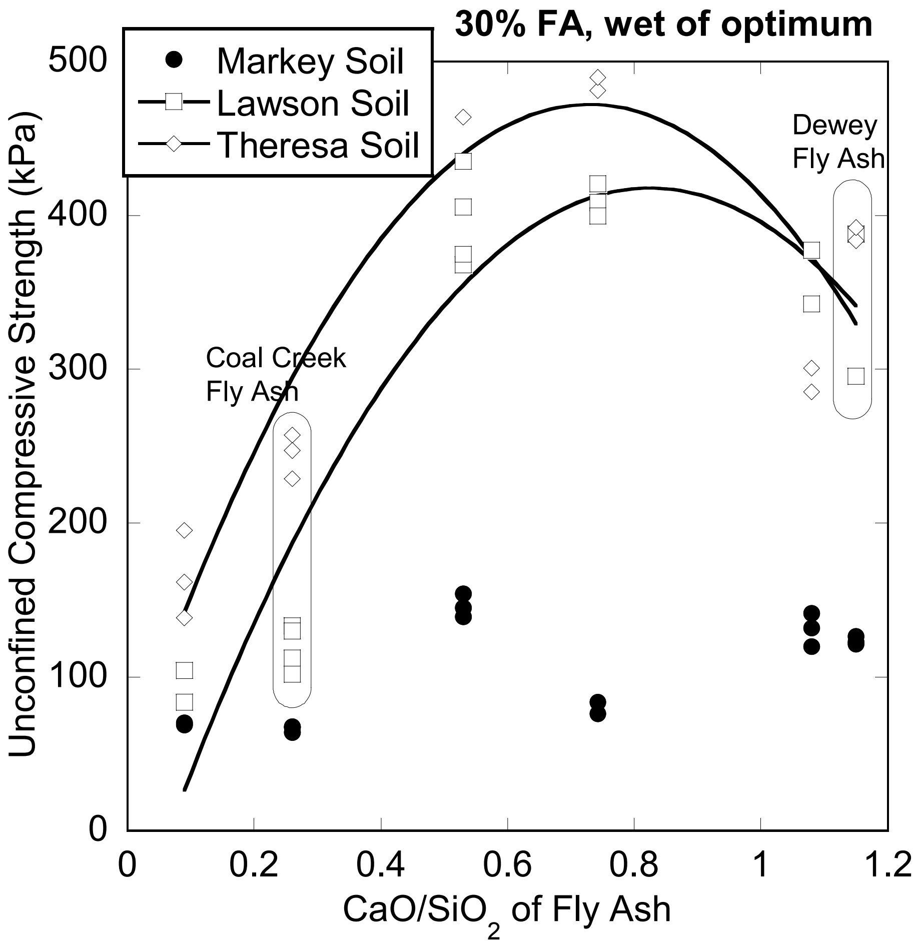


Figure 1.4. Resilient modulus of organic soil-fly ash mixtures as a function of CaO content of the fly ash.



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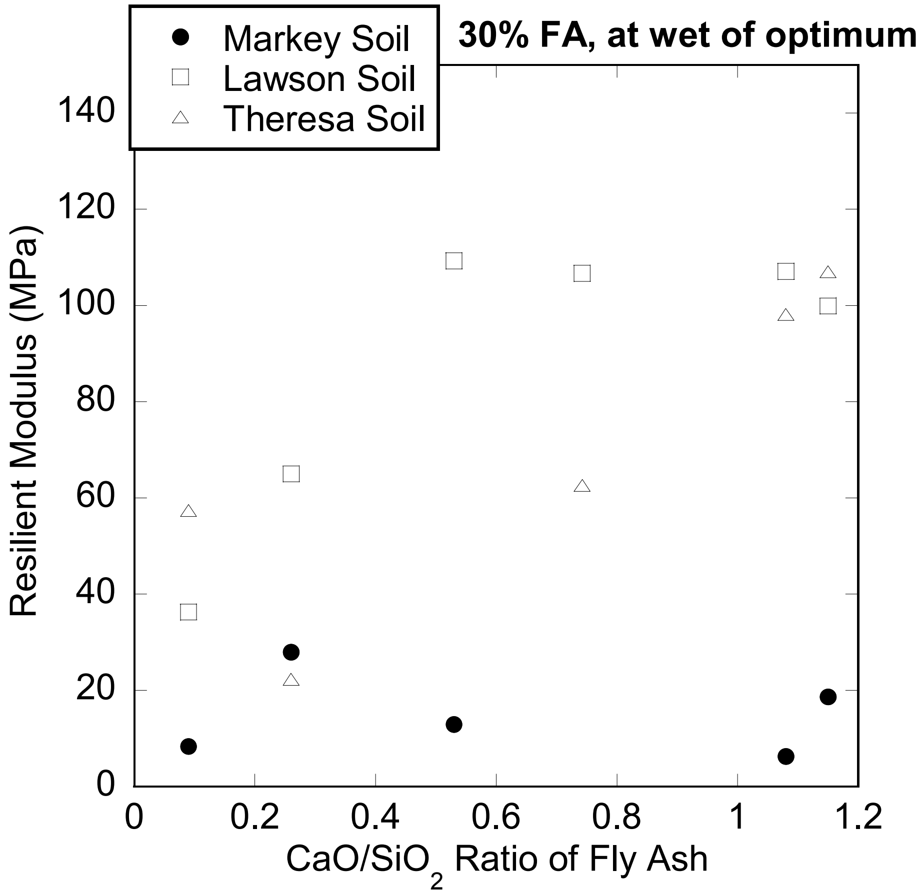

Figure 1.6. Resilient modulus of organic soil-fly ash mixtures as a function of CaO/SiO_2 ratio of the fly ash.

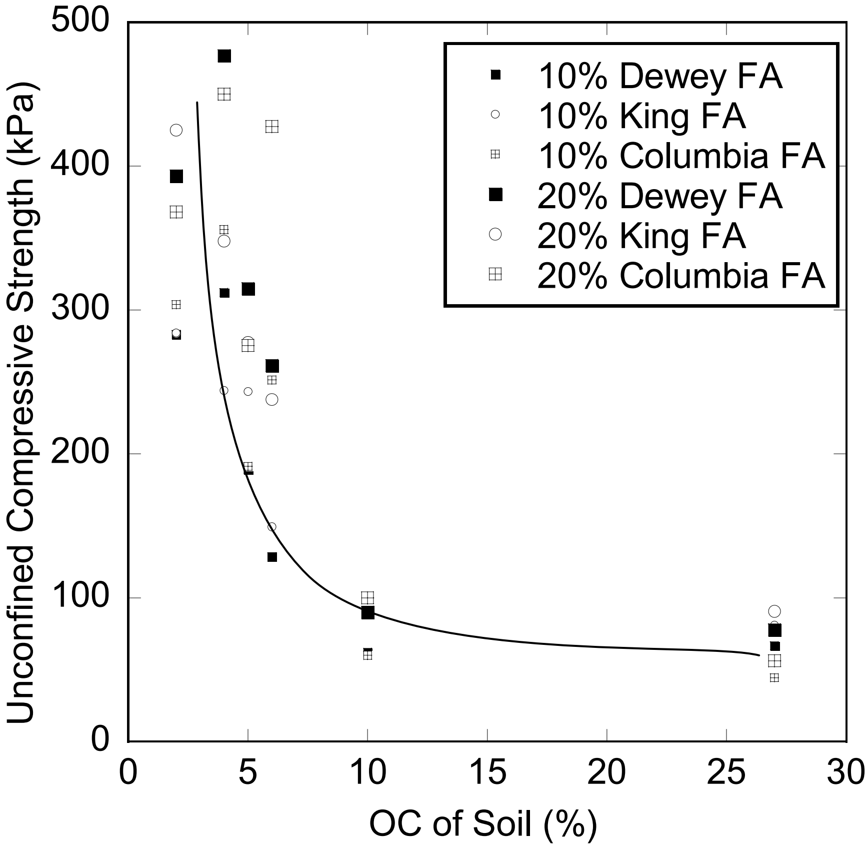

Figure 1.7. Unconfined compressive strengths of organic soil-fly ash mixtures as a function of CaO content of fly ash.

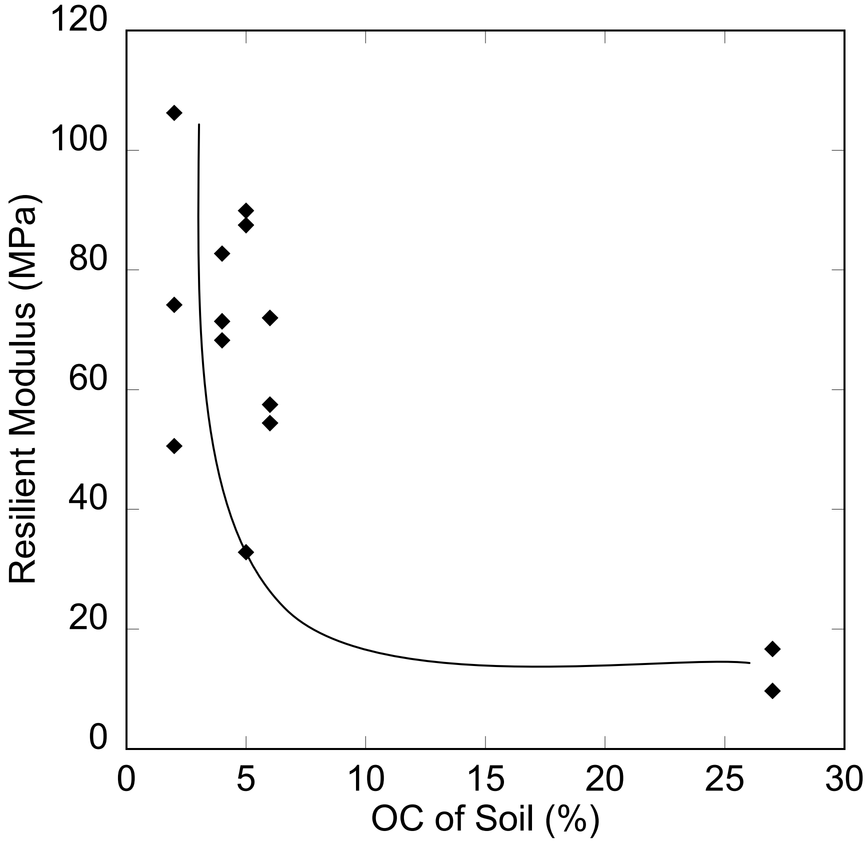

Figure 1.8. Resilient modulus of organic soil-fly ash mixtures as a function of CaO content of fly ash.

CHAPTER 2

2.1 INTRODUCTION

Construction of roadways on soft organic soils can be problematic because organic soils typically have low shear strength and high compressibility (Edil 1997). Current approaches for construction of roadways over organic soil subgrade include (i) removal of the organic soil to a sufficient depth and replacement with a crushed rock (referred to as "cut-and-replace"), (ii) preloading to improve engineering properties, and (iii) chemical stabilization with binders like cement, lime, and fly ash (Keshawarz and Dutta 1993, Sridharan et al. 1997, Kaniraj and Havanagi 1999, Parsons and Kneebone 2005). The cut-and-replace approach can be costly and time consuming, and preloading often is impractical because of the relatively long time that is required. In contrast, chemical stabilization can be conducted rapidly and at low cost, and therefore is becoming an important alternative (Hampton and Edil 1998).

Chemical stabilization of soft soils involves blending a binder into the soil to increase its strength and stiffness. The binder is intended to cement the soil solids, thereby increasing strength and stiffness. The binders generally are added as dry solids. Thus, addition of binder generally reduces the water content of the soil, which also results in an increase in strength and stiffness. Common binders include cement, lime, fly ash, or mixtures thereof. The use of fly ash as a binder is attractive because fly ash is an abundant industrial byproduct that is relatively inexpensive compared to cement and lime (Federal Highway Administration 2003). In addition, reusing fly ash for soil stabilization, particularly fly ashes that otherwise would be landfilled, promotes sustainable construction.

Many fly ashes can be used to effectively stabilize soft inorganic soils (Ferguson 1993, Acosta et al. 2003, Prabakar et al. 2004, Trzebiatowski, et al. 2005), but little is known regarding the effectiveness of stabilizing soft organic soils with fly ash. However, organic soils are known to be more difficult to stabilize chemically than inorganic soils (Janz and Johannson, 2002). This laboratory study was conducted to evaluate whether fly ashes can be used to increase the unconfined compressive strength and resilient modulus of soft organic soils. Three organic soils and six fly ashes were used in the study. The soils were Markey soil (sitly sandy peat), Lawson soil (moderately plastic organic clay), and Theresa soil (low plasticity organic sandy clay) and the organic content of these soils ranged from 5% to 27%. The fly ashes had a broad range of carbon content, CaO content, and relative abundance of CaO and SiO_2. The portion of the study dealing with unconfined compressive strength is described in this chapter.

2.2 BACKGROUND

2.2.1 Chemical Stabilization

When binders like lime and fly ash are blended with soil and water, a set of reactions occur that result in dissociation of lime in the binders and the formation of cementitious gels:

$$CaO + H_2O \Rightarrow Ca(OH)_2 \tag{1}$$

$$Ca(OH)_2 \Rightarrow Ca^{++} + 2[OH]^- \tag{2}$$

$$Ca^{++} + 2[OH]^- + SiO_2 \Rightarrow CSH \tag{3}$$

(calcium silicate hydrate gel)

$$Ca^{++} + 2[OH]^- + Al_2O_3 \Rightarrow CASH \tag{4}$$

(calcium aluminate silicate hydrate gel)

Eq. 1 is a hydration reaction that results in formation of calcium hydroxide, $Ca(OH)_2$. $Ca(OH)_2$ dissolves into Ca^{++} and $(OH)^-$ ions and liberation of $(OH)^-$ ions increases the pH of the pore water (Eq. 2).

Eqs.3 and 4 are referred to as pozzolanic and/or cementitious reactions that result in the formation of cementitious gels. The source for the pozzolans in Eqs.3 and 4 is either the soil or the binding agent. These reactions contribute to stabilization of soils in two ways. First, plasticity of the soil is reduced by the exchange of calcium ions in the pore water with monovalent cations on clay surfaces and by compression of the adsorbed layer due to the elevated ionic strength of the pore water (Rogers and Glendinning (2000)). Second, the CSH or CASH gels formed by pozzolanic reactions bind the solid particles together, and this binding produces stronger soil matrix (Arman and Munfakh 1972). When cement is used as a binder, reactions do not exactly happen as in Eqs.1-4, yet end products are similar, such as CSH gels. For organic soils, the binding reactions are expected to be more important for stabilization.

The abundance of CaO and pozzolans (a siliceous or aluminous material that has no cementing property alone, but forms cements in the presence of water and calcium hydroxide, Malhotra and Mehta 1996) in binders such as lime, fly ash, and cement influence their effectiveness as soil stabilizers. For example, because lime does not contain pozzolans like Si, Al, or Fe, the ability of binders to form in lime-amended soil is controlled by the availability of pozzolans from the soil.

As lime mixed with moist soil, the hydration of calcium oxide (CaO) ends in formation of $Ca(OH)_2$ (hydration reaction, Eq.1), and dissociation of $Ca(OH)_2$ (Eq. 2) favors dissolution of silica in clay particles by increasing the pH of the pore water. Then, silica-$Ca(OH)_2$ reaction (referred as pozzolanic reactions as in Eq3) gives rise to CSH formation around soil particles.

Both fly ash and portland cement contain lime and pozzolans, and therefore are self cementing. In fly ash, the pozzalans are in oxides such as Al_2O_3 and SiO_2. The effectiveness of a given fly ash is expected to depend on the relative abundance of CaO and oxides providing pozzolans. For example, Class C fly ashes (i.e., fly ashes meeting the requirements in ASTM C 618) have a CaO content > 20% (by weight) and a Al_2O_3+Fe_2O_3+SiO content between 50% and 70%. In contrast, Class F fly ashes have < 10% CaO. Consequently, Class C ashes generally are more effective at forming CSH and CASH gels than Class F ashes (Sridharan et al. 1997).

Janz and Johansson (2002) indicate that the CaO/SiO_2 ratio is an indicator of the potential for pozzolanic reactions and that binders having larger CaO/SiO_2 are likely to be more effective stabilizers. For example, C_3S clinker, which is a strong binder, has CaO/SiO_2 ratio of 3. Similarly, the ratio $CaO/(SiO_2+Al_2O_3)$ can be used as an indicator of the potential to form CSH and CASH gels. However, binders with a high CaO/SiO_2 ratio (or $CaO/(SiO_2+Al_2O_3)$ ratio) can be ineffective if pozzolanic reactions are limited by the availability of pozzolans (e.g., too little SiO_2 and or Al_2O_3)

2.2.2 Inhibition of Cementing Reactions by Organic Matter

Fly ash specifications for concrete applications usually include an upper bound on organic carbon content of the fly ash. This upper bound is normally characterized by the loss on ignition (LOI) measured with ASTM C 311. Similarly, organic matter in soil is known to affect stabilization using cements or fly ashes. For example, Tremblay et al. (2002) evaluated how cement stabilization of an inorganic soil (a clay having PI=26) was affected by organic content by adding organic compounds to the soil such as acetic acid, humic acid, tannic acid, ethylenediaminetetraacetic acid (EDTA), and sucrose. Specimens were prepared with 10% ordinary Portland Cement (Type 10) with and without organic ammendments. The undrained shear strengths of the soil-cement mixtures with some organic compounds, such as acedic acid and humic acid, did not exceed 15 kPa. A similar specimen without organic ammendments had an undrained shear strength exceeding 800 kPa. Tremblay et al. (2002) also suggested that pozzolanic reactions are likely to be inhibited if the pH of the soil-cement mixture is less than 9.

Clare and Sherwood (1954) indicated that the organic matter in organic soils adsorbs Ca^{2+} ions. When cement, lime or fly ash (any source of Ca^{2+} ions) is added to organic soils, following the hydration of lime, released Ca^{2+} ions are likely to be exhausted by the organic matter, which limits the availability of Ca^{2+} ions for pozzalanic reactions. Thus, the amount of CaO in fly ash should be large enough to compensate the consumption of Ca^{2+} ions by the organic matter in the soil. The interactions of organic compounds with pozzolanic minerals (Ca^{2+} or Al^{+3}) or $Ca(OH)_2$ can be summarized as follows; (1) calcium ions can be adsorbed by the organic matter instead of reacting with pozzolanic minerals, (2) organic compounds reacts with $Ca(OH)_2$ and precipitate which forms insoluble compounds and limits the availability Ca^{2+} ions for pozzolanic reactions, (3) alumina can form stable complexes with organic compounds, and calcium ions can also complex with organic compounds but Young (1972) stated that complexes formed by Ca^{2+} ions were not stable and would not affect the calcium ion equilibria, and (4) organic compounds can adsorb on $Ca(OH)_2$ nuclei which poison their growth and formation of CSH.

Hampton and Edil (1998) stated that organic matter in soils can preserve large amounts of water and they can reduce the amount of available water for hydration reactions when cementitious additive is blended with soil.

2.3 MATERIALS AND METHODS

2.3.1 Soils

Three soft organic soils having different organic contents were used in the study: Markey, Lawson, and Theresa. All soils were collected within 1.5 m of the ground surface and are typical of organic soils encountered as subgrade during roadway construction in Wisconsin. Index properties of the soils are summarized in Table 2.1 and the particle size distributions are shown in Figure 2.1. Compaction curves corresponding to standard Proctor effort (ASTM D 698) are shown in Figure 2.2. Optimum water content and maximum dry unit weight for each soil are summarized in Table 2.1.

The Markey soil is silty sandy peat (Pt designation in the Unified Soil Classification System, USCS), the Lawson soil is moderately plastic organic clay (OL-OH), and the Theresa soil is low plasticity organic sandy clay (OL in the USCS). Organic content (OC) of each soil was determined by loss on ignition (LOI) at 440 ^{o}C following ASTM D 2974. The Markey soil has the highest OC (27%). The Lawson and Theresa soils have similar OC (5 and 6%) and have much less organic matter than the Markey soil. All three soils have bell-shaped compaction curves (Fig. 2.2), but the maximum dry unit weight of these soils is lower than the typical for soils from Wisconsin having similar plasticity (Edil et al. 2005).

A silt from Boardman, Oregon (Boardman silt) was also used in the testing program. Index properties of the silt are summarized in Table 2.1 and the particle size distribution is shown in Fig. 2.3. This silt, which has similar particle size distribution as the fly ashes in the study, was used as a non-reactive binder in some of the mixtures to separate the effects of cementing and reduction in water content by adding dry solid.

2.3.2 Fly Ashes

Six fly ashes and one Type I Portland Cement were used in the study. The fly ashes were obtained from electric power plants in the upper Midwestern US and were selected to provide a broad range of carbon content (0.5-42%), CaO content (3.2-25.8%), and CaO/SiO_2 ratio (0.1-1.2). General properties of the fly ashes are summarized in Table 2.2 and particle size distributions of fly ashes are shown in Figure 2.3. Organic content of the fly ashes was measured by LOI at 550 ^{o}C following ASTM C 311.

The Stanton and Columbia fly ashes classify as Class C ash and the Coal Creek fly ash classifies as Class F ash according to ASTM C 618. The remainders are referred to as “off-specification” (OS) fly ashes because they do not meet the requirements for either Class C or Class F fly ashes in ASTM C 618. The Dewey, King, and Columbia fly ashes are derived sub-bituminous coals, the Presque Isle fly ash is derived from bituminous coal, and the Coal Creek and Stanton fly ashes are derived from burning lignite. All of the fly ashes, except for the Presque Isle fly ash which was collected by fabric filters, were collected by electrostatic precipitators and stored dry in silos.

Among the six fly ashes, Dewey has the highest carbon content (LOI=42%) and Coal Creek has the lowest carbon content (LOI=0.5%). King has the highest (CaO) content (25%) and Presque Isle has the lowest (CaO) content (3.2%). Dewey and King have the highest CaO/SiO_2 ratios (1.2 and 1.1), Stanton and Columbia have mid-range CaO/SiO_2 ratios (0.5 and 0.7), and Presque Isle and Coal Creek have the lowest CaO/SiO_2 ratios (0.1 and 0.2). All of the fly ashes have less CaO and a smaller CaO/SiO_2 ratio than the Type 1 Portland Cement (CaO content = 62%, CaO/SiO_2 ratio = 2.9). The fly ashes generally are comprised of silt-size particles (< 75 μm and > 2 μm), with a coarse fraction between 5% and 35% and a 2 μm fraction between 5% and 35%.

2.3.3 pH

pH of each soil was measured using both ASTM D 4972 (for inorganic soils) and ASTM D 2976 (for peats). These methods differ in the ratio of dry solid to distilled water that is used (1:1 for D 4972, 1:16 for D 2976). All three soils had near-neutral pH and both test methods yielded a similar pH.

pHs of each fly ash was measured using ASTM D 5239 and the procedure in Eades and Grim (1966). ASTM D 5239 uses a solid-distilled water ratio = 1:4 and allowance of 2 hr lag between mixing and pH measurement. The Eades and Grim method uses a solid-distilled water ratio of 1:5, and lag of 1 hr, and requires the use of CO_2-free distilled water. pH of the each fly ash was also measured at 1, 2, 6, 24, 48, and 96 hr after mixing to assess the pH change over time.

2.3.4 Unconfined Compression Testing

Unconfined compression (UC) tests were conducted on specimens prepared from the soils and soil-fly ash mixtures following ASTM D 5102. The strain rate was 0.21%/min, which is the rate same rate used by Edil et al. (2005) for evaluating soil-fly ash mixtures prepared with inorganic soils.

Test specimens were prepared in following steps; (1) mixing the dry soil and the dry fly ash, (2) spraying the water onto the mixture, (3) allowing the mixture to wait for two hours to simulate field conditions, and (4) compacting the mixture in a steel mold having a diameter of 33 mm and height of 71 mm. Compactive effort for specimen preparation was adjusted in such a way that the same impact energy per unit volume as in the standard proctor effort was applied (details are provided in Appendix A). After the compaction, the specimens were sealed in plastic and cured for one week in a room maintained at 100% relative humidity and 25ºC.

2.3.5 Statistical Analysis Methods

Statistical investigation of any relation between soil or fly ash characteristics and UCS of soil-fly ash mixtures was conducted in four stages: (i) calculating the Pearson product moment correlation coefficient (r), which varies between -1 and 1, (ii) testing for the existence of correlation, t-test, (iii) if correlation exists, trials of linear and quadratic curvilinear regression models to see which model best describes the relation based on F-test, and (iv) multiple regression model including all significant characteristics (Details are given in Appendix D). Multiple regression model included second order or transformed functions of properties investigated. Possible correlations between independent variables were also checked and highly correlated variables were dropped from the model.

2.4 RESULTS AND ANALYSIS

Soil-fly ash mixtures were prepared with fly ash contents (dry weight) of 10, 20, and 30%. Most of the tests were conducted on specimens prepared at a “very wet” water content corresponding to 9-11% wet of optimum water content for the Theresa and Lawson soils and 13-15% wet of optimum for the Markey soil. The “very wet” condition is intended to simulate the natural conditions in soft subgrades in the upper Midwestern US (Edil et al. 2005). Additional tests were conducted with the soil fraction at optimum water content per standard Proctor. These tests were conducted as well-defined control condition and to assess the effect water content. For the specimens prepared at optimum water content, fly ashes contents were only 10% and 20% (the specimens were unrealistically dry with 30% fly ash). Soil-cement mixtures were prepared at the “very wet” of optimum with 10% cement.

2.4.1 General Effect of Fly Ash

UC strengths of the soil-fly ash mixtures prepared at the very wet condition are shown as a function of fly ash type in Figure 2.4. UC strengths of mixtures prepared with organic soil and Boardman silt (non-reactive binder) or Type 1 Portland Cement (highly reactive binder) are also included in Figure 2.4 for comparison. Also shown in Figure 2.4 are UC strengths of each soil alone (no fly ash) when compacted at optimum water content and at the very wet condition. All unconfined compression test results are provided in Table 2.3.

Addition of fly ash to the soil resulted in a significant increase in UC strength relative to that of the unstabilized soil in the very wet condition. Once stabilized with fly ash, both the Lawson and Theresa soils classify as at least “stiff” subgrade (UC strength between 100 and 200 kPa (Bowles 1979), instead of “soft” (25-50 kPa) or “very soft” (0-25 kPa) in their unstabilized “very wet” condition. UC strengths exceeding 100 kPa were not always obtained for the Markey soil in the very wet conditions, but adding fly ash to the Markey soil did increase the UC strength by a factor of 1.0 to 10.1.

Comparison of the UC strengths obtained with different fly ashes indicates that the criteria used to define fly ashes for concrete applications (Class C) are not necessarily indicative of the effectiveness for soil stabilization. For example, in some cases the Dewey and King fly ashes both of which are OS fly ashes, resulted in comparable or greater increases in strength than the Columbia and Stanton Class-C fly ashes, which are used as concrete additives.

The effect of reactivity of the binder can be evaluated by comparing the UC strengths of the soil-fly ash mixtures to the UC compressive strengths obtained using cement and Boardman silt as the binder. UC strengths obtained with 10% cement at the very wet condition were always higher than those obtained 10% fly ash at the same water content, and in many cases 10% cement resulted in a higher UC strength than obtained with 30% fly ash. In contrast, the mixtures prepared with Boardman silt generally had lower UC strength than comparable soil-fly ash mixtures and, in some cases, the soil-fly ash mixtures had lower UC strength (e.g., some mixtures prepared with Lawson soil and Coal Creek or Presque Isle fly ashes). Thus, the increase in strength obtained by fly ash stabilization generally (but not always) is due to reactions as well as the reduction in water content obtained by adding dry solid, but the significance of the reactions depends on the type of fly ash.

The importance of reactivity is also illustrated in the effect of fly ash content. For most of the mixtures, the UC strength increased as the fly ash content increased (Fig. 2.4). The exceptions are the mixtures prepared with the less reactive fly ashes (Presque Isle and Coal Creek). Additionally, UC strength does not increase linearly with fly ash content. In most cases, the increase in UC strength obtained as the fly ash content was raised from 0-10% or 10-20% was larger than that obtained when the fly ash content was increased from 20-30%. Thus, the benefits accrued by adding more fly ash diminish as the fly ash content increases.

2.4.2 Effect of Fly Ash Characteristics

Graphs relating UC strength and to properties of the fly ash (LOI, CaO/SiO_2 ratio, $CaO/(SiO_2+Al_2O_3)$ ratio, CaO content, pH, and fineness) were prepared to identify characteristics of the fly ashes that had an important role in improving the UC strength of the organic soils (Figure 2.5). UC strengths of mixtures prepared at the very wet condition were shown because this condition is practical interest for the field (Edil et al. 2005). More discussion on the effect of water content is in a subsequent section.

The relationship between UC strength and each of the fly ash characteristics was tested for statistical significance by determining whether the Pearson correlation coefficient between UC strength and each of the fly ash variables is statistically different from zero. For this statistical analysis, the t-statistic (t) is computed from the correlation coefficient (r) as:

$$t = \frac{r-\rho}{\sqrt{\frac{1-r^2}{n-2}}} \tag{2.5}$$

where ρ is the population correlation coefficient (assumed to be zero) and n is the number of degrees of freedom (228 in this analysis). A comparison then is made between t and the critical t (t_{cr}) corresponding to a significance level α. If $t > t_{cr}$, then the Pearson correlation coefficient is significantly different from zero and a significant relationship exists between UC strength and the fly ahs property. In this analysis, α was set at 0.05 (the commonly accepted significance level), which corresponds to t_{cr} = 1.96.

Inspection of Figure 2.5 suggests that UC strength is not affected by LOI, pH, or fineness (percentage retained on 0.044 mm sieve, an index of surface area) of the fly ash. This observation is consistent with the statistical analysis, which shows that UC strength is not correlated (t < 1.96) with LOI, pH, or fineness. In contrast, UC appears related to CaO content, CaO/SiO_2, and $CaO/(SiO_2+Al_2O_3)$, and the statistical analysis supports this observation ($t > 1.96$ for CaO content, CaO/SiO_2, and $CaO/(SiO_2+Al_2O_3)$). Relatively strong relationships exist between UC strength and these parameters for the Lawson and Theresa soil, whereas weaker relationships exist for the Markey soil. The relationships between UC strength and CaO/SiO_2 and $CaO/(SiO_2+Al_2O_3)$ for the Lawson and Theresa soils are illustrated with second-order non-linear regressions, shown as solid lines in Figures 2.5b and 2.5c.

The graphs in Figure 2.5 suggest that both CaO and CaO/SiO_2 or CaO and $CaO/(SiO_2+Al_2O_3)$ are important variables affecting the UC strength of the soil-fly ash mixtures prepared with the Lawson and Theresa soils. The highest UC strengths were obtained when the CaO content was at least 10, CaO/SiO_2 was between 0.5 and 1.0, and $CaO/(SiO_2+Al_2O_3)$ was between 0.4 and 0.7. A similar conclusion can be drawn for the Markey soil, although the trends in UC for the Markey soil are modest. As illustrated in Figure 2.5d, CaO content alone is not sufficient to evaluate whether a fly ash will cause an increase in UC strength. The circled data in Figure 2.5d correspond to mixtures prepared with the Lawson and Theresa soils and Coal Creek (CaO content = 13%) or Dewey fly ash (CaO content = 9%). Appreciably higher strengths are obtained with Dewey fly ash, even though the Coal Creek fly ash also has greater CaO because the Coal Creek fly ash has a significantly lower CaO/SiO_2 ratio (0.26) than Dewey fly ash (1.15).

2.4.3 Effect of Soil Type

The influence of organic soil type was evaluated by graphing UC compressive strength against OC and PI (Figure 2.6). Soil pH was not included in the analysis because the pH varied over a narrow range (6.1-7.3). As in the analysis of fly ash properties, the UC strengths of mixtures prepared shown in Figure 2.6 correspond to the very wet condition.

Data for soil-fly ash mixtures from the study conducted by Edil et al. (2005) were also included in the analysis to increase the generality of the findings. Edil et al.

(2005) used variety of soils (7 different soils) having different organic contents ranging from 1% to 10% and plasticity indexes ranging from 15 to 38 and they mixed these soils with 4 different fly ashes. Three fly ashes (Dewey, King and Columbia) they used were from the same source with the ones used in this study. UC strength data for different mixtures each having one of the following soils, inorganic clay (OC=2%, PI=38), slightly organic clay (OC=4%, PI=35) and organic clay (OC=10% and PI=19) and one of the following fly ashes, Dewey, King and Columbia fly ashes were adopted from their study.

As shown in Figure 2.6a, UC decreases significantly as the OC increases to 10%, and then levels off for higher OC. This inverse relationship between UC and OC may reflect the inhibitition of pozzolanic reactions by organic matter. Alternatively, the inverse relationship between UC and OC may reflect the weakness of organic solids relative to mineral solids. Regardless, the trend in Figure 2.6a suggests that fly ash stabilization is unlikely to be effective when the OC exceeds 10%.

The effect of PI on UC is shown in Figure 2.6b. Higher UC strengths are obtained when the PI is 8 or more. However, the apparent effect of PI in Figure 2.6b probably is spurious. The trend is more likely related to OC, because the Markey soil had the highest OC and the lowest PI of the soils that were tested. A broader range of soils is needed to adequately assess the effect of PI.

2.4.4 Effect of Water Content

The effect of water content on the stabilization was investigated by graphing the UC strength of the soil-fly ash mixture prepared at very wet of optimum vs. the UC strength of the soil-fly ash mixture prepared at optimum water content. (Figure 2.7) When the fly ash percentage is 10%, soil-fly ash mixtures prepared at optimum water content usually have higher UC strengths as opposed to the ones prepared at very wet optimum. On the other hand, as the fly ash percentage is increased to 20%, soil-fly ash mixtures prepared at optimum water content usually have lower UC strength than mixture prepared at very wet of optimum, unlike the 10% fly ash case. The shear strength of cohesive soils generally is inversely related to water content (Seed and Chan, 1959). However, according to Figure 2.7, soil-fly ash mixture prepared at wet of optimum, particularly when the fly ash percentage is high, can have higher UC strength than that of the mixture prepared at optimum water content. There are two possible explanations for this observation; (1) the specimen disturbance, which reduces UC strength, is more significant for relatively dry specimens prepared at optimum water content than the disturbance for the ones prepared at very wet of optimum, and (2) the specimens prepared at optimum water content may have had lower strengths in some cases because of inadequate water for the pozzolanic reactions. For example, in Fig. 2.8, UC strengths of the mixtures prepared with Boardman silt (non-reactive binder) are graphed vs. UC strengths of mixtures prepared with the fly ashes. In nearly all cases, the soil-fly ash mixtures have higher UC strengths than the mixtures prepared with Boardman silt for the very wet condition. However, at optimum water content, the UC strengths tend to be more similar for the soil-fly ash mixtures and the mixtures prepared with Boardman silt. That is, the reactivity effect appears to diminish as the water content decreases.

2.4.5 Effect of pH of the Soil-Fly Ash Mixture

pHs measurements at 1, 2, 24, 48, and 96 hours were not significantly different When Lawson and Theresa soils were mixed with a fly ash having CaO content higher than 10, pH of the mixture reached above 9 which indicates that cementitious reactions are not likely to be inhibited (Tremblay et al. 2002). pH of the mixtures involving Markey soil were also above 9 as the percentage of fly ash, the ones having CaO content more than 10%, was increased to 30%.

The effect of pH on the UC strength of the soil-fly ash mixtures is shown in Figure 2.9. There is no apparent relationship between UC strength and mixture pH.

Tremblay et. al mixed 14 different organic compounds with the soil (two soils, a clay and a silt)-cement (two cements, ordinary Portland type 10 and sulphate-rich geolite 20) mixture and investigated the effect of organic compound on the soil stabilization. They reported that if an organic compound caused a pore solution pH of less than 9, no strength gain was noted. However, they also mentioned that having a pore solution pH of more than 9 does not always indicate significantly high strengths. Figure 2.9 seems to verify their conclusion that having pH higher than 9 does not indicate higher UC strengths.

2.4.6 Model for Stabilization of Organic Soils with Fly Ashes

The important factors in stabilization of organic soils with fly ash can be summarized as follows: (1) fly ash properties: CaO content and CaO/SiO_2 ratio, (2) soil properties: OC and (3) mixture characteristics: fly ash content and water content. Each of these variables was included in a non-linear regression analysis to find an equation that can be used to predict the UC of organic soil-fly ash mixtures. Only data for the very wet condition were included because this condition is of practical importance. The UC of the soil alone was also included in the analysis. Details of the method used to conduct the non-linear regression are described in Appendix E.

The following regression model was proposed,

$$\begin{aligned} q_{u-treated} &= -320 + 795(CaO/SiO_2) - 573(CaO/SiO_2)^2 - 125673(e^{-OC}) \\ &+ 6(FAperc) + 25(q_{u-untreated}) - 33(pH_{mixture}) \end{aligned} \tag{2.6}$$

where FAperc= fly ash percentage, pHmixture= ph of the soil-fly ash mixture after one hour, $q_{u\text{-treated}}$= stabilized UC strength of soil, $q_{u\text{-untreated}}$= untreated UC strength of soil and OC is in percent, q_u is in kPa, and others are ratios. According to Eq.2.3, followings can be inferred; (i) there is an optimum $(CaO/SiO)_2$ ratio which maximizes the stabilized strength of the soil, (ii) increase in fly ash percentage increases UC strength of the soil-fly ash mixture, and (iii) higher UC content of the soil indicates less UC strength of the soil-fly ash mixture. The model does not include CaO, because it is highly correlated with other terms in the mode. However, the physical effect of CaO content is still reflected in the model by mixture pH term.

A comparison of predicted UC strength versus the measured unconfined strength is shown in Figure 2.10. According to Figure 2.10, regression model predicts the UC strength of the soil-fly ash mixture with an R^2 of 0.71.

2.5 CONCLUSION

The objective of this study was to determine if unconfined compressive (UC) strength of soft organic soils can be increased by blending fly ash into the soil. Tests were conducted with three organic soils and six fly ashes (a cement and a silt was also used as a binder for reference purposes). Fly ashes were mixed with the soil at three different percentages and two different water contents.

Results of the testing program showed that the UC compressive strength of organic soils can be increased using fly ash, but the amount of increase depends on the type of soil and characteristics of the fly ash. Large increases in UC compressive strength (from 30 kPa without fly ash to > 400 kPa with fly ash) were obtained for two clayey soils with an organic content (OC) less than 10% when blended with some of the fly ashes. More modest increases in UC strength (from 15 kPa without fly ash to > 100 kPa with fly ash) were obtained for a highly organic sandy silty peat having OC = 27%. The increases in strength were attributed primarily to cementing caused by pozzolanic reactions, although the lower water content obtained by adding dry fly ash solid also contributed to the increase in UC strength.

The significant characteristics of fly ash affecting the increase in UC strength include CaO content and CaO/SiO_2 ratio (or $CaO/(SiO_2 + Al_2O_3)$ ratio). The highest UC strengths were obtained when the CaO content was greater than 10% and the CaO/SiO_2 ratio was between 0.5-0.8. Comparable increases in UC strength were obtained with the Class C ashes, normally used in concrete applications, and the off-specification fly ashes meeting the aforementioned criteria for CaO content and

CaO/SiO_2 ratio. However, much lower UC strengths were obtained with one Class F ash one off-specification fly ash primarily due to their low CaO content and CaO/SiO_2 ratio. Carbon content of the fly ash seemed to have no bearing on the UC strength of the soil-fly ash mixtures.

For most of the cases UC strength increased when fly ash percentage was increased. Exceptions were mixtures having less reactive Presque Isle and Coal Creek fly ashes ($CaO<10\%$ and $CaO/SiO_2<0.5$)

The reactivity effect appears to diminish as the water content decreases, i.e, improvement in the UC strength of the soil due to addition of a fly ash or a silt to the soil was approximately the same for the mixtures prepared at optimum water content. When the fly ash percentage in the mixture is 10%, expected trend of having higher UC strengths when water content decreases was observed. On the other hand, as the fly ash percentage is increased to 20% (more reduction in water content compared to 10% fly ash case), soil-fly ash mixtures prepared at very wet of optimum water content usually had higher UC strengths than the ones prepared at optimum water content had. The unexpected trend of having stronger mixtures at very wet conditions as opposed to the ones prepared at optimum water content is attributed to either inadequate water for pozzolanic reactions or more significant specimen disturbance for the mixtures prepared at optimum water content.

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Table 2.1. Index properties and classifications of soils used in study.

Soil Name	Liquid Limit	Plasticity Index	Percent Fines	Specific Gravity Solids	OC (%)	Classification		pH		γ_d (kN/m^3)	w_{OPT}
						USCS	AASHTO	ASTM D 4972	ASTM D 2976		
Markey	53	1	25	2.23	27	Pt	A-8 (0)	5.9	6.3	10.3	47
Theresa	31	8	75	2.57	6	OL	A-4 (5)	7.6	7.1	15.2	21
Lawson	50	19	97	2.58	5	OL-OH	A-7-5 (23)	6.9	6.8	13.3	28
Boardman	22	1	79	2.67	1	ML	A-2-4(0)	-	-	17.3	16.5

OC = organic content measured by loss on Ignition, , γ_d = maximum dry unit weight, w_{opt}=optimum water content, numbers in parantheses a AASHTO classification are group indices

Table 2.2. Properties and classifications of fly ashes.

Parameter	Dewey	King	Presque Isle	Coal Creek	Columbia	Stanton	Type 1 Portland Cement
SiO_2 (%)	8.0	24.0	35.6	50.4	31.1	40.2	20.4
Al_2O_3 (%)	7.0	15.0	18.0	16.4	18.3	14.7	4.8
Fe_2O_3 (%)	2.6	6.0	3.5	7.2	6.1	8.7	2.7
CaO (%)	9.2	25.8	3.2	13.3	23.3	21.3	64.9
MgO (%)	2.4	5.3	1.0	4.3	3.7	6.6	-
CaO/SiO_2	1.2	1.1	0.1	0.3	0.8	0.5	3.2
$CaO/(SiO_2+Al_2O_3)$	0.9	0.9	0.1	0.2	0.4	0.6	2.6
pH	9.9	10.9	11.3	11.9	12.8	11.7	-
Fineness (%)	27	41	25	28	12	23	-
Loss on Ignition (%)	42	12	34	0.5	0.7	0.8	-
Specific Gravity	2.00	2.66	2.11	2.59	2.63	2.63	-
Classification	OS	OS	OS	F	C	C	-

OS = off specification, not meeting C or F designations in ASTM C 618.

Table 2.3. Summary of Unconfined Compressive Strengths

Addtive	Markey Soil							Lawson Soil							Organic Theresa Soil						
	Wet of Optimum				Optimum			Wet of Optimum				Optimum			Wet of Optimum				Optimum		
	Soil Alone	10%	20%	30%	Soil Alone	10%	20%	Soil Alone	10%	20%	30%	Soil Alone	10%	20%	Soil Alone	10%	20%	30%	Soil Alone	10%	20%
Dewey	13.94	44.2	88.3	121.6	41.9	70.1	26.2	41.3	196.2	349.5	112.1	112.1	193.3	229.1	31.6	114.3	285.9	383.6	129.2	271.6	408.2
	16.20	51.8	105.0	122.7	42.7	42.8	47.9	58.2	193.1	296.9	121.3	121.3	179.1	246.8	42.9	148.6	279.9	391.9	126.0	260.9	381.1
	15.75	62.0	104.3	126.4	56.5	61.2	27.5	71.8	178.5	306.3	135.9	135.9	189.3	272.4	33.3	122.6			144.0		
	(60)	*(61)*	*(61)*	*(57)*		*(48)*	*(50)*	*(36)*	*(36)*	*(37)*	*(38)*	*(30)*	*(28)*	*(30)*	*(29)*	*(33)*	*(43)*	*(29)*	*(22)*	*(23)*	*(22)*
King		42.1	67.4	120.0		46.5	32.9		248.4	326.6	377.4		273.2	275.4		150.4	236.6	285.4	129.2	429.0	239.2
		49.5	82.1	141.4		50.1	24.1		238.8	327.9	342.6		327.4	295.4		158.9	247.9	300.6	126.0	452.1	262.5
		55.1	81.4	132.0		57.8	43.4			306.2			307.0			138.8	229.3		144.0		253.7
		(60)	*(63)*	*(58)*		*(53)*	*(50)*		*(37)*	*(36)*	*(39)*		*(28)*	*(31)*		*(32)*	*(36)*	*(30)*		*(24)*	*(21)*
Presque Isle		57.7	82.5	70.1		52.4	23.9		145.2	200.9	104.0		215.6	139.8		119.9	134.8	161.6	129.2	122.0	
		68.5	99.8	69.0		29.6	24.1		130.9	225.8	83.5		232.7	157.4		124.8	172.8	195.2	126.0	112.4	
		69.6	92.4			64.8	24.3		137.0	230.7			251.2			131.4	129.0	138.6	144.0	117.6	
		(62)	*(60)*	*(58)*		*(51)*	*(50)*		*(36)*	*(39)*	*(39)*		*(30)*	*(29)*		*(31.5)*	*(31)*	*(31)*		*(21)*	*(22)*
Coal Creek		50.7	77.7	67.7		36.7	73.0		274.8	256.0	112.4		389.2	238.3		129.6	127.6	228.7	129.2	254.9	284.7
		46.8	88.5	67.4		32.6	58.2		237.7	249.8	133.1		340.0	245.4		101.4	144.4	257.2	126.0	239.1	171.6
		49.7	90.2	64.0		39.6	59.2		248.4	241.6	129.9		391.2	241.8		98.1	167.7	247.1	144.0	247.0	176.2
		(61)	*(61)*	*(59)*		*(51)*	*(56)*		*(37)*	*(39)*	*(42)*		*(28)*	*(30)*		*(32)*	*(31)*	*(30)*		*(20)*	*(21)*
Stanton		53.4	91.4	145.0		63.4	37.3		296.5	353.1	368.0		172.6	194.5		212.2	401.6	513.6	129.2	278.5	378.7
		74.7	106.7	139.0		81.1	45.9		279.2	416.9	435.0		180.3	210.8		199.6	376.3	463.8	126.0	220.2	351.8
		83.9	101.7	153.9		81.3	65.4		251.7		405.5		156.2			204.6			144.0	199.9	
		(61)	*(62)*	*(61)*		*(48)*	*(50)*		*(38)*	*(37)*	*(37)*		*(23)*	*(28)*		*(29)*	*(28)*	*(29)*		*(21)*	*(22)*
Columbia		39.2	38.7	145.0		84.5	86.8		176.6	252.1	420.3		336.3	252.1		228.1	438.2	481.2		287.7	
		41.4	50.4	76.0		74.2	120.0		197.2	286.0	408.2		321.6	266.9		235.8	395.0	489.6		217.5	
		53.3	79.7	83.5		82.1	96.8		200.0	288.6	399.6						448.8				
		(64)	*(58)*	*(58)*		*(50)*	*(48)*		*(41)*	*(40)*	*(40)*		*(31)*	*(32)*		*(31)*	*(30)*	*(30)*		*(21)*	*(19)*
Boardman Silt		33.9	46.6	52.4		106.3	111.8		90.6	135.3	192.8		223.0	303.6		45.9	56.6	102.3		161.3	220.6
		32.0	55.7	54.8		106.3	118.4		93.3	145.8	215.6		278.9	269.5		56.5	61.7	113.6		217.5	167.6
		33.7	67.5	65.8		125.6	122.1		129.0	135.0	221.2		306.7			67.3	83.8	105.6		238.7	
		(60)	*(64)*	*(61)*		*(52)*	*(53)*		*(36)*	*(36)*	*(36)*		*(26)*	*(26)*		*(33)*	*(32)*	*(32)*		*(22)*	*(23)*
Type 1 Portland Cement		101.0							510.9							457.2					
		103.0							456.6							525.9					
		83.9							467.2							423.4					
		(65)							*(39)*							*(30)*					

*Numbers in parantheses indicate water contents at which specimens are prepared

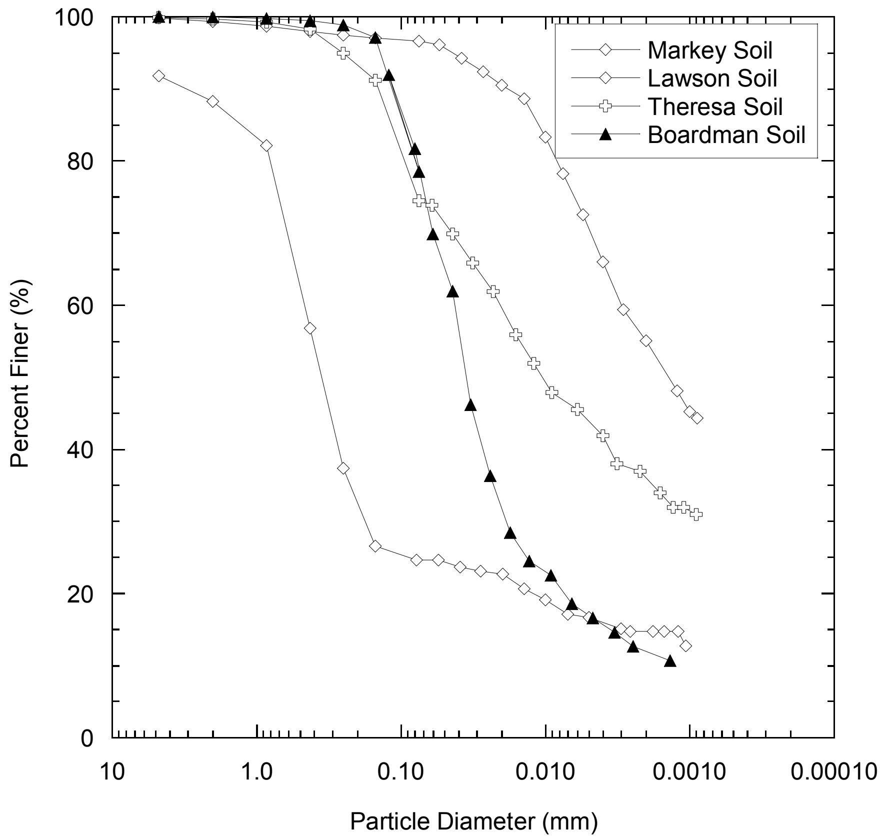

Figure 2.1. Particle size distributions of soils.

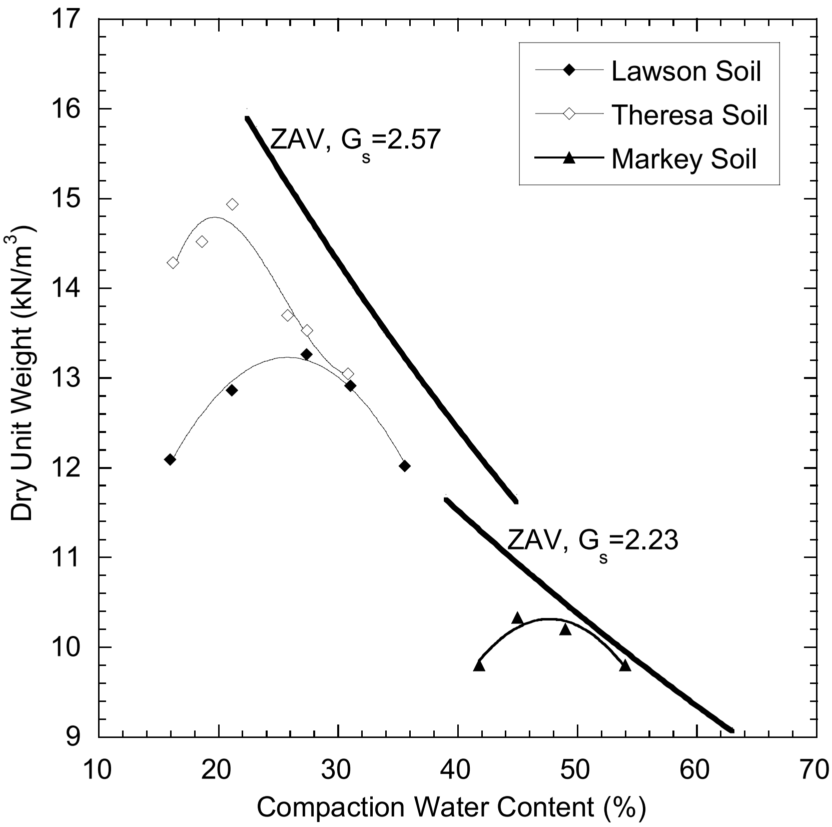

Figure 2.2. Compaction curves for soils corresponding to standard Proctor effort (ASTM D 698).

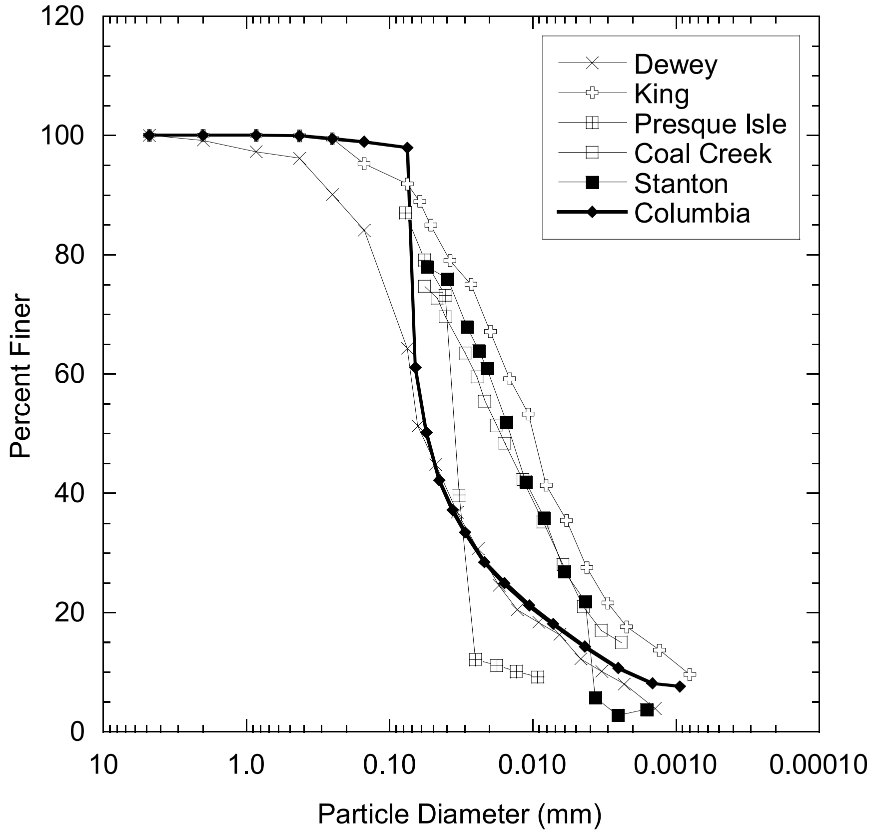

Figure 2.3. Particle size distributions of fly ashes.

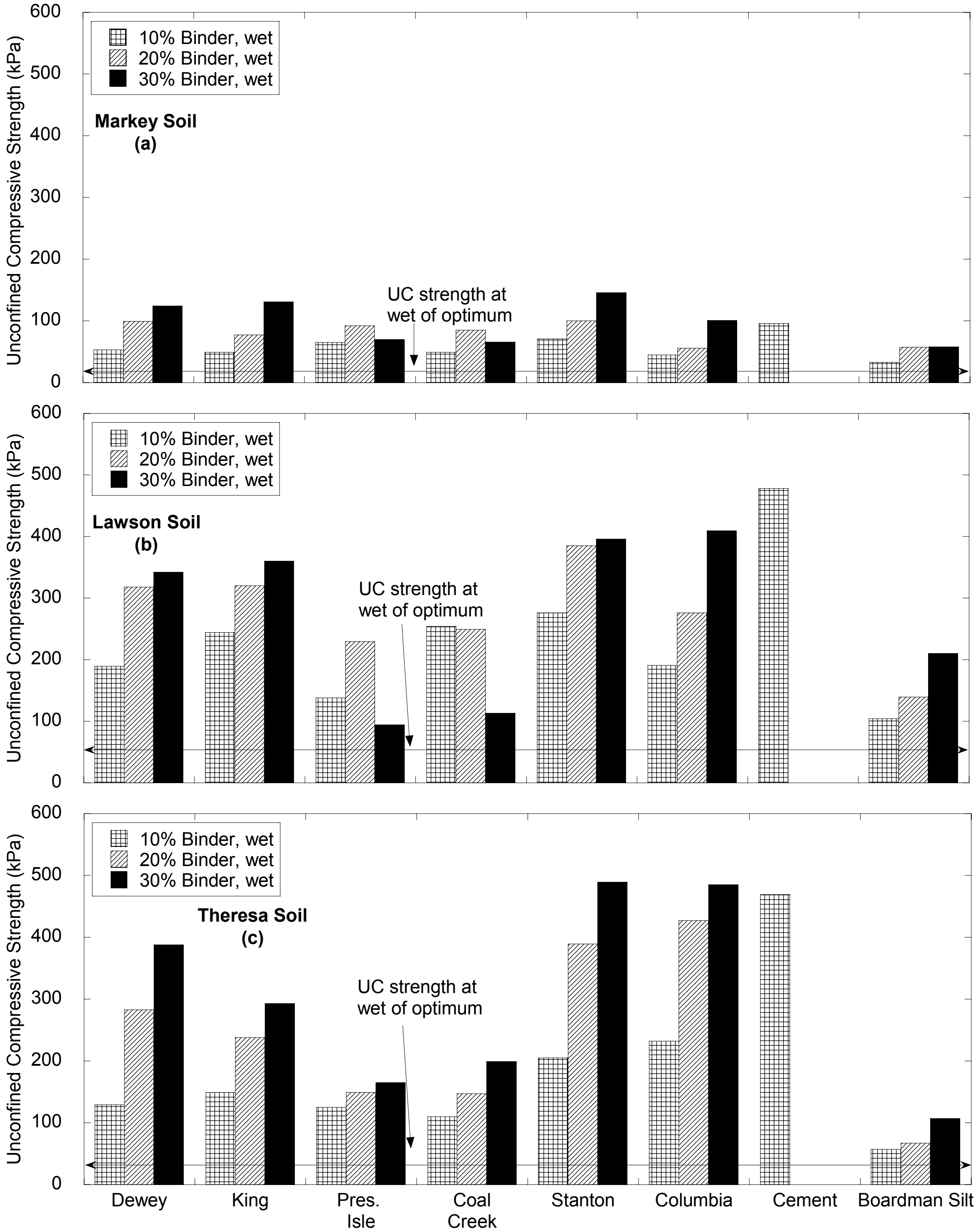

Figure 2.4. UC strength of mixtures prepared with various fly ashes, Type I Portland cement, and Boardman silt at very wet water content: (a) Markey Soil, (b) Lawson Soil, and (c) Theresa Soil. FA=fly ash

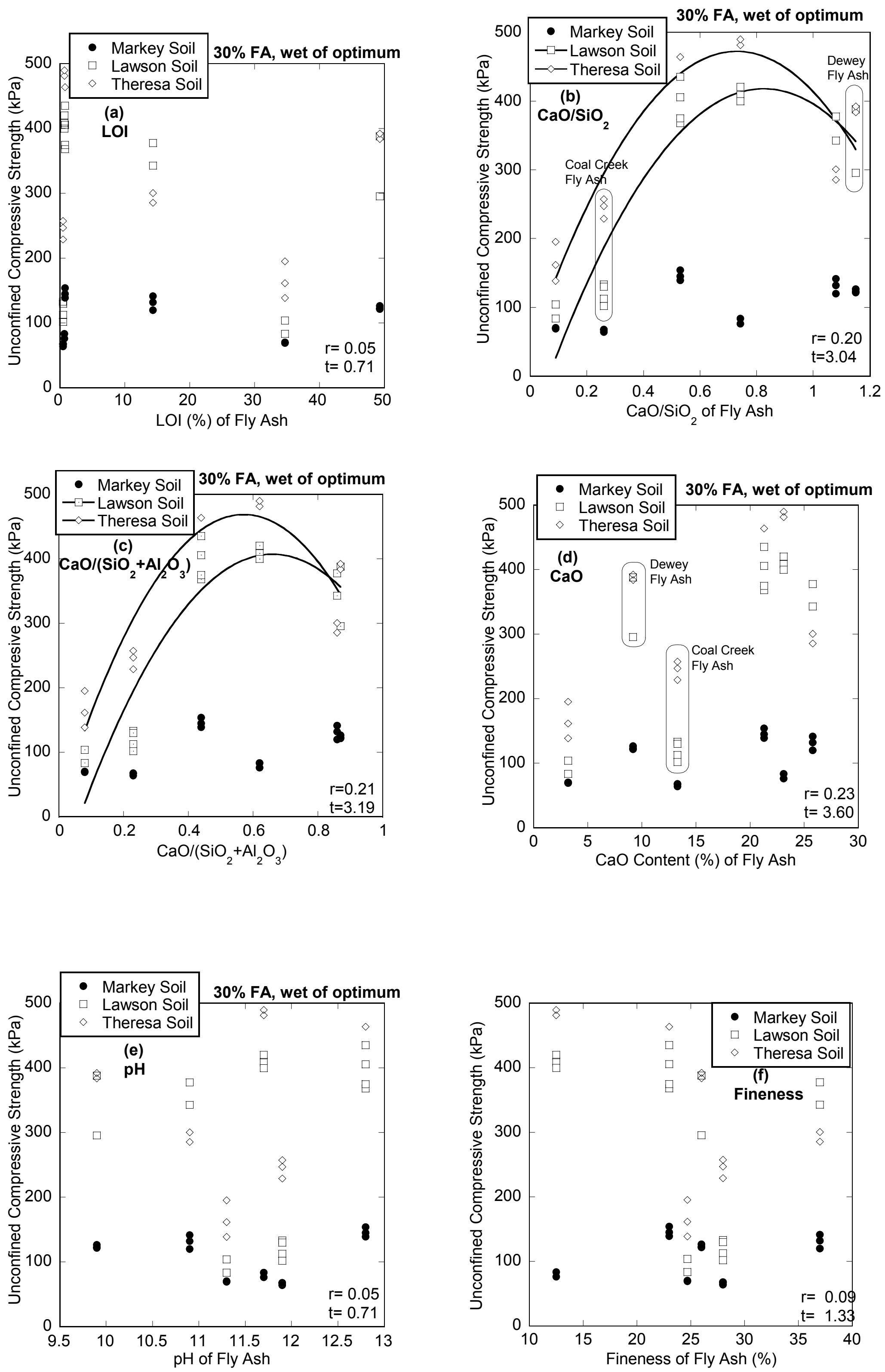

Figure 2.5. UC strength of soil-fly ash mixtures prepared at very wet water content as a function of fly ash properties: (a) LOI, (b) CaO/SiO_2 ratio, (c) $CaO/(SiO_2+Al_2O_3)$ ratio, (d) CaO Content, and (e) pH, and (f) fineness.

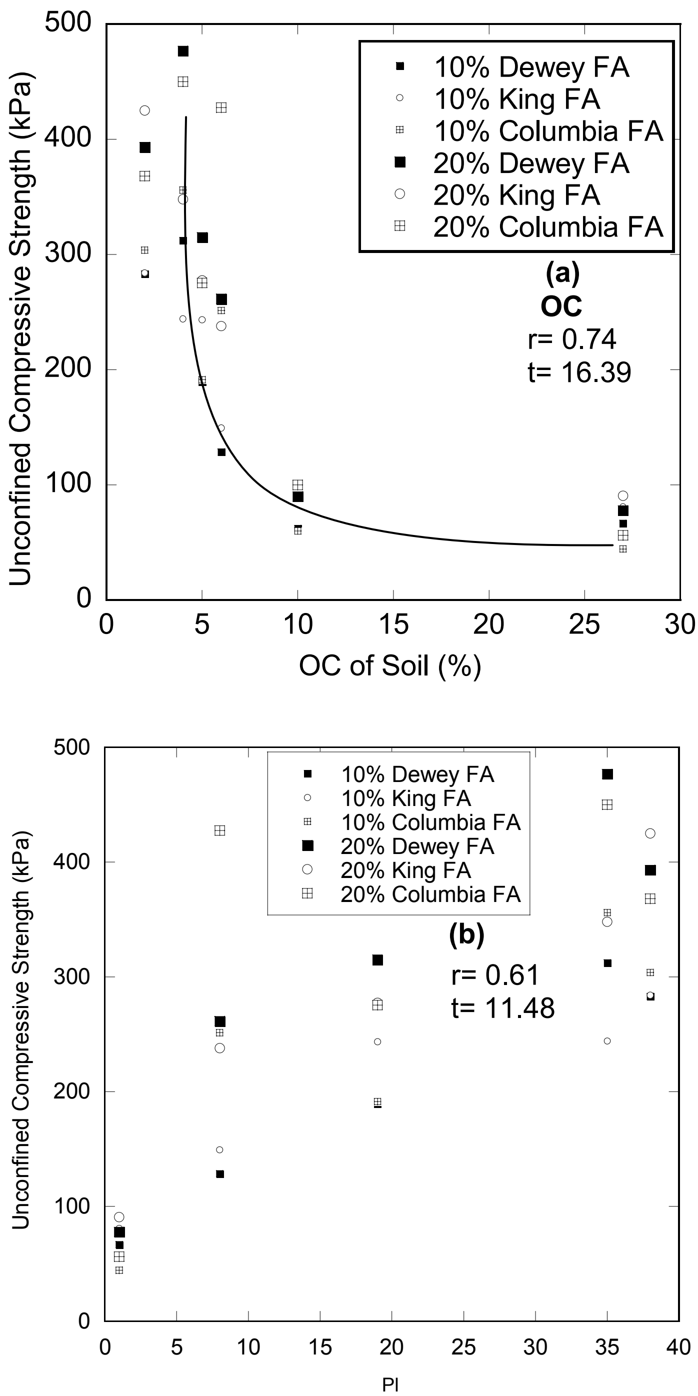

Figure 2.6. UC strength of soil-fly ash mixtures as a function of (a) OC and (b) PI of soil. FA=fly ash .

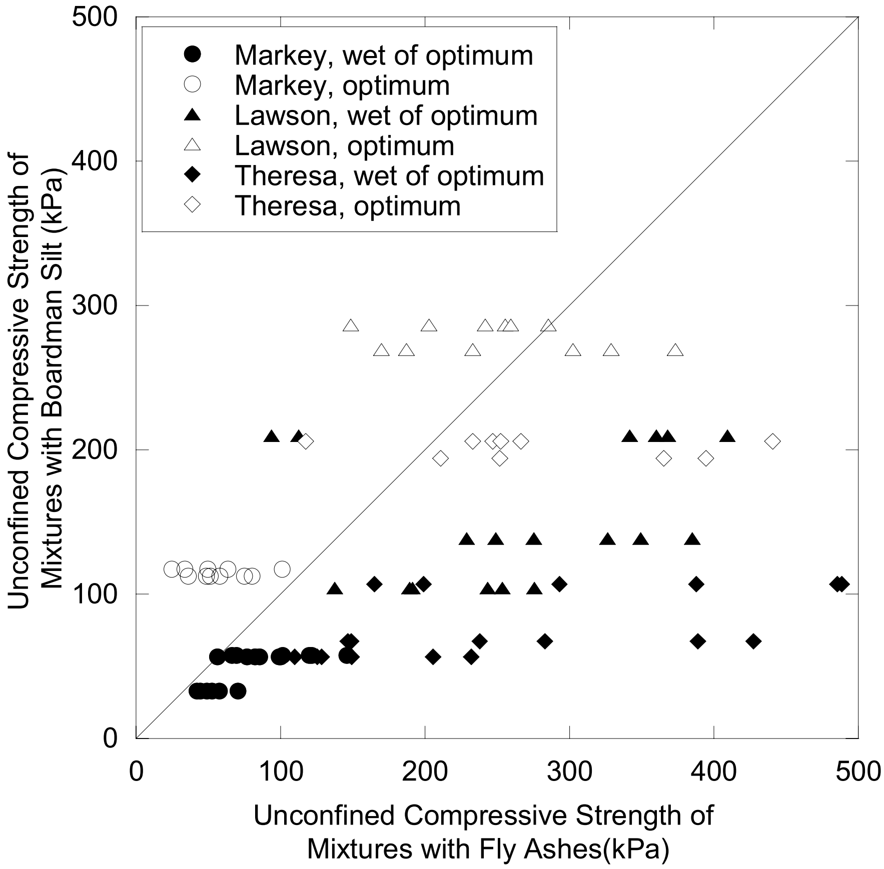

Figure 2.7. UC strength of mixtures prepared with Boardman silt vs. unconfined compressive strength of soil-fly ash mixtures prepared at the same binder content and water content.

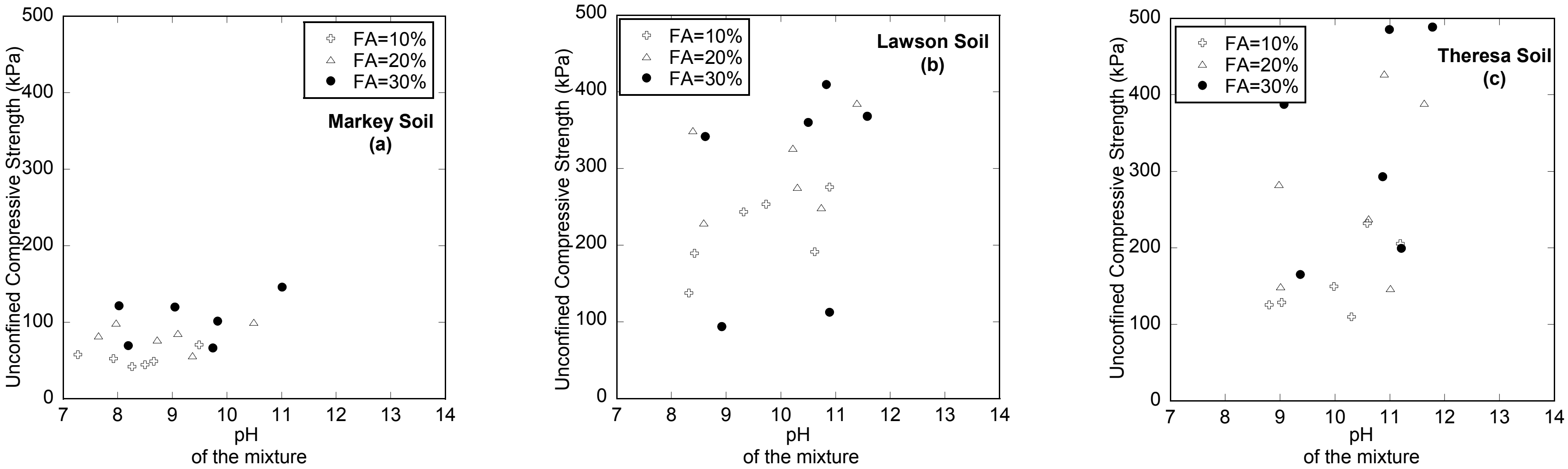

Figure 2.8. Unconfined compressive strength of soil-fly ash mixtures prepared at very wet water content as a function of mixture pH after one hour: (a) Markey Soil, (b) Lawson Soil, and (c) Theresa Soil. FA=fly ash percentage.

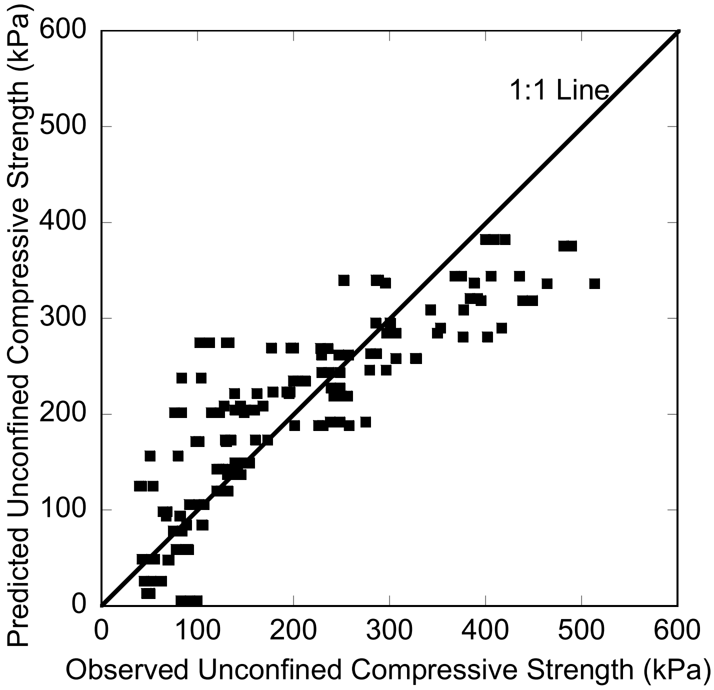

Figure 2.9 Predicted unconfined compressive strength of soil-fly mixture using the model vs. measured unconfined compressive strength

CHAPTER 3

3.1 INTRODUCTION

Organic soils have low shear strength and high compressibility (Edil 1997) and, thus, construction of roadways over organic soils is problematic. Blending fly ash to ameliorate the engineering properties of organic soil stands as a more convenient alternative over other options such as cut-replace approach or preloading since fly ash stabilization can be conducted rapidly and at low cost (Chapter 2). The advantage of using fly ash originates from its abundance and relatively inexpensive (Ferguson 1993, Federal Highway Administration, 2003).

Fly ash stabilization involves blending soil with the fly ash to increase the strength and stiffness of the soil. Fly ash is blended as a dry powder with the soil. Therefore, addition of fly ash generally reduces the water content of the soil.

The use of fly ash to stabilize subgrade soils has been investigated by many researchers and they reported that many fly ashes improved the engineering properties of soft inorganic subgrade soils such as unconfined compressive strength, CBR and Resilient Modulus (Lee and Fishman (1992), Turner 1997, Sridharan et al. 1997, Edil et al. 2002, Acosta et al. 2003, Trzebiatowski et al. 2005). However, research on the use of fly ash for stabilization of organic soils is sparse.

Organic soils are known to be more difficult to stabilize chemically than inorganic soils (Janz and Johannson, 2002). This laboratory study was conducted to evaluate whether fly ashes can be used to increase the unconfined compressive strength and resilient modulus of soft organic soils. Three organic soils and six fly ashes were used in the study. The soils were Markey soil (sitly sandy peat), Lawson soil (low plasticity organic sandy clay), and Theresa soil (moderately plastic organic clay) and the organic content of these soils ranged from 5% to 27%. The fly ashes had a broad range of carbon content, CaO content, and relative abundance of CaO and SiO_2. The portion of the study dealing with resilient modulus is described in this chapter.

3.2 BACKGROUND

3.2.1 Fly Ash Stabilization

Fly ash stabilization is a type of chemical stabilization in which pozzolanic reactions happen as follows:

$$CaO + H_2O \Rightarrow Ca(OH)_2 \quad (3.1)$$

$$Ca(OH)_2 \Rightarrow Ca^{++} + 2[OH]^- \quad (3.2)$$

$$Ca^{++} + 2[OH]^- + SiO_2 \Rightarrow CSH \quad (3.3)$$

(CSH=calcium silicate hydrate gel)

$$Ca^{++} + 2[OH]^- + Al_2O_3 \Rightarrow CASH \quad (3.4)$$

(CASH=Calcium aluminate silicate hydrate gel)

End products, CSH and CASH, are formed on the surface of soil particles, bind soil particles, reduce the pore space and form a stronger soil matrix. Fly ashes having high lime content are likely to increase pore solution pH with the liberation of more $[OH]^-$ ions (Eg.3.2). Ca^{++} ions, liberated after disassociation of $Ca(OH)_2$, react with pozzolans (Si or Al) and form cementitious gels (Eq.3.3). A pozzolan is a siliceous or aluminous material which has no cementing property but forms compounds having cementitous properties in the presence of moisture and calcium hydroxide (Malhotra and Mehta 1996). If sulfate is present, after CASH is formed, formation of ettringite is also likely. Ettringite formation is accompanied by swelling (Janz and Johansson 2002). Heebink and Hassett (2001) stated that ettringite formation decreases the water content of wet soils and contribute strength improvement. On the other hand, Hampton and Edil (1998) reported that ettringite is not as strong or stable as CSH gels.

Formation of gels (Eqs. 3.3 and 3.4) depends on CaO and pozzolanic mineral content of fly ash and the lack of either one of them impedes pozzolanic reactions.

Hanz and Johansson (2002) defined CaO/SiO_2 ratio as an indicator of binder reactivity. This ratio can also be interpreted as $CaO/(SiO_2+Al_2O_3)$ to account for formation of both possible pozzolanic reaction end products, CSH and CASH. Sufficient Ca^{++} ions are provided for pozzolanic reactions when a fly ash having high CaO/SiO_2 ratio is used. However, very high CaO/SiO_2 ratio, such as 5-10 represents an abundance of CaO but lack of SiO which indicates that pozzolanic reactions can not be completed.

ASTM C 618 classification for fly ashes considers fly ashes having LOI (loss on ignition test at 550ºC) of greater than 6% as off-specification fly ashes. Soil stabilization with Class-C fly ash, having LOI of less than 6%, has been a major topic of research in the past (Misra 1998, Parsons and Milburn 2003). However, a relatively small amount of research has been directed to use of off-specification fly ashes in soil stabilization. Acosta et al. (2003) pointed out that the use of off-specification fly ashes can prove effective results in soil stabilization. They also discovered that one of the off-specification fly ashes they used was a very effective stabilizer for an organic soil with OC of 10%. This is significant because such fly ashes ordinarily have limited reuse potential as they do not meet the criteria as a cement additive.

Specific surface of fly ash particles is likely to affect the rate of pozzolanic reactions. The higher specific surface can accelerate pozzolanic reactions. Fly ash property which can be considered as analogous to specific surface is fineness defined by ASTM C 618. Fineness is defined as the percentage of fly ash retained on #325 (0.044 mm) sieve. The definition of fineness by ASTM C 618 implies that higher fineness is associated with coarser fly ash and less specific surface.

In Chapter 2, the effectiveness of fly ashes in improving the unconfined compressive (UC) strength (stabilization) of organic soils was evaluated. Two class-C, one class F and three off-specification fly ashes were mixed with three different organic soils with organic contents (OC) ranging from 5% to 27%. Fly ashes had a broad range of CaO contents (3.2% to 25.8%), LOI (0.5% to 49%), and CaO/SiO_2 ratios (0.1 to 1.2). The test results indicated that UC strength of organic soils having OC<10% can significantly be improved when blended with fly ashes. Highly organic soil (OC=27%) can also be stabilized with a fly ash, yet the improvement in the strength is not as significant as in the case of organic soils with OC<10%. Some off-specification fly ashes were also found to be as effective as Class C fly ashes in stabilizing organic soils. CaO content and CaO/SiO_2 ratios of fly ashes and OC of soils were determined to be the important properties affecting the stabilization. No dependency of UC strength of soil-fly ash mixture on the LOI, fineness, pH of fly ash or pH of soil was observed.

3.2.2 Stabilizing Organic Soils with Fly Ash

Strength or stiffness of fly ash stabilized soils depends on the amount of cementitous gels formed at the end of pozzolanic reactions, and organic soils were proven to have organic matter inhibiting these reactions (Tremblay et al. 2002, Young 1972).

Clare and Sherwood (1954) explained the effect of organic matter on setting of cement-soil mixtures. Young (1972) illustrated mechanisms involved in the retardation of cementitous reactions due to existence of organic matter when an organic soil is blended with cement. Both of these researchers focused on the soil-cement mixtures. Nevertheless, fly ash and cement can both produce CSH gels at the end of pozzolanic or cementitious reactions and for both binders Ca^{2+} ions and pozzolanic minerals play a crucial role in the pozzalanic or cementitious reactions. Young (1972) mentioned that organic matter, when mixed with cement, consumes Ca^{++} ions which are to be used for CSH formation, and consumption can happen through different processes such as absorption, precipitation, complexation, and nucleation. Hampton and Edil (1998) reported another drawback of having organic soils in addition to mechanisms described by Young (1972), organic soils can preserve large amounts of water, preventing the water from being used for hydration reactions.

3.2.3 Resilient Modulus Test

Resilient modulus indicates the stiffness of a soil under a confining stress and a repeated axial load. Stiffness is calculated based on the recoverable deformation as given in Eq.3.5.

$$M_r = \frac{\sigma_d}{\varepsilon_r} \tag{3.5}$$

where M_r=resilient modulus

σ_d=deviator stress

ε_r=recoverable strain

Different confining and deviator stresses are applied to the soil provided that they cover the range of expected *in situ* stresses. Each deviator stress is applied a certain number of times as given in AASHTO T 292-91(1996) standards. Resilient modulus of a subgrade soil resembles the elastic behavior of the soil, even though some permanent deformation after each load application is evident. However, if the load is small compared to strength of the subgrade, deformations can be nearly completely recoverable. Resilient modulus is a widely used index property in a flexible pavement design as explained in AASHTO Pavement Design Manual (1993).

An empirical relation between a modulus from an unconfined compression test and resilient modulus would be useful for a rapid assessment of the resilient modulus by conducting a relatively easier unconfined compression test instead of resilient modulus test, even though the deformation levels for unconfined compressive and resilient modulus tests are quite different. For comparison, the secant modulus, which is the slope of the stress-strain curve between zero stress and 50% of the peak strength for the unconfined compression test, is used.

3.3 MATERIALS AND METHODS

3.3.1 Soils

Three soft organic soils having different organic contents were used in the study: Markey, Lawson, and Theresa. All soils were collected within 1.5 m of the ground surface and are typical of organic soils encountered as subgrade during roadway construction in Wisconsin. Index properties of the soils are summarized in Table 3.1 and the particle size distributions are shown in Figure 3.1. Compaction curves corresponding to standard Proctor effort (ASTM D 698) are shown in Figure 3.2. Optimum water content and maximum dry unit weight for each soil are summarized in Table 3.1.

The Markey soil is silty sandy peat (Pt designation in the Unified Soil Classification System, USCS), the Lawson soil is a low plasticity organic sandy clay (OL in the USCS), and the Theresa soil is a moderately plastic organic clay (OL-OH). Organic content (OC) of each soil was determined by loss on ignition (LOI) at 440 ^{o}C following ASTM D 2974. The Markey soil has the highest OC (27%). The Lawson and Theresa soils have similar OC (5 and 6%) and have much less organic matter than the Markey soil. All three soils have bell-shaped compaction curves (Fig. 3.2), but the maximum dry unit weight of these soils is lower than the typical for soils from Wisconsin having similar plasticity (Edil et al. 2005).

A silt from Boardman, Oregon (Boardman silt) was also used in the testing program. Index properties of the silt are summarized in Table 3.1 and the particle size distribution is shown in Fig. 3.3. This silt, which has similar particle size distribution as the fly ashes in the study, was used as a non-reactive binder in some of the mixtures to separate the effects of cementing and reduction in water content by adding dry solid.

3.3.2 Fly Ashes

Six fly ashes and one Type I Portland Cement were used in the study. The fly ashes were obtained from electric power plants in the upper Midwestern US and were selected to provide a broad range of carbon content (0.5-42%), CaO content (3.2-25.8%), and CaO/SiO_2 ratio (0.09-1.15). General properties of the fly ashes are summarized in Table 2.2 and particle size distributions of fly ashes are shown in Figure 3.3. Organic content of the fly ashes was measured by LOI at 550 ^oC following ASTM C 311.

The Stanton and Columbia fly ashes classify as Class C ash and the Coal Creek fly ash classifies as Class F ash according to ASTM C 618. The remainders are referred to as "off-specification" (OS) fly ashes because they do not meet the requirements for either Class C or Class F fly ashes in ASTM C 618. The Dewey, King, and Columbia fly ashes are derived sub-bituminous coals, the Presque Isle fly ash is derived from bituminous coal, and the Coal Creek and Stanton fly ashes are derived from burning lignite. All of the fly ashes, except for the Presque Isle fly ash which was collected by fabric filters, were collected by electrostatic precipitators and stored dry in silos.

Among the six fly ashes, Dewey has the highest carbon content (LOI=42%) and Coal Creek has the lowest carbon content (LOI=0.5%). King has the highest (CaO) content (25%) and Presque Isle has the lowest (CaO) content (3.2%). Dewey and King have the highest CaO/SiO_2 ratios (1.2 and 1.1), Stanton and Columbia have mid-range CaO/SiO_2 ratios (0.5 and 0.7), and Presque Isle and Coal Creek have the lowest CaO/SiO_2 ratios (0.1 and 0.2). All of the fly ashes have less CaO and a smaller CaO/SiO_2 ratio than the Type 1 Portland Cement (CaO content = 62%, CaO/SiO_2 ratio = 2.9). The fly ashes generally are comprised of silt-size particles (< 75 μm and > 2 μm), with a coarse fraction between 5% and 35% and a 2 μm fraction between 5% and 35%.

3.3.3 Resilient Modulus Test

Specimens for resilient modulus test were prepared in a PVC mold having a diameter of 102 mm (4”) and a height of 203 mm (8”). Prior to compaction, air-dried-soil and fly ash were blended and the required amount of water was sprayed onto the mixture. To simulate the field applications, two hours waiting time was allowed before compaction of the moistened fly ash-soil mixture. Compactive effort was adjusted in such a way that the same compaction energy per unit volume with the one specified in standard proctor compaction method (ASTM D 698) was applied (600 kN/m^3) (details are provided in Appendix A). Required compactive effort was obtained when number of blows with the standard proctor hammer was 22 and number of compacted layers was 6. After compaction, specimens were cured for seven days in a wet room, maintained at 25ºC and 100% humidity. Specimens were extruded from PVC molds after curing and tested according to Resilient Modulus Test procedure specified in AASHTO T 292-91 (1996). The loading sequence for cohesive soils was followed and conditioning load was applied as 21 kPa instead of 41 kPa since some specimens were too soft to withstand 41 kPa conditioning stress. Confining stress was 21 kPa for all loading sequences. Test sequence is provided in Table 3.3.

Resilient modulus was calculated using Eq.3.6 and the last five cycles of each loading sequence were used in calculations since the closest match between the applied and the desired load was usually obtained during the last five cycles. Exponential curves were fit to resilient moduli vs. deviator stress data by using the following equation,

$$M_r = K_1(\sigma_d)^{K_2} \tag{3.6}$$

where K_1 and K_2 are the curve fitting parameters (AASHTO Guide for Design of Pavement Structures). Resilient modulus for each test is reported as the modulus corresponding to 21 kPa deviator stress calculated by Eq.3.6.

3.4 RESULTS AND ANALYSIS

Soil-fly ash mixtures were prepared at "very wet" water content and optimum water content. Very wet water content corresponded to 13-15% wet of optimum for Markey soil and 9-11% wet of optimum for Theresa and Lawson soils. The "very wet" conditions were to simulate natural water contents at which these soils would be encountered in upper Midwestern US (Edil et al. 2005). Fly ash percentages for the mixtures prepared at very wet of optimum were 10, 20, and 30% (based on dry weight of the soil). Specimens at optimum water content were prepared to have well-defined control condition and to evaluate the effect of water content. For the specimens prepared at optimum water content, fly ash percentages were 10% and 20%, since specimens with 30% fly ash were unrealistically dry.

3.4.1 General Effect of Fly Ash

Shown in Figure 3.4 are the resilient moduli of soil-fly ash mixtures as a function of binder types. The results are also summarized in Table 3.4. Markey, Lawson and Theresa soils were too soft to be tested at very wet conditions (very wet conditions: for Markey soil=13% wet of optimum, for Lawson & Theresa soils=10% wet of optimum). Resilient modulus of Markey soil, even with 30% fly ash, never reached 35 MPa at very wet conditions meaning that Markey soil can be considered as a very soft subgrade (Table 3.5) even if it is stabilized with 30% fly ash. Markey soil-Boardman Silt mixtures were too soft at very wet conditions to withstand conditioning stress even with 30% silt showing that addition of fly ash is more effective than addition of silt at very wet conditions. Lawson soil when admixed with 20% Dewey or Columbia fly ashes at very wet conditions had resilient moduli more than 60 MPa. When stabilized with 30% Dewey, King, Stanton or Columbia fly ash, Lawson soil had a resilient modulus as high as 100 MPa at very wet conditions. At optimum water content, resilient modulus of stabilized Lawson soil was always, even with 10%

fly ash, higher than 50 MPa. Theresa soil admixed with 20% Dewey, King, Stanton or Columbia fly ash at very wet conditions had resilient modulus between 50-70 MPa. When the percentage of these fly ashes was increased to 30% at very wet conditions, resilient modulus varied between 65 and 105 MPa indicating that stabilization process produced significant improvement in resilient modulus considering that untreated soil (no fly ash) was too soft to be tested. At optimum water content, resilient modulus of stabilized Theresa Soil varied between 50 and 130 MPa depending upon the fly ash type and percentage used.

Admixing of 10% fly ash with Markey, Lawson and Theresa soils at very wet conditions was not enough to obtain resilient moduli of higher than 50 MPa.

Figure 3.5 displays the relative effect of pozzolanic reactions on resilient modulus as opposed to water content lowering due to addition of fly ash. To differentiate the effect of these two factors, resilient moduli of fly ash stabilized soils are compared to those of mixed with a natural silt at the same additive percentages and water contents. Addition of a silt or a fly ash increases the amount of dry solids and consequently decreases the water content, which increases resilient modulus, yet only fly ash can further improve the resilient modulus through pozzolanic reactions. In Figure 3.5, the higher moduli observed for fly ash mixtures compared to those of silt mixtures are attributable to the pozzolanic reactions knowing that both silt and fly ash causes water content lowering but fly ash also causes pozzolanic reactions.

Change in resilient modulus of untreated soil with respect to deviator stress is shown in Figure 3.6a for the soil specimens prepared at the optimum water content. Only for Lawson soil, increase in deviator stress decreases the resilient modulus as in the case of cohesive soils (AASHTO Pavement Design Manual,1993). Markey and Theresa soils have almost constant resilient moduli as deviator stress is increased. Variations in the resilient modulus of soil fly ash mixtures as a function of deviator stress are given in Figure 3.6b for Markey soil, in Figure 3.6c for Lawson soil, and in Figure 3.6d for Theresa soil. For Markey soil, just like the behavior observed for the untreated soil, resilient modulus of stabilized specimens, regardless of the fly ash type, remains constant as deviator stress is increased. Lawson soil, when admixed with Boardman silt still exhibits the behavior of cohesive soils. Resilient moduli of Lawson soil stabilized with Dewey, King or Columbia fly ashes increase with increasing deviator stress. However, this trend is not observed when the fly ash percentage or water content is changed (not shown in Figure 3.6). Stabilized Lawson soil with either Coal Creek or Presque Isle fly ashes has a constant resilient modulus over the range of applied deviator stresses. Resilient modulus of stabilized Theresa soil also remains constant over the range of applied deviator stresses. Only stabilization with the Presque Isle fly ash produces a decrease in the resilient modulus with the increase in deviator stress. As a result, as untreated, only Lawson soil exhibit the resilient modulus behavior of cohesive soils indicating that organic soils are likely to behave differently. No identifiable pattern in the variation of resilient modulus as a function of the deviator stress is discernable.

3.4.2 Effect of Fly Ash Characteristics

Effect of fly ash properties on the resilient modulus of soil-fly ash mixtures was investigated by plotting resilient modulus of the mixture vs. each property (Fig. 3.7). For Markey soil, resilient moduli are too low to draw a conclusion on the effect of any fly ash characteristics, i.e., differentiating between the effects of different fly ashes based on resilient modulus was not realistic. Figure 3.7a and 3.7b show the effect of CaO/SiO_2 and $CaO/(SiO_2+Al_2O_3)$ ratios of fly ashes on resilient modulus of soil-fly ash mixtures. Increase in either one of the ratios results in higher resilient modulus. For the mixtures prepared with Lawson soil, highest resilient moduli was obtained when the soil was mixed with the fly ash having CaO/SiO_2 ratio of about 0.5. For Theresa soil mixtures, increase in CaO/SiO_2 and $CaO/(SiO_2+Al_2O_3)$ ratio resulted in continuous increase in resilient modulus without any tapering-off after a certain ratio.

Figure 3.7c shows the relation between CaO content of fly ash and resilient modulus of the soil-fly ash mixture. Increase in resilient modulus in response to higher lime (CaO) content is evident for mixtures having Lawson or Theresa soils. The circled data points, in Fig.3.7c, representing the data points for soil-Coal Creek fly ash mixtures, suppress the trend of increasing resilient modulus with increasing lime content. Coal Creek fly ash (CaO/SiO_2=0.26, CaO=13.3%) has lower CaO/SiO_2 ratio than Dewey fly ash (CaO/SiO_2=1.15, CaO=9.2%), and higher CaO content than Dewey fly ash. Therefore, in Figure 3.7c, suppression of increase in resilient modulus as lime content of fly ash increases can be attributed to the effect of low CaO/SiO_2 ratio of Coal Creek fly ash. Requirement for a fly ash having at least 10% CaO and CaO/SiO_2 ratio more than 0.5 is evident for successful stabilization in terms of acquiring stiffer organic soil-fly ash mixtures based on Figure 3.7a. and Figure 3.7c.

Figure 3.7d depicts the effect of LOI of fly ash on the resilient modulus of organic soil-fly ash mixtures. No trend between LOI of fly ash and resilient modulus can be identified from Figure 3.7d. Based on resilient modulus test results, no deleterious effect of higher LOI was observed as long as fly ashes had high enough CaO content and CaO/SiO_2 such as 10% and 0.5, respectively.

In Figures 3.7e and 3.7f, the effects of fly ash fineness and pH on the resilient modulus of the soil-fly ash mixtures are shown. Neither, pH nor fineness of fly ash was found to be important characteristics of fly ash in terms of affecting the resilient modulus of the soil-fly ash mixture.

In summary, important characteristics of fly ashes affecting the resilient modulus of soil-fly ash mixtures are CaO/SiO_2 (or $CaO/(SiO_2+Al_2O_3)$) ratio and CaO content of fly ash. LOI, fineness, and pH of fly ash do not have significant effects on the resilient modulus of soil-fly ash mixture. Based on Figure 3.7 and findings in Chapter 2, fly ash properties having a significant effect on the stabilization of organic soils are the same according to both resilient modulus and UC strength tests.

3.4.3 Effect of Soil Characteristics

Effect of organic content (OC) and PI of the soil on the resilient modulus of soil-fly ash mixture is shown in Figure 3.8. Data from the study of Edil et al. (2005) was also included in Figure 3.8. Edil et al. (2005) used Dewey, King and Columbia fly ashes which were obtained from the same source with the fly ashes used in this study. They prepared soil-fly ash mixtures at 7% wet of optimum water content of the soil. Only difference between their mixtures and the mixtures in this study was assumed to be the soil type which produced a broader range of OC and PI while assessing the effect of OC and PI on resilient modulus of soil-fly ash mixture.

Increase in the OC of the soil resulted in significantly lower resilient modulus for soil-fly ash mixtures. Figure 3.8a demonstrates an exponential decay in resilient modulus of soil-fly ash mixture in respond to increase in OC. Higher OC content is an indication of lack of inorganic mineral which reduces the stiffness of the soil. Shown in Figure 3.8b is the effect of soil PI on the resilient modulus of the soil-fly ash mixture. Higher resilient moduli obtained when PI is higher than 8. Furthermore, the change in PI, in Fig. 3.8b, also implies the change in OC of the soil and the lowest resilient modulus for the lowest PI in Figure 3.8b actually represents the Markey Soil which has the highest OC among the soils used. The lowest resilient modulus is attributed to high OC rather than low PI. The variability of soil pH was not sufficient to investigate its effect on the resilient modulus of soil-fly ash mixture.

As a result, the most important characteristics of organic soils to consider for stabilization with fly ash, is the organic content (OC) of the soil. However, further research investigating the effect of soil pH on stiffness of soil-fly ash mixture may be appropriate.

3.4.4 Effect of Water Content and Fly Ash Percentage

Resilient modulus test specimens for each soil-fly ash combination were prepared at two different water contents, optimum water content and very wet of optimum water content. Comparison of resilient moduli for the samples having the same binder at two different water contents is given in Figure 3.9. Specimens prepared at optimum water content almost always had higher resilient moduli than specimens prepared at very of optimum water content. Pore water exceeding the amount needed for pozzolanic reactions can be deleterious for the stiffness of the soil-fly ash mixture.

Variations of resilient modulus of soil-fly ash mixtures as a function of fly ash percentage are given in Figure 3.10. Blending higher percentages of Coal Creek fly ash into Lawson soil does not increase the resilient modulus of the soil-fly ash mixture. However, resilient modulus of soil-fly ash mixture decreases when the Presque Isle fly ash percentage blended into Lawson soil is increased from 20% to 30%. Increase in fly ash percentage, regardless of the fly ash type, never has a deleterious effect on the resilient modulus of the Theresa soil-fly ash mixture in Figure 3.10b. Increase in the percentages of effective fly ashes (CaO>10% and CaO/SiO_2 > 0.5) always resulted in increase in resilient modulus whereas increase in the percentage of fly ashes like Coal Creek (CaO=13.3%, CaO/SiO_2=0.26) and Presque Isle (CaO=3.19%, CaO/SiO_2=0.09) did not necessarily indicate higher mixture resilient modulus.

3.4.5 Correlations between UCS and Resilient Modulus Test Results

The relation between unconfined compressive strengths (UCSs) and resilient moduli at 21 kPa deviator stress for organic soil-fly ash mixtures having the same fly ash type and percentage, prepared at the same water content and cured for the same time interval are given in Figure 3.11. Figure 3.11 includes UCS data from two different tests , (1) tests on small size specimens (33 mm (1.4”) diameter and 72mm (2.8”) height), and (2) tests on larger specimens (102 mm (4”) diameter and 203mm (8”) height) which were previously tested in resilient modulus test. Comparisons of these two UCS test results (q_u) with the corresponding resilient moduli (M_r) are given in Figure 3.11. According to Figure 3.11a, which includes UC strengths for small size specimens, conversion factor for q_u (kPa) to obtain resilient modulus (kPa) varies between 70 and 570, and curve fit has the slope of 270. In Figure 3.11b, where UC strengths are the strengths of larger samples (102 mm diameter and 203 mm high), conversion factor from q_u (kPa) to resilient modulus (kPa) was 213. The coefficient corresponding to the slope of curve fit in Figure 3.11a and the coefficient obtained in Figure 3.11b were close.

Secant modulus at 50% (E_{50}) was obtained by dividing the half of the peak strength ($q_u/2$) with the strain observed at that stress level in UCS test. Comparison of E_{50} with resilient modulus is given in Figure 3.12. Figure 3.12a shows the comparison of E_{50} obtained from UCS tests run on small size specimens and resilient modulus obtained from the tests run on large size specimens. In Figure 3.12a, resilient modulus varies between $1.6E_{50}$ and $20E_{50}$. Figure 3.12.b depicts the comparison of E_{50} and resilient modulus which were obtained by using the same specimens (larger specimens) in UCS and resilient modulus tests. In this case, resilient modulus varies between $1.8E_{50}$ and $12E_{50}$. For both Figure 3.12a and 3.12b, resilient modulus is higher than E_{50}.

3.5 CONCLUSIONS

The purpose of this study was to see whether resilient moduli of organic soils could be improved by blending a fly ash into the soil. Resilient modulus tests were conducted with three organic soils and six fly ashes. Soil-fly ash mixtures were prepared at two different water contents, very wet of optimum and optimum water content. Fly ash percentages in the mixtures were 10, 20 and 30% for the mixtures prepared at very wet of optimum and 10% and 20% for the mixtures prepared at optimum water content.

Resilient modulus tests could not be run on organic soils at very wet conditions since specimens were too soft. The addition of fly ash, at very wet conditions, to the slightly organic soils, Lawson and Theresa (OC=5% and 6%, respectively) produced resilient moduli varying between 10 to 100 MPa depending upon the type and percentage of the fly ash. At optimum water content, resilient modulus for these soils could be improved up to 120 MPa with addition of fly ash. However, for Markey soil (OC=27%), stabilization with fly ash never produced resilient modulus higher than 30 MPa no matter what fly ash type and percentage, was used.

Organic soils can behave different than cohesive soils in resilient modulus test. Identifying a particular trend of increasing or decreasing resilient modulus as a function of deviator stress based on fly ash type is not possible based on fly ash-soil specimens tested.

Increase in stiffness of soil when stabilized with fly ash originates mainly from pozzolanic reactions, and stiffness increase due to lowering water content is not as significant as the increase caused by pozzolanic reactions.

Important fly ash characteristics affecting the resilient modulus of soil-fly ash mixture was determined as CaO content, CaO/SiO_2 or $CaO/(SiO_2+Al_2O_3)$ ratio. LOI of fly ash was proven to have non-deleterious effect on the resilient modulus of the soil-fly ash mixture indicating that off-specification fly ashes could be used for stabilization purposes.

Soil organic content is detrimental characteristic for stabilization. Increase in organic content of soil indicates that strength of soil-fly ash mixture will decrease exponentially. No effect of soil pH and PI on resilient modulus of fly ash stabilized soil could be identified. However, more research on the effect of these characteristics is required since variability in pH and PI soils in this study was not sufficient.

Fly ash stabilization of soils at optimum water content always resulted in higher resilient modulus than the one at very wet conditions. Multiplication factor for q_u (in kPa) to obtain resilient modulus (in kPa) varies between 70 and 570. Estimation of resilient modulus based on E_{50} could be achieved by multiplying E_{50} with the coefficient in the range of 1.6 to 20 which shows that resilient modulus is always higher than E_{50}.

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TABLES

Table 3.1. Index Properties and Classifications of Soils Used

Soil Name	LL	PI	Percent Fines	G_s	OC (%)	Classification		pH		w_N	γ_d (kN/m^3)	w_{OPT}
						USCS	AASHTO	ASTM D4972	ASTM D2976			
Markey Soil	53	1	25	2.23	27	Pt	A-8 (0)	5.9	6.3	57	10.3	47
Theresa Soil	31	8	75	2.57	6	OL	A-4 (5)	7.6	7.1	20	15.2	21
Lawson Soil	50	19	97	2.58	5	OL-OH	A-7-5 (23)	6.9	6.8	28	13.3	28
Boardman Soil	22	1	79	2.67	1	ML	A-2-4(0)	-	-	11	17.3	17

LL= Liquid limit, PI= Plasticity Index, G_s= Specific Gravity, LOI= Loss on Ignition, w_N=Natural Water Content, γ_d = maximum dry unit weight, w_{opt}=Optimum Water Content, and numbers in parantheses in AASHTO classification= GI number

Table 3.2. Properties and Classifications of Fly Ashes

Parameter	Dewey	King	Presque Isle	Coal Creek	Columbia	Stanton	Typical Class C*	Typical Class F*
SiO_2 (%)	8.0	24.0	35.6	50.4	31.1	40.2	40.0	55.0
Al_2O_3 (%)	7.0	15.0	18.0	16.4	18.3	14.7	17.0	26.0
Fe_2O_3 (%)	2.6	6.0	3.5	7.2	6.1	8.7	6.0	7.0
CaO (%)	9.2	25.8	3.2	13.3	23.3	21.3	24.0	9.0
MgO (%)	2.4	5.3	1.0	4.3	3.7	6.6	5.0	2.0
CaO/SiO_2	1.15	1.08	0.09	0.26	0.75	0.53	0.60	0.16
Fineness(%)	27	41	25	28	12	23	-	-
Loss on Ignition (%)	49.0	12.0	34.0	0.5	0.7	0.8	6	6
Specific Gravity	2.00	2.66	2.11	2.59	2.63	2.63	-	-
Classification	Off-Spec	Off-Spec	Off-Spec	Class F	Class C	Class C	Class C	Class F

Off-Spec= Off Specification

Table 3.3. Load sequence in Resilient Modulus Test

Phase	Sequence Number	Deviator Stress (kPa)	Number of Repetitions
Specimen Conditioning	0	21	1000
Testing	1	21	50
	2	34	50
	3	48	50
	4	69	50
	5	103	50

Note: A confining pressure of 21 kPa and a seating load of 13.8 kPa were used.

Table 3.4 Summary of resilient moduli

Fly Ash	Markey Soil							Lawson Soil							Organic Theresa Soil						
	Wet of Optimum				Optimum			Wet of Optimum				Optimum			Wet of Optimum				Optimum		
	Soil Alone	10%	20%	30%	Soil Alone	10%	20%	Soil Alone	10%	20%	30%	Soil Alone	10%	20%	Soil Alone	10%	20%	30%	Soil Alone	10%	20%
Dewey		F	9.72 (55)	18.6 (59)		13.02 (48)	20 (51)		16.5 (39)	89.93 (35)	99.86 (34)		105.6 (26)	107.9 (26)		29.86 (29)	54.48 (31)	106.9 (30)		66.86 (20)	130.7 (23)
King		F	16.65 (52)	6.22 (60)		5.15 (49)	5.3 (52)		15.27 (38)	32.82 (34)	107.0 (37)		62.08 (27)	108.6 (26)		16.3 (30)	72.04 (26)	98.14 (31)		127.46 (20)	98.61 (21)
Presque Isle		F	9.11 (55)	8.35 (57)		5.9 (50)	10.84 (51)		18.58 (38)	59.08 (38)	36.24 (36)		55.6 (28)	59.2 (26)		21.27 (29)	28.46 (28)	57.38 (31)		61.13 (22)	48.11 (21)
Coal Creek	F	F	6.96 (55)	27.99 (57)	4.4	-	10.75 (46)	F	66.2 (39)	64.12 (36)	65.02 (36)	26.3	123.4 (27)	88.03 (29)	F	7.42 (29)	10.23 (29)	22.3 (29)	13.1	89.59 (20)	71.29 (21)
Columbia		F	-	-		5.87 (52)	6.53 (48)		34.02 (37)	87.52 (36)	106.7 (37)		70.37 (26)	103.2 (26)		19.09 (32)	57.53 (30)	62.58 (32)		71.23 (20)	86.97 (21)
Stanton		F	-	12.92 (54)		18.22 (47)	22.15 (51)		48.24 (41)	92.25 (42)	109.3 (40)		72.42 (25)	113.9 (26)		17.05 (31)	66.55 (30)	-		90.71 (20)	70.97 (21)
Boardman Silt		F	F	F		4.98 (49)	6 (48)		23.32 (38)	31.63 (37)	51.52 (36)		82.12 (26)	57.73 (28)		F	9.31 (29)	10.75 (29)		66.1 (21)	79.76 (20)

* Hypen= no test was run, F= Failure during the test, i.e, too soft to test

Table 3.5. Subgrade Evaluation Criteria Based on Resilient Modulus

(Asphalt Institute 1992)

Subgrade Consistency	Resilient Modulus MPa
Very Soft	0-35
Soft	35-61
Medium-stiff	61-119
Stiff	119-215

FIGURES

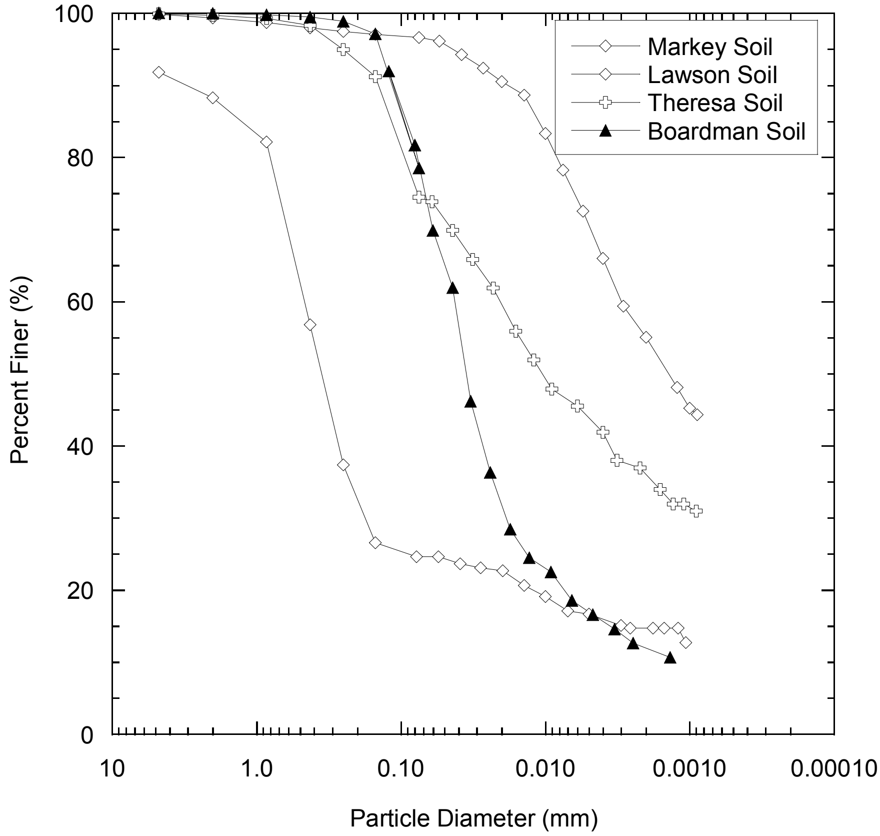


Figure 3.1. Particle size distributions of soils

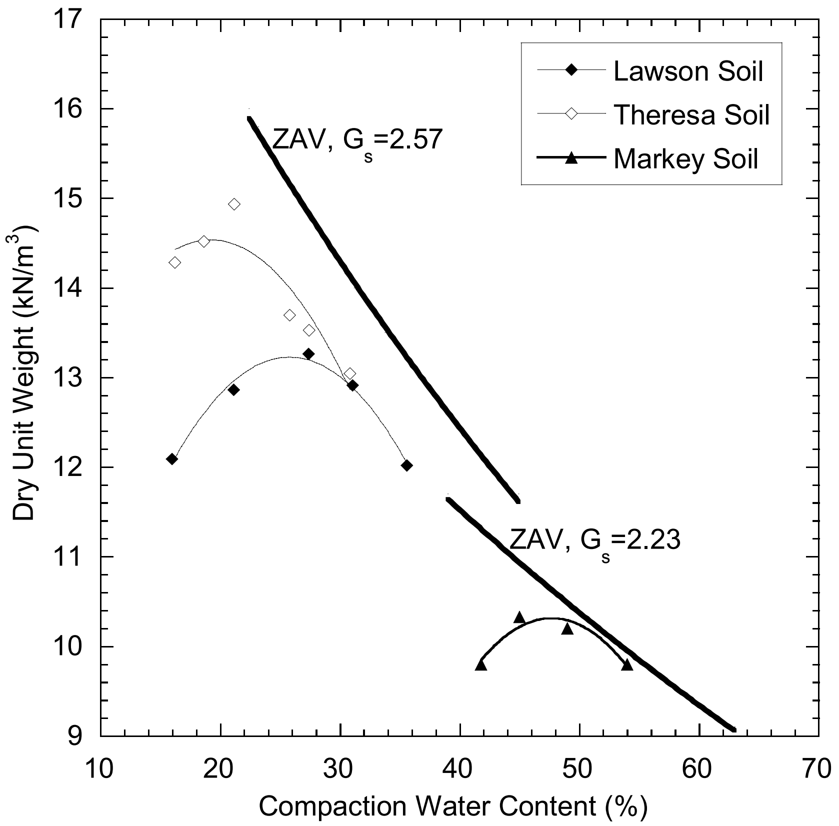


Figure 3.2. Compaction Curves for Soils for Standard Proctor

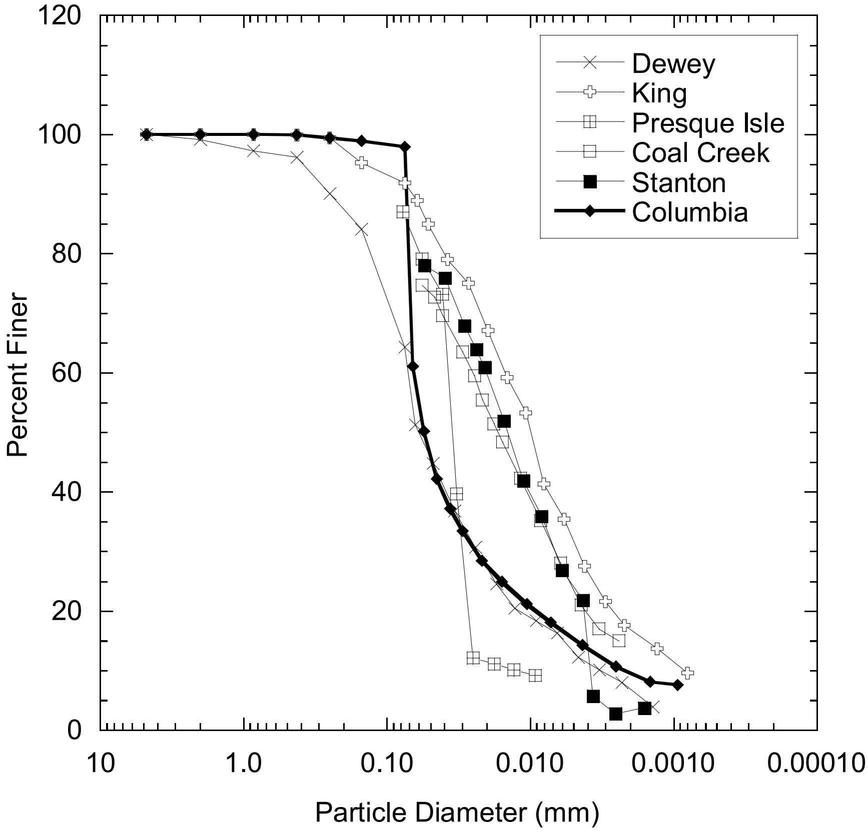


Figure 3.3. Particle size distributions of fly ashes

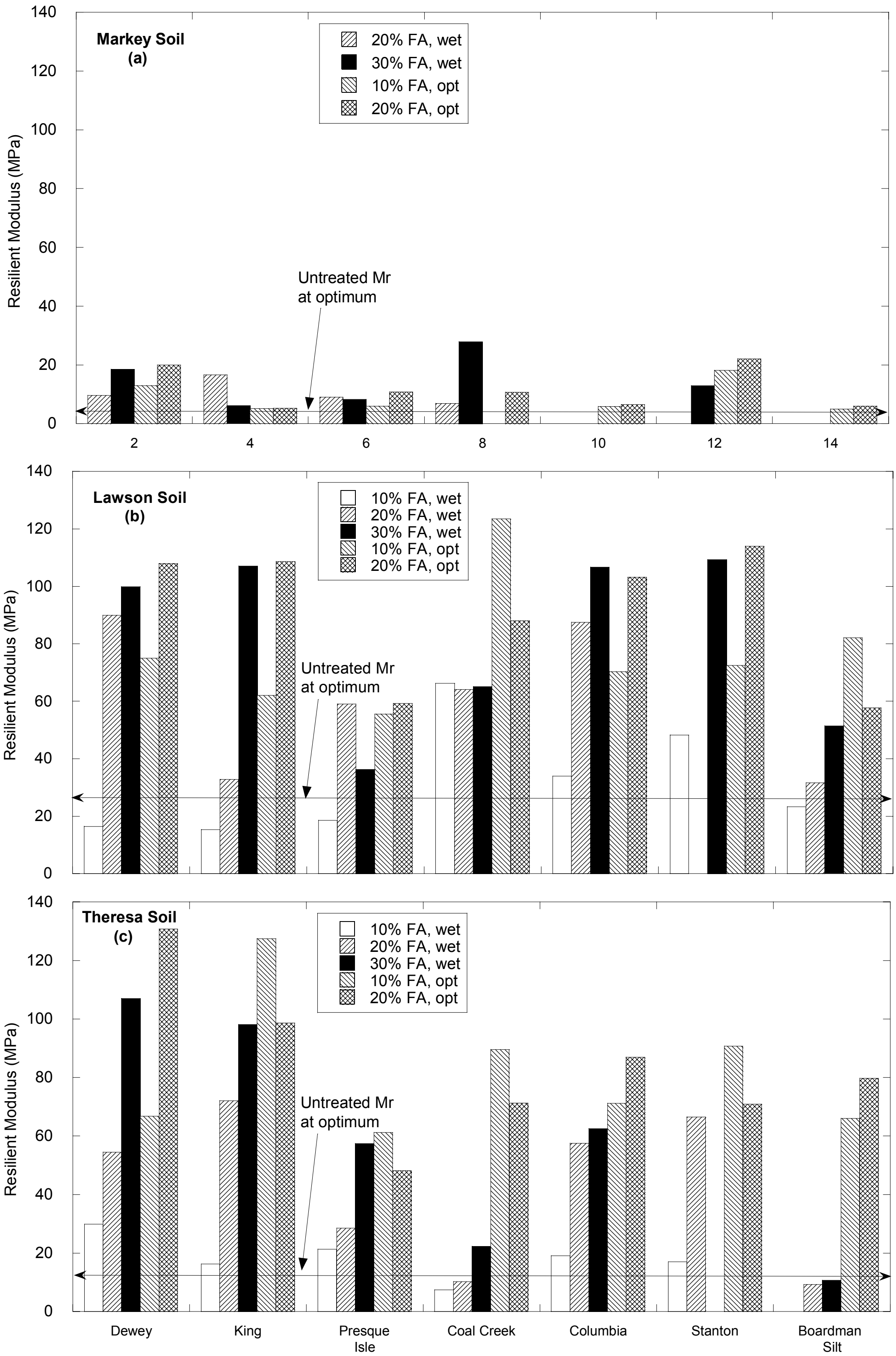


Figure 3.4. Resilient Moduli (Mr) of soil-fly ash mixtures prepared with various fly ashes and Boardman Silt: (a) Markey Soil, (b) Lawson Soil, and (c) Theresa Soil. FA=fly ash, wet=wet of optimum, opt=optimum water content

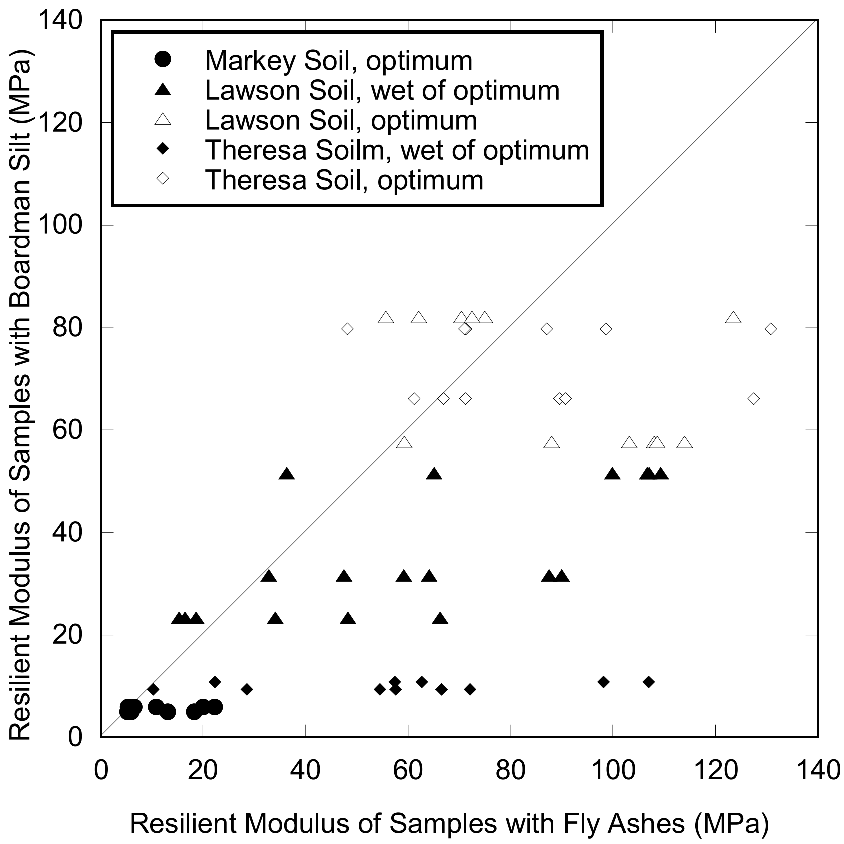


Figure 3.5 Resilient Modulus of Soil-Boardman Silt mixtures vs. resilient modulus of soil-fly ash mixtures at the same water content and binder percentage

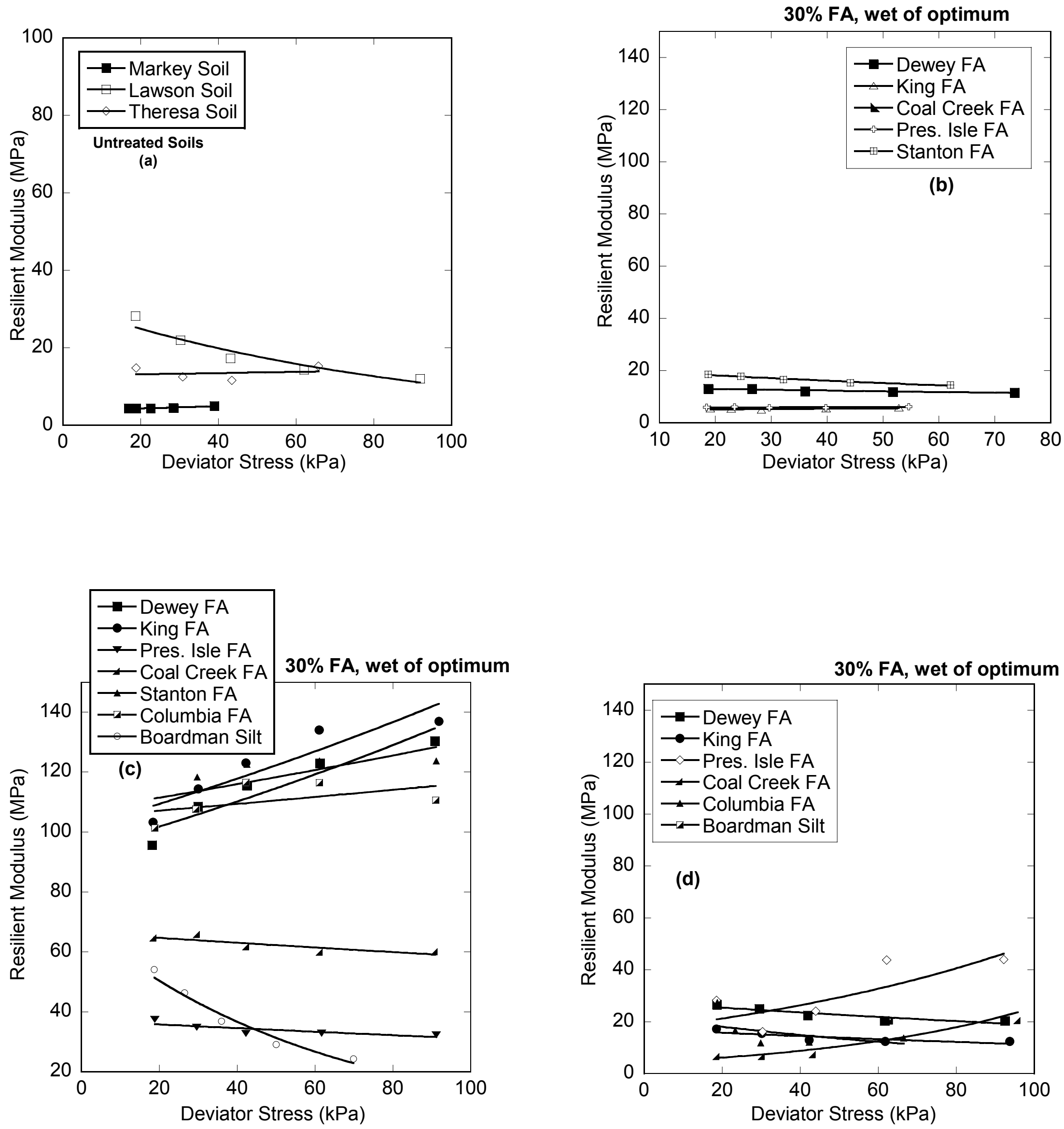


Figure 3.6. Resilient modulus as a function of deviator stress, (a) untreated soil specimens, and stabilized (b) Markey soil specimens, (c) Lawson soil specimens, and (d) Theresa soil specimens.

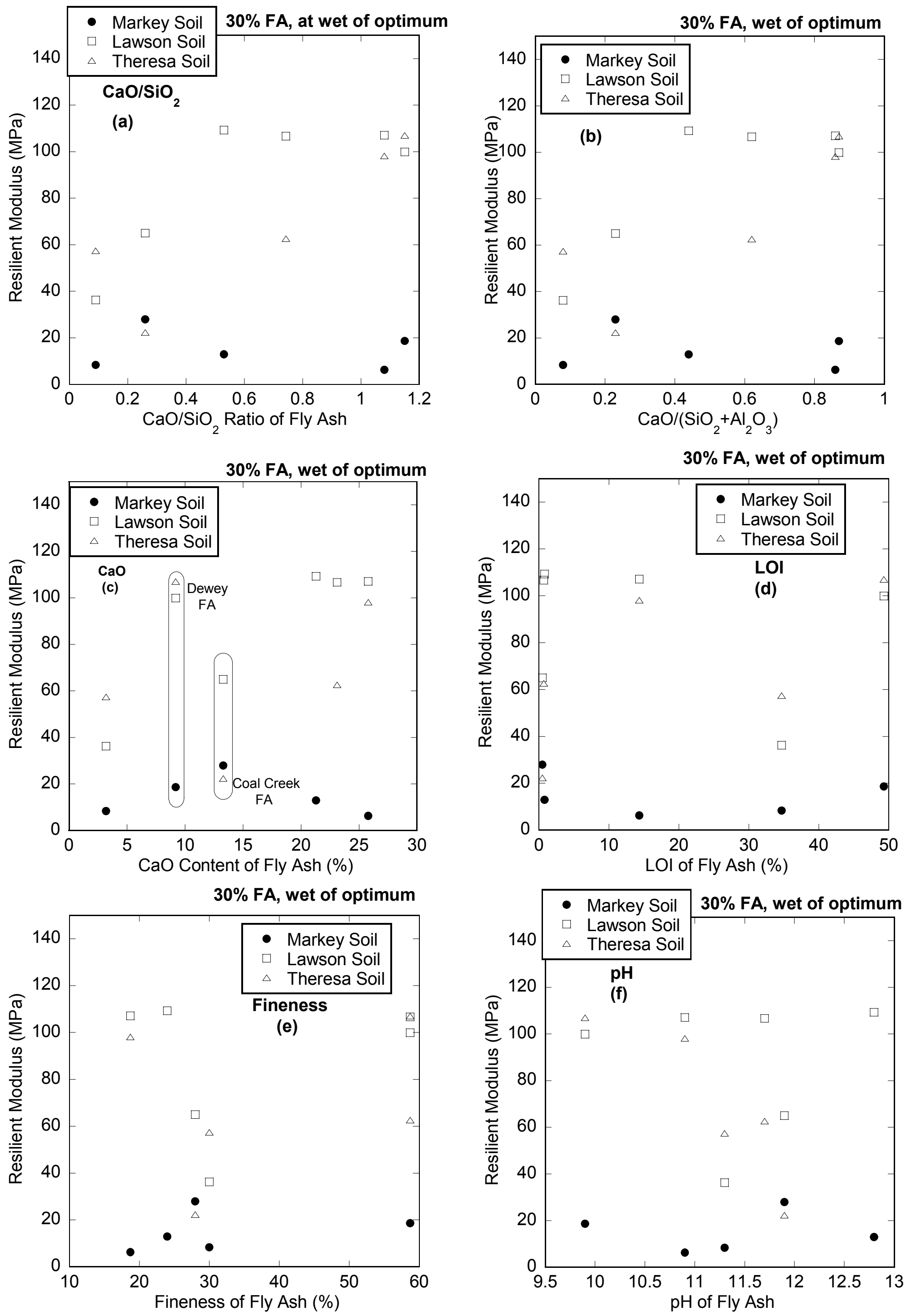
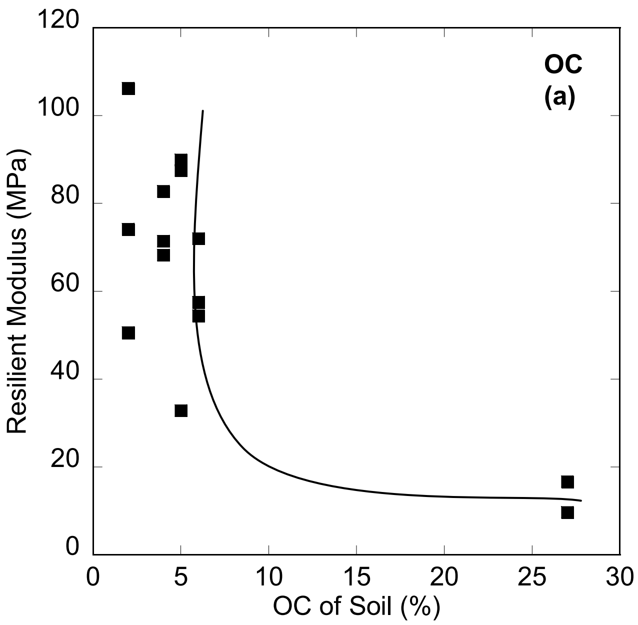


Figure 3.7. Resilient modulus as a function of characteristics of fly ashes: (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) pH, and (e) Fineness of fly ashes, wet of optimum=water content at wet of optimum



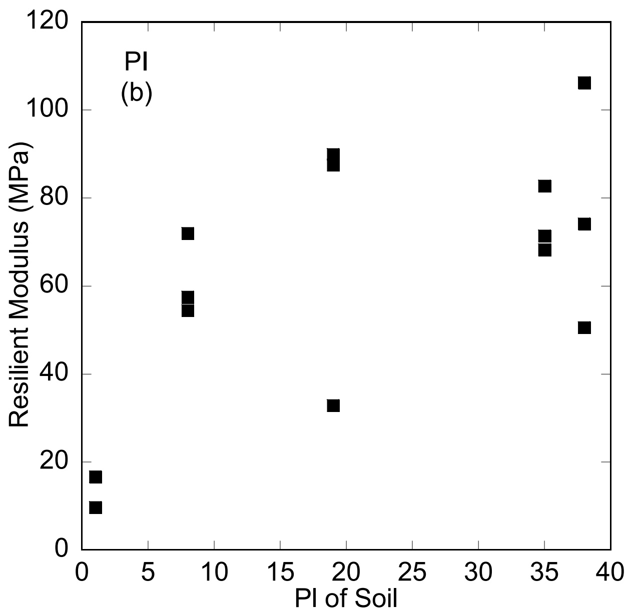


Figure 3.8. Resilient modulus as a function of soil index properties: (a) OC, (b) pH, and (c) PI=plasticity index of soils; Wet= water content at wet of optimum, FA=fly ash

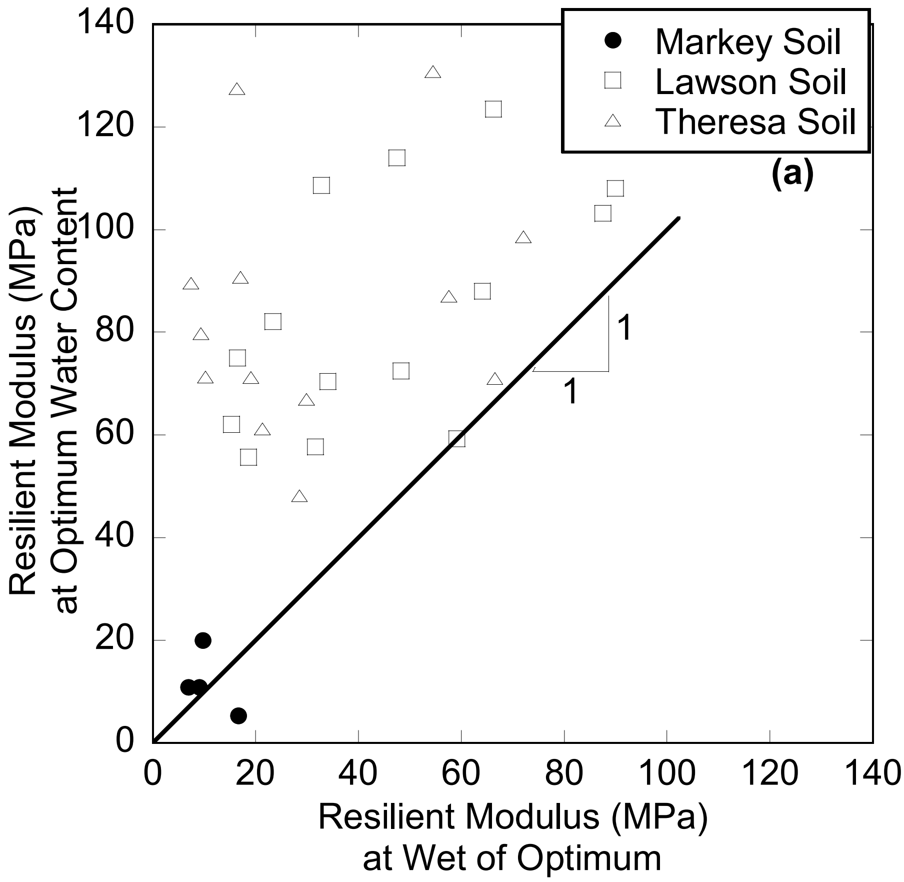
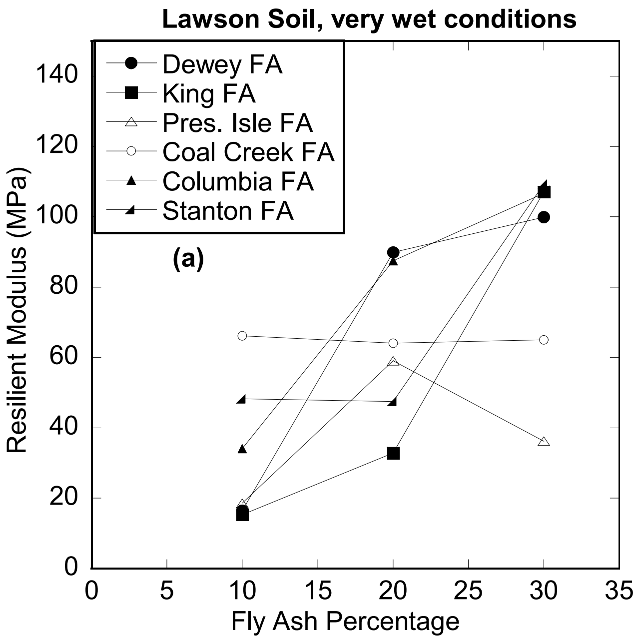


Figure 3.9 Resilient modulus of soil-fly ash mixtures prepared at optimum and wet of optimum water contents with the same binder type and percentages



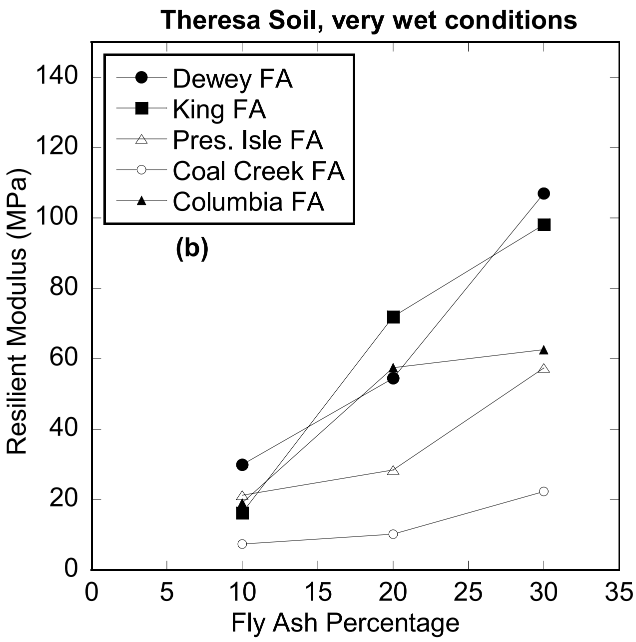
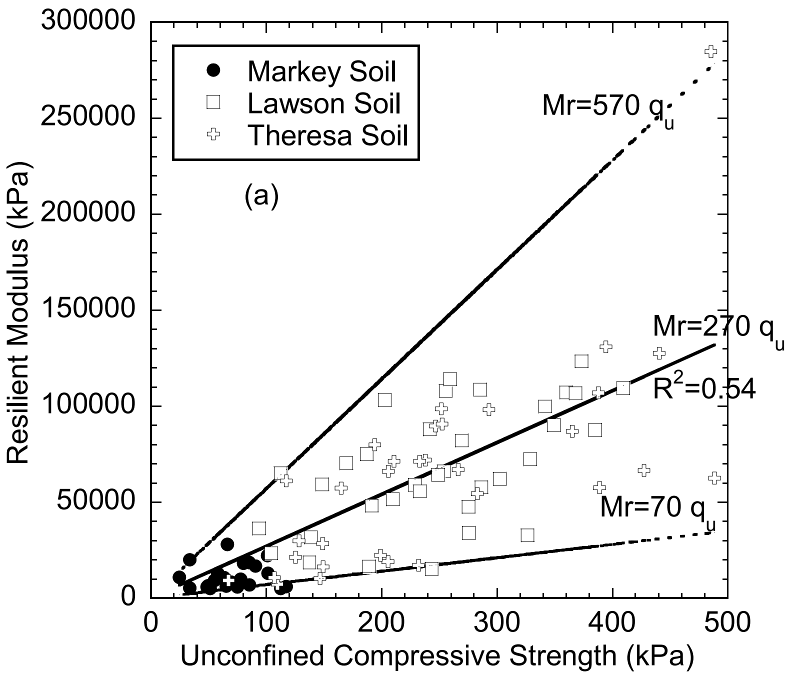


Figure 3.10. Resilient modulus of soil-fly ash mixtures as a function of fly ash percentage in the mixture for (a) Lawson soil, and (b) Theresa soil.



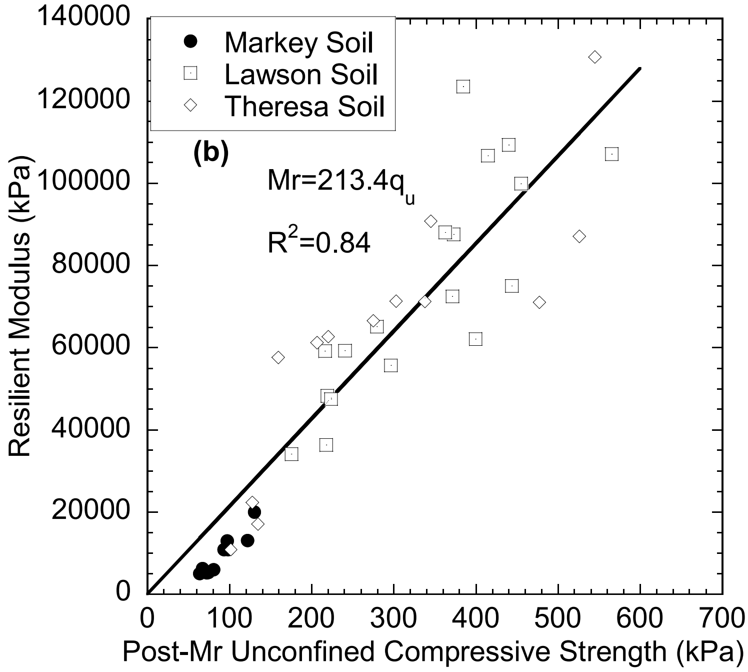
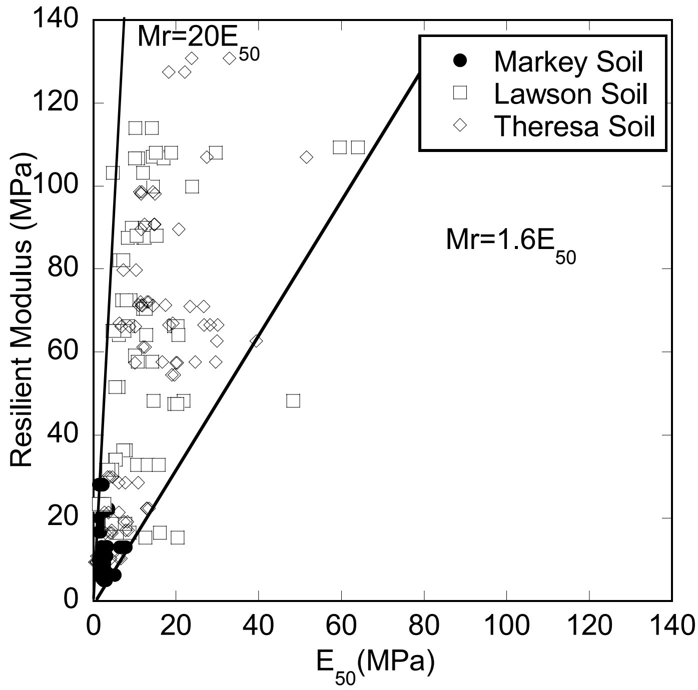


Figure 3.11. Relations between resilient modulus and UC strength of soil fly ash mixtures: (a) UC strength tests run on 1.4” diameter and 2.8” height specimens and resilient modulus tests run on 4” by 8” specimens, (b) 4” diameter and 8” height specimens for both UC strength and resilient modulus tests.



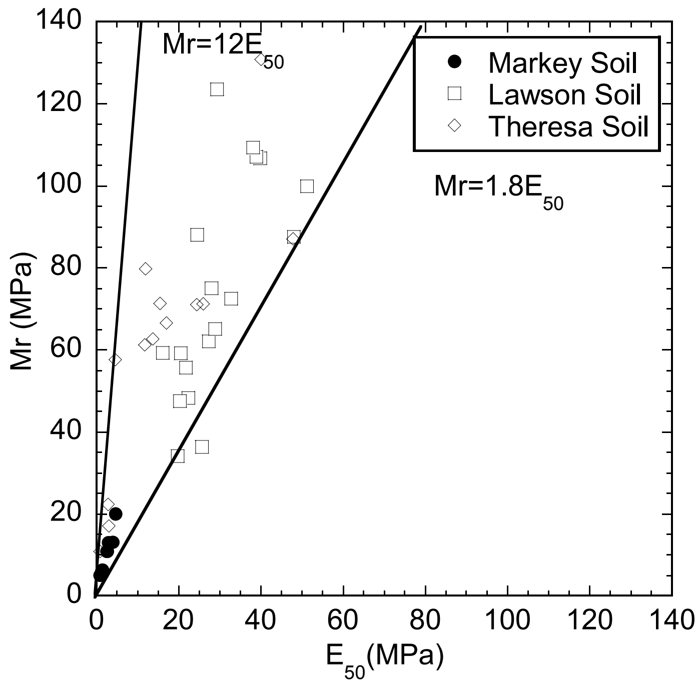


Figure 3.12. Relations between resilient modulus and UC strength of soil fly ash mixtures: (a) UC strength tests run on 1.4” diameter and 2.8” height specimens and resilient modulus tests run on 4” by 8” specimens, (b) 4” diameter by 8” height specimens for both UCS and resilient modulus tests.

APPENDIX A
SMALL SCALE COMPACTION METHOD

Harvard Miniature Compaction tests (ASTM D4609) were run with the following modifications, (1) dynamic compaction (i.e., tamping with drop weight) method was used, and (2) the same compaction energy per unit volume as in the standard proctor effort was applied. This compaction method is called Small Scale Compaction, SSC. Results of SSC compared to standard proctor test results are shown in Figure A.1. In SSC, the impact energy was transferred to the soil through a specially designed hammer. During the design of the hammer, the following points were considered:

1. The ratio of the impact area of hammer to the miniature Harvard compaction mold area is the same as the ratio specified in ASTM D 698,
2. The same compaction energy with the one specified in ASTM D 698 per unit volume is applied, and
3. The number blows per layer and blow layers were chosen as 3 and 25, respectively.

Taking all these points into consideration, the drop height and the weight of hammer were calculated as 102 mm (4”) and 907 g (2 lbs), respectively. Two more inorganic soils were also tested with both SPC and SSC to compare these two methods at a broader range of soils. For all soils, the differences between the maximum dry densities obtained from SSC and SPC were below 0,5 kN/m^3 and the differences between the optimum water contents were not more than 2%. As optimum water contents found by SPC and SSC were plotted in one to one scale, linear curve fit had R^2 of 0.99 showing that they produce almost the same optimum water contents for a given soil. Similarly, when maximum dry unit weights obtained by SSC and SPC were plotted one to one, linear curve fit had R^2 of 0.97 indicating maximum dry unit weights obtained with two methods are reasonably close. SSC and SPC produce slightly different dry unit weights for a given water content at the dry side of optimum water content. At wet side of optimum water content, both methods tend to give approximately the same dry unit weights for a given water content. Since this study involved preparing specimens at optimum and very wet of optimum water contents, SSC was considered to be an acceptable method for compacted specimen preparation.

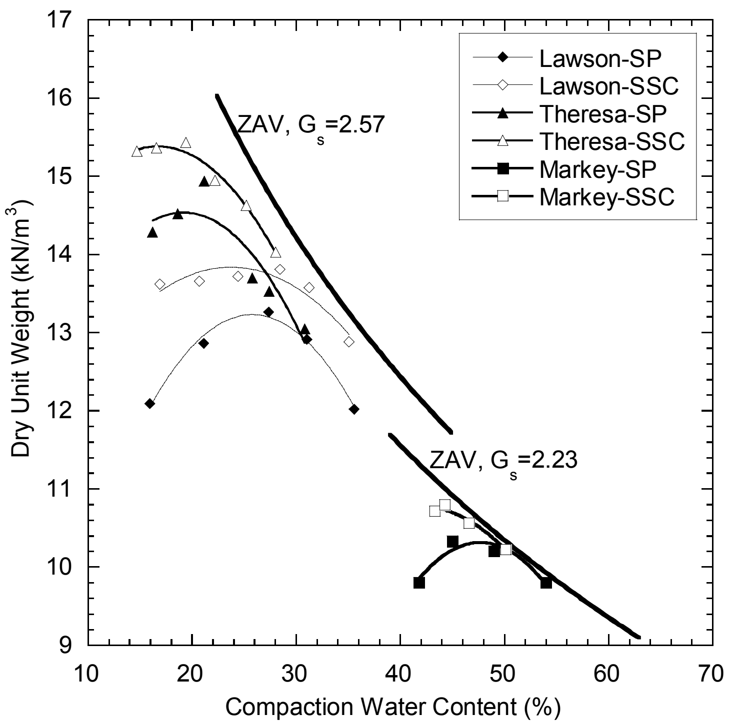


Figure A.1. Compaction curves obtained from small scale compaction and standard proctor compaction tests.

APPENDIX B

ALL PLOTS SHOWING THE EFFECT OF CHARACTERISTICS OF FLY ASHES ON UNCONFINED COMPRESSIVE STRENGTH

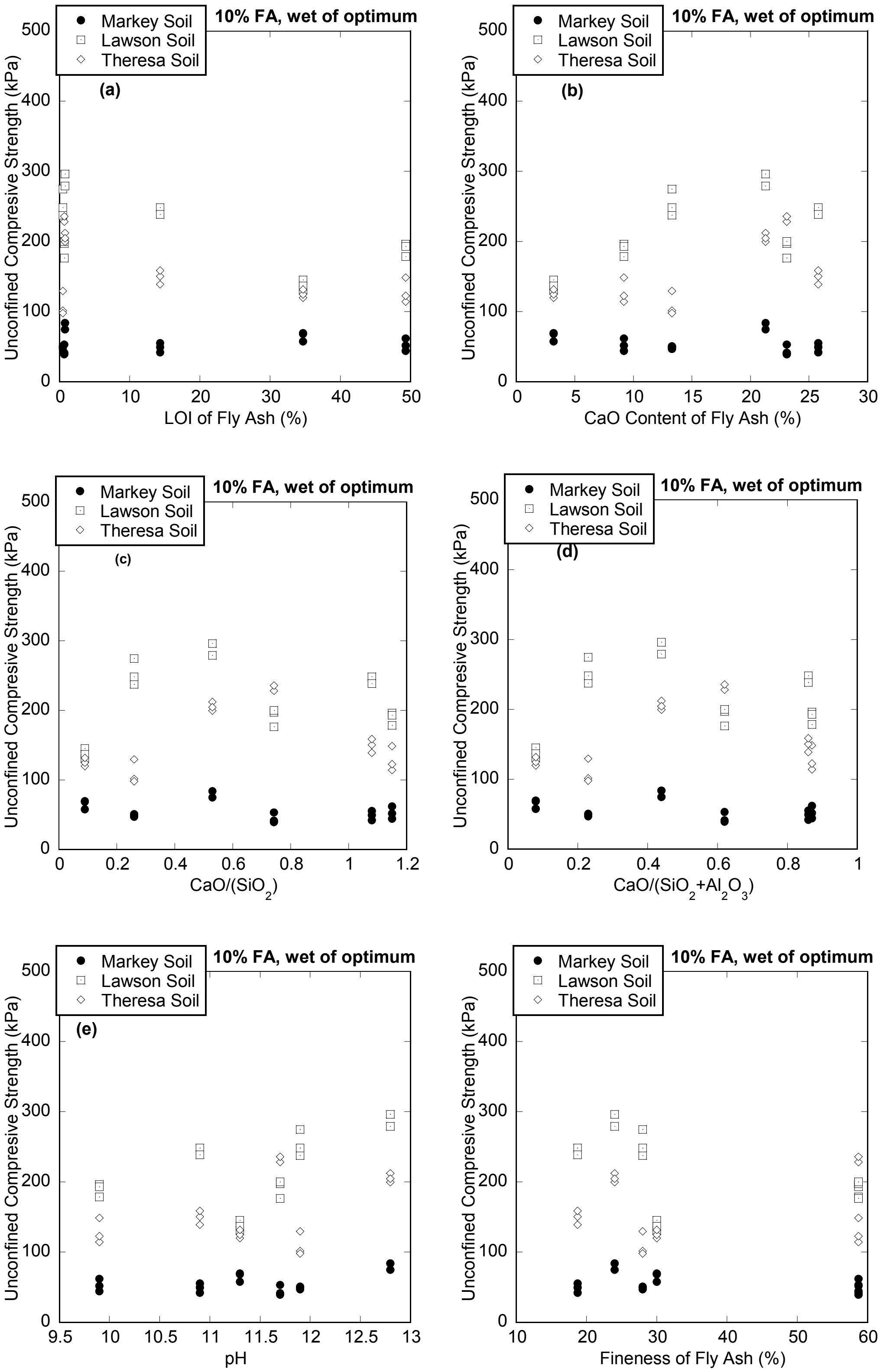


Figure B.1. Variation of unconfined compressive strength as a function of chemical properties of fly ashes (fly ash percentage=10%, moisture state=wet of optimum): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

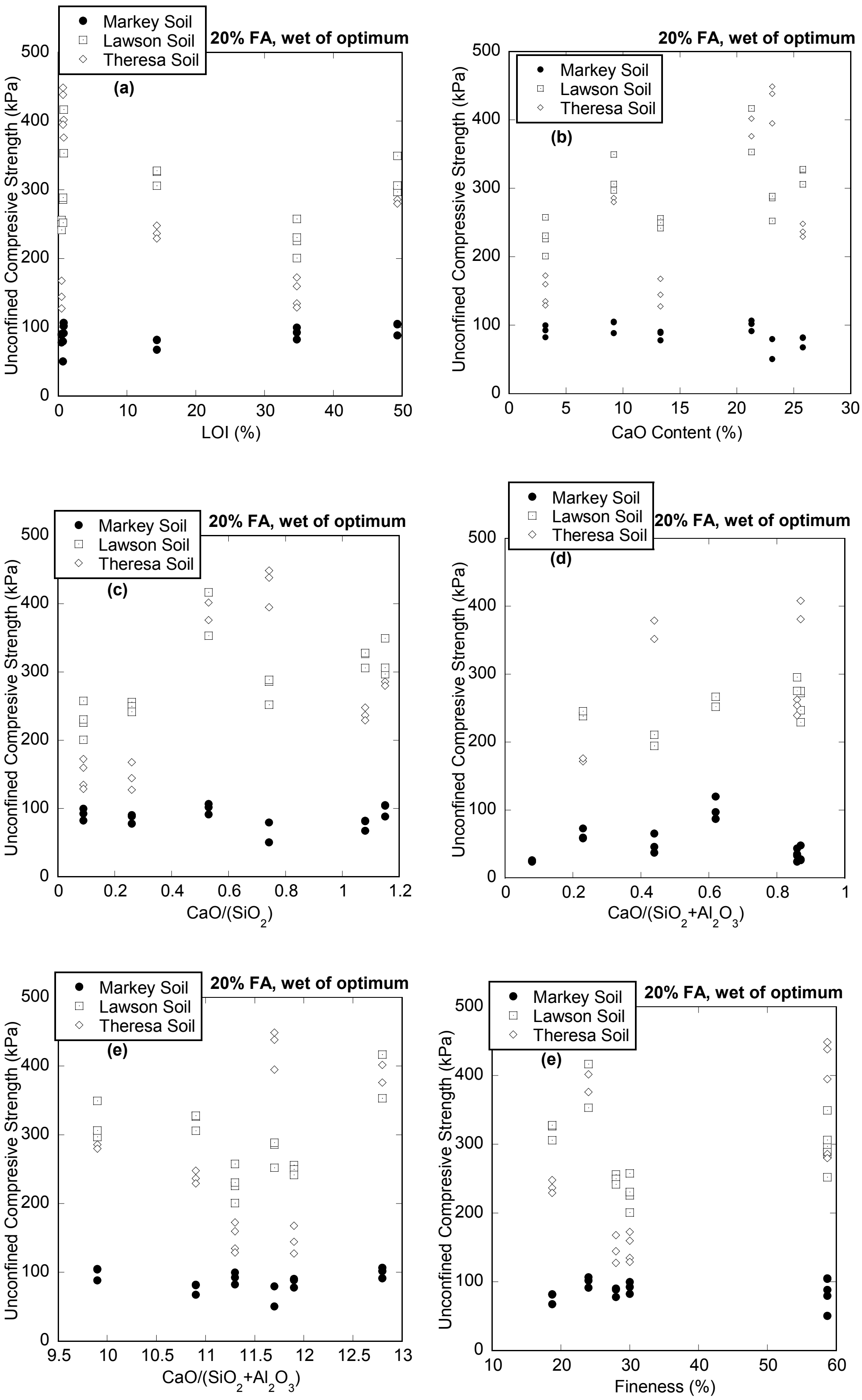


Figure B.2. Variation of unconfined compressive strength as a function of chemical properties of fly ashes (fly ash percentage=20%, moisture state=wet of optimum): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

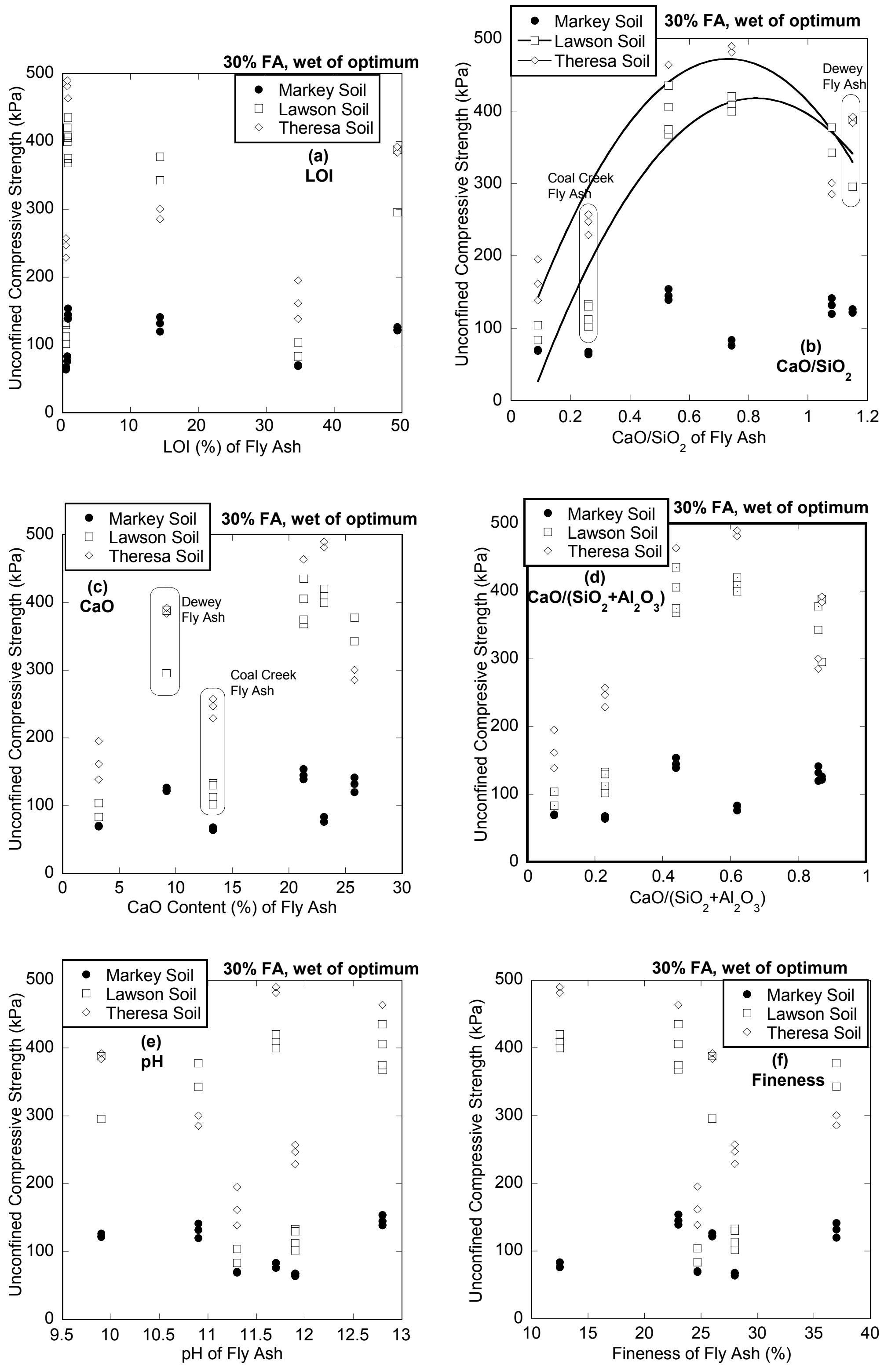


Figure B.3. Variation of unconfined compressive strength as a function of chemical properties of fly ashes (fly ash percentage=20%, moisture state=wet of optimum): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

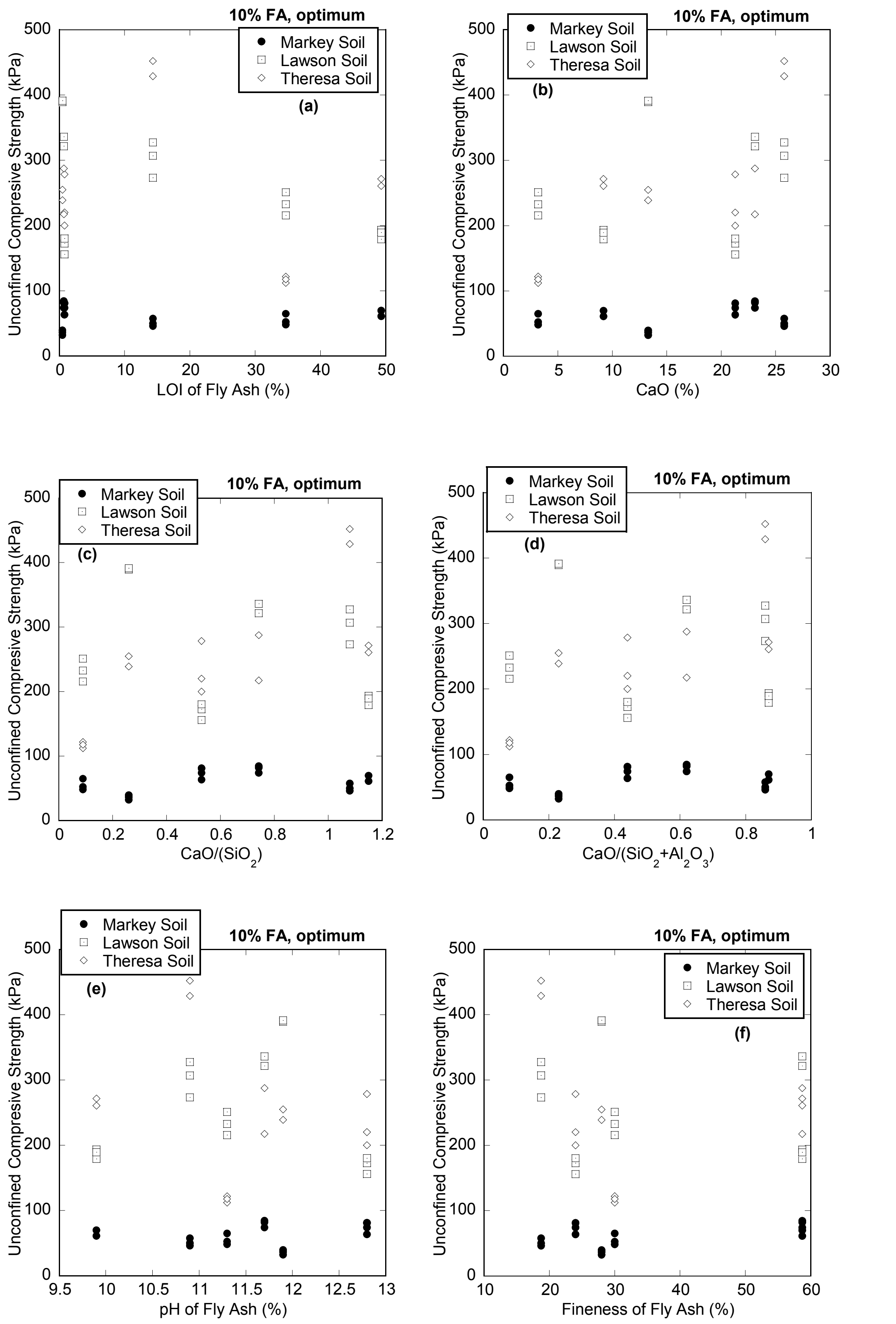


Figure B.4. Variation of unconfined compressive strength as a function of chemical properties of fly ashes (fly ash percentage=10%, moisture state= optimum water content): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

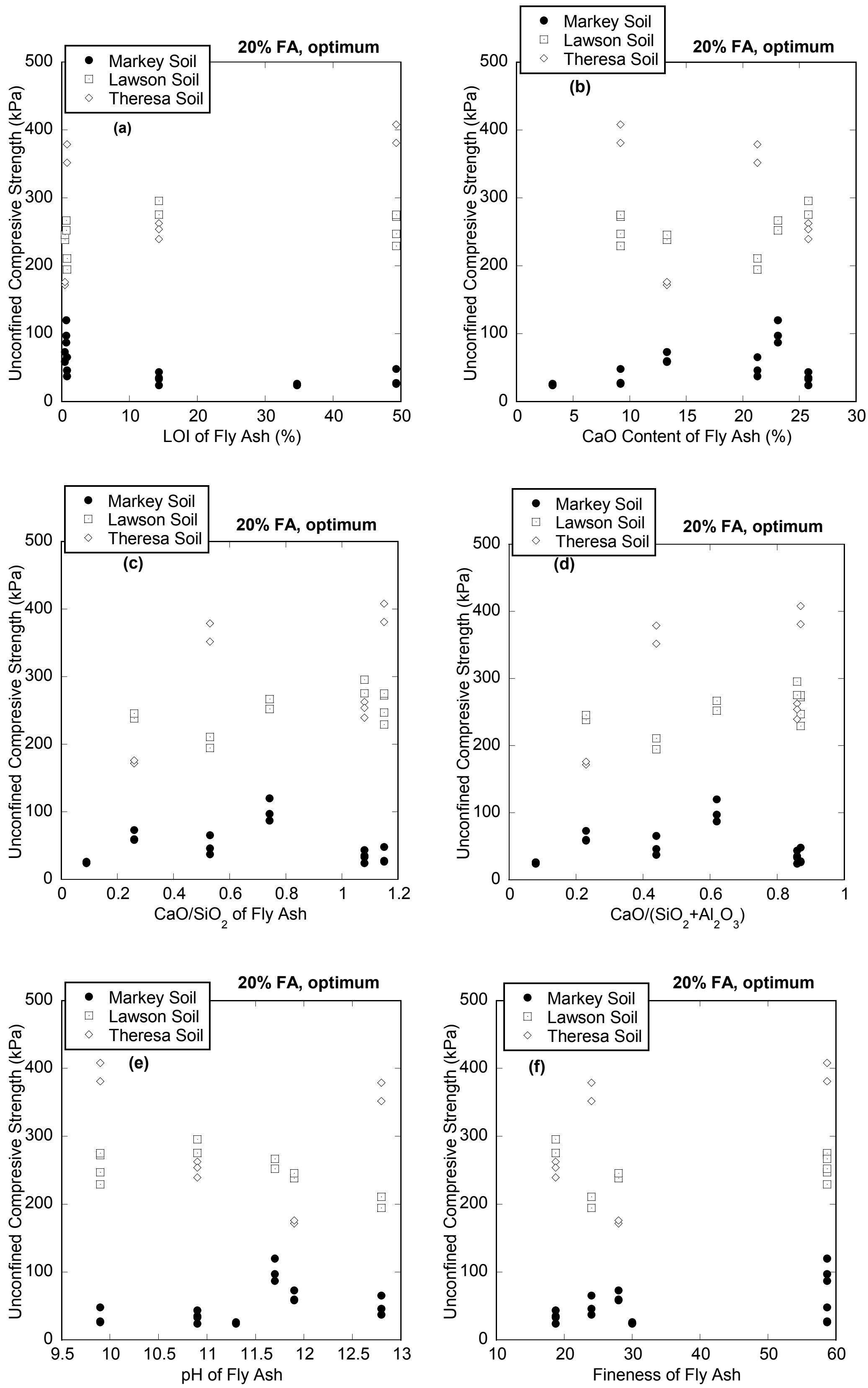


Figure B.5. Variation of unconfined compressive strength as a function of chemical properties of fly ashes (fly ash percentage=20%, moisture state= optimum water content): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

APPENDIX C

ALL PLOTS SHOWING THE EFFECT OF CHARACTERISTICS OF SOILS ON UNCONFINED COMPRESSIVE STRENGTH

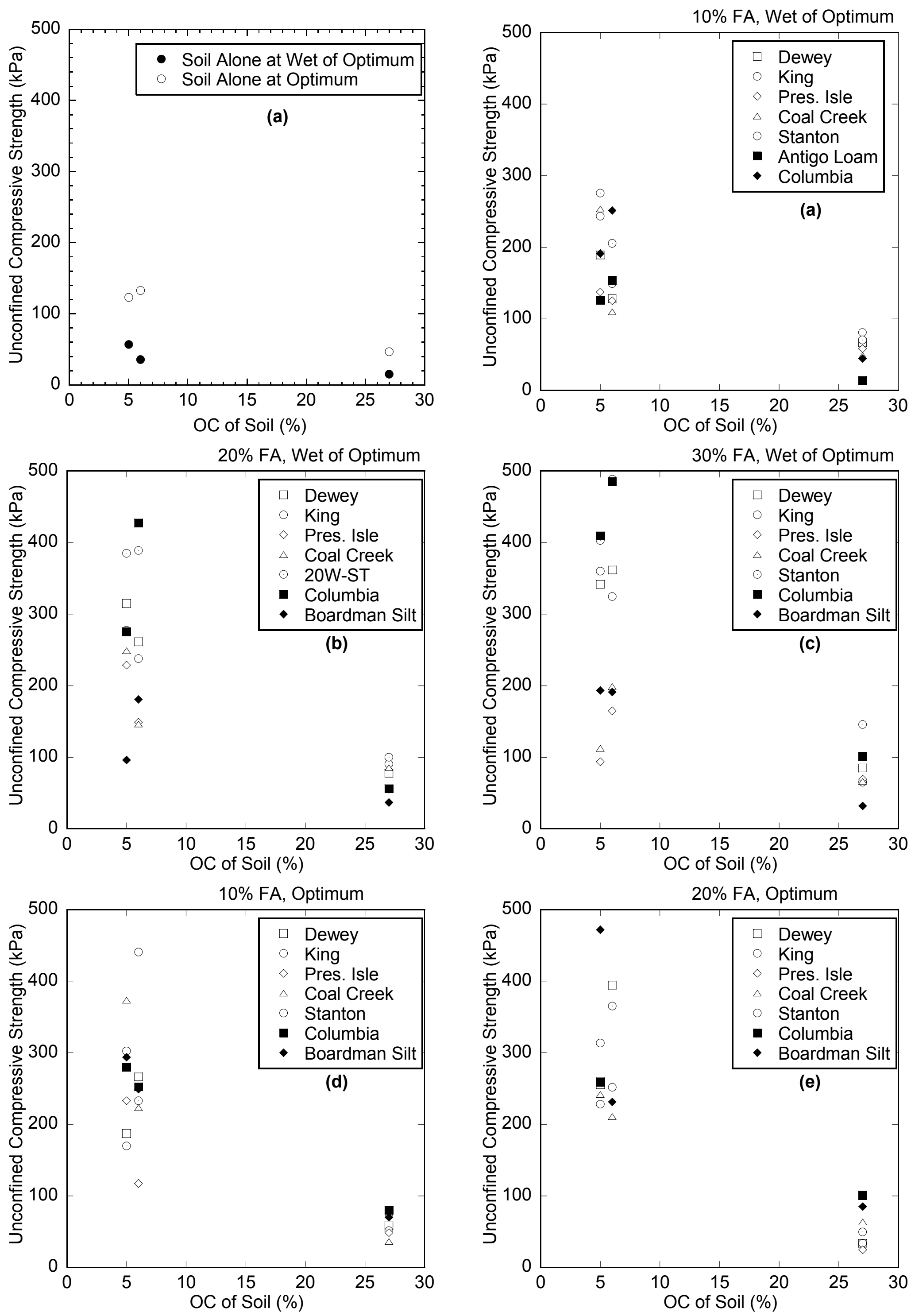


Figure C.1. Variation of unconfined compressive strength as a function organic content of the soil and fly ash type: (a) Soil alone, untreated, (b) 10% fly ash at wet of optimum, (c) 20% fly ash at wet of optimum, (c) 30% fly ash at wet of optimum, (d) 10% fly ash at optimum water content, (e) 20% fly ash, optimum water content

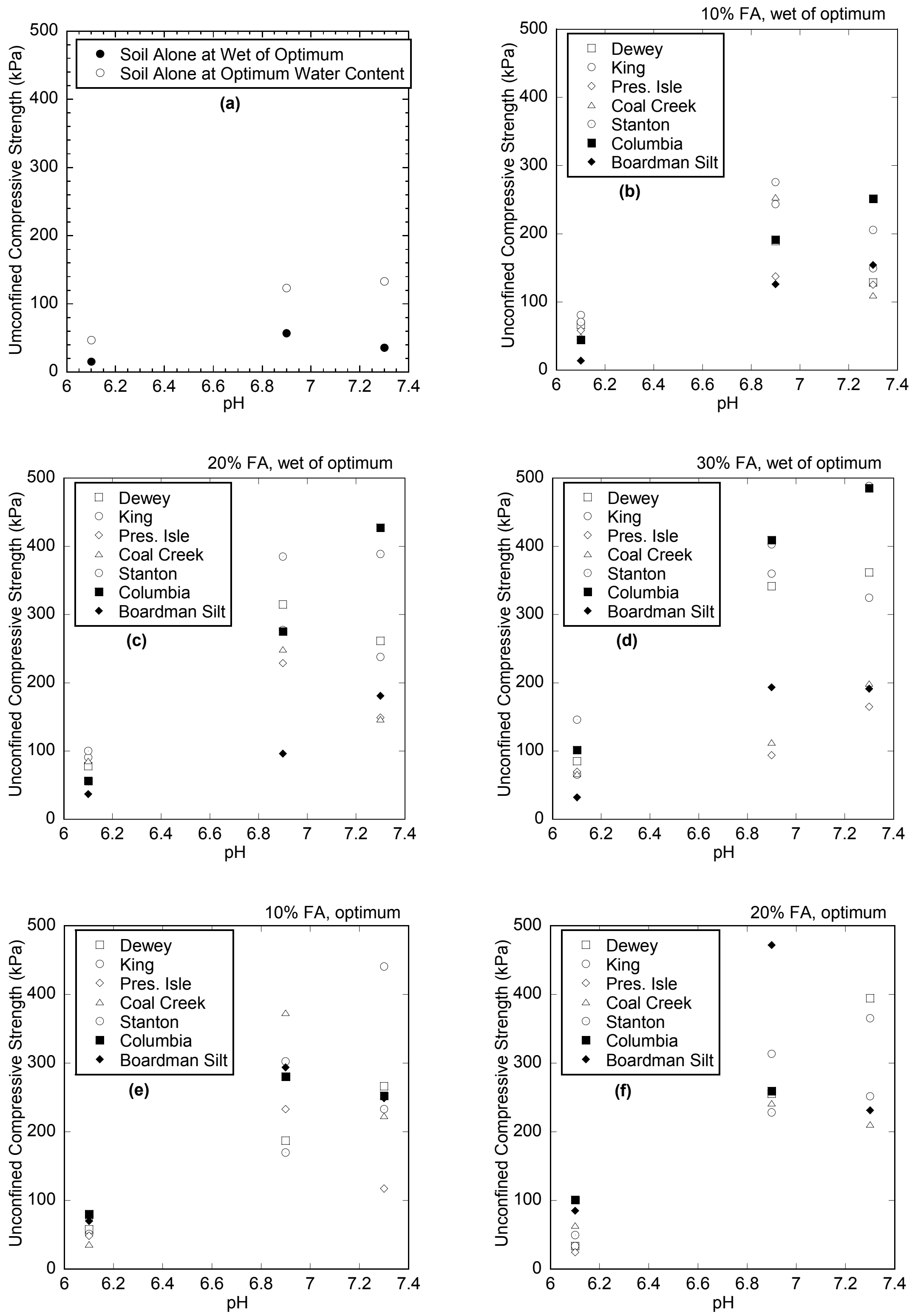


Figure C.2. Variation of unconfined compressive strength as a function pH of the soil and fly ash type: (a) Soil alone, untreated, (b) 10% fly ash at wet of optimum, (c) 20% fly ash at wet of optimum, (c) 30% fly ash at wet of optimum, (d) 10% fly ash at optimum water content, (e) 20% fly ash, optimum water content

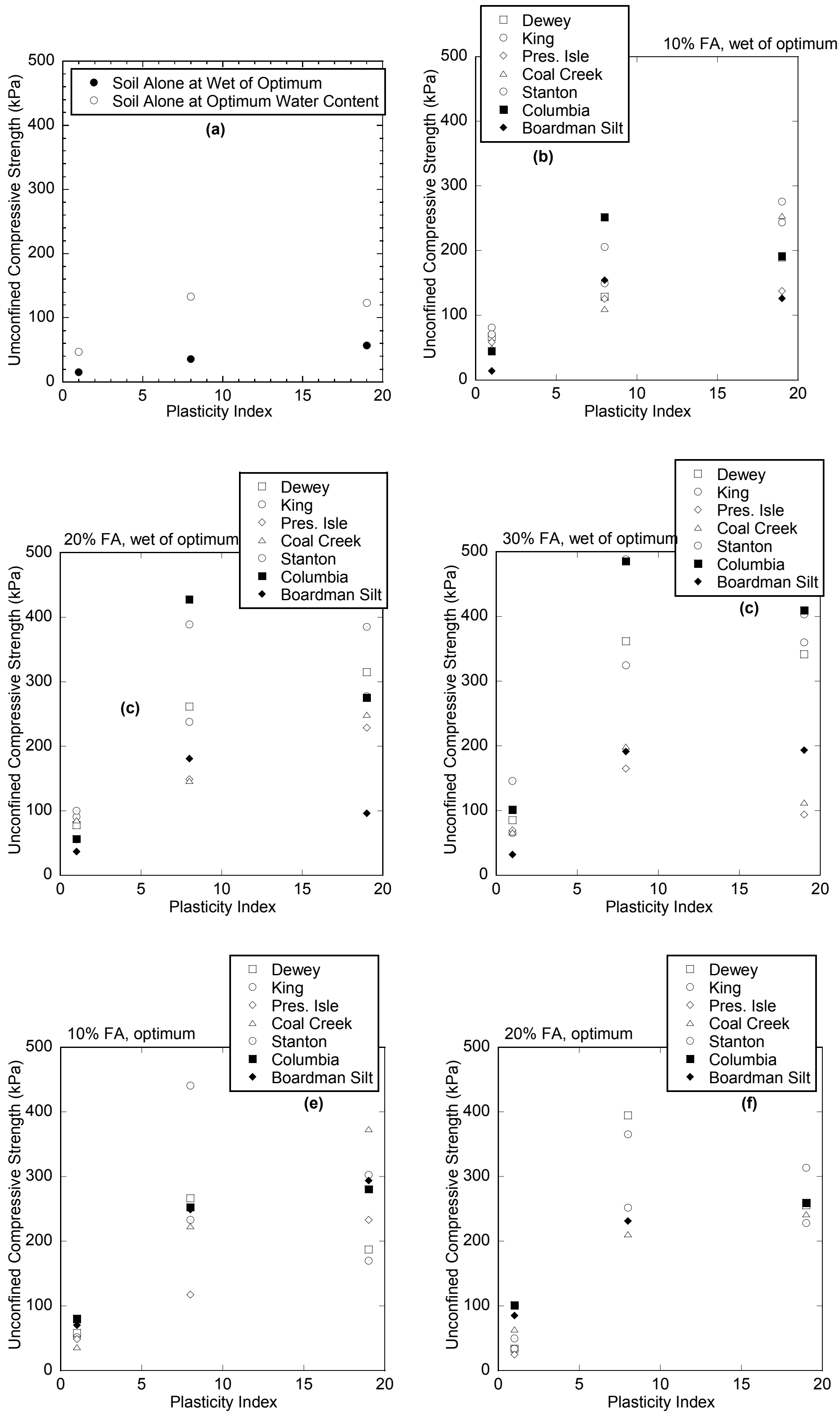


Figure C.3. Variation of unconfined compressive strength as a function plasticity index of the soil and fly ash type: (a) Soil alone, untreated, (b) 10% fly ash at wet of optimum, (c) 20% fly ash at wet of optimum, (c) 30% fly ash at wet of optimum, (d) 10% fly ash at optimum water content, (e) 20% fly ash, optimum water content

APPENDIX D

DETAILS OF STATISTICAL ANALYSIS

Statistical investigation of any relation between soil or fly ash characteristics and UCS of soil-fly ash mixtures was conducted in four stages: (i) calculating the Pearson product moment correlation coefficient (r), which varies between -1 and 1, (ii) testing for the existence of correlation, t-test, (iii) if correlation exists, trials of linear and quadratic curvilinear regression models to see which model best describes the relation based on F-test, and (iv) multiple regression model including all significant characteristics. Multiple regression model included second order or any transformed functions of properties investigated. Possible correlations between independent variables were also checked and highly correlated terms were dropped from the model.

The data set consists of independent variables such as fly ash characteristics and a dependent variable, UCS in this study. Each independent variable and UCS correlation was treated separately. Pearson correlation coefficient, r, was calculated according to Eq.2.1 between populations of dependent (Y) and independent variable (X).

$$r = \frac{n\left(\sum XY\right) - \left(\sum X\right)\left(\sum Y\right)}{\sqrt{\left[n\sum X^2 - \left(\sum X\right)^2\right]\left[n\sum Y^2 - \left(\sum Y\right)^2\right]}} \qquad \text{(A.1)}$$

where n=number of data points. After calculating the Pearson correlation coefficient (r), a null hypothesis is assumed as follows: H_0:ρ=0 (there is no correlation). The t test with n-2 degrees of freedom was used to test the null hypothesis. Using the 0.05 level of significance and the degree of freedom (number of data points-2) , t_{cr} was obtained as 1.96 from the statistical tables for t-test (Levine, Ramsey and Smidt 2001). If t statistics calculated using Eq.2.2 is higher than t_{cr},1.96, null hypothesis is rejected and there is a correlation between two variables.

$$t = \frac{r-\rho}{\sqrt{\frac{1-r^2}{n-2}}} \quad \text{(A.2)}$$

Linear and quadratic curvilinear regressions between each soil or fly ash characteristics and UCS were conducted. Then, regression mean squares (MSR) and error mean squares (MSE) for each case were calculated. F statistics for each case, as the ratio of (MSR/MSE) were determined and compared to the critical F corresponding to n-2 degrees of freedom and at 0.05 significance level. If the calculated F is greater than the critical F, regression is statistically significant.

Statistix 8 and Statistica 4.3 softwares were used for regression analysis. After determining all significant characteristics and their significant regressions with UCS one by one, a multiple regression analysis was conducted. First, without any second order terms or exponential terms, a multiple linear regression analysis was conducted. Collinearity of two different independent variables are investigated based on variation inflation factor (VIF), depicted in Eq.2.3 (Levine, Ramsey and Smidt 2001)

$$VIF_j = \frac{1}{1-R_j^{\,2}} \quad \text{(A.3)}$$

where R_j^2= coefficient of multiple determination of explanatory variable X_j with all other X variables. If a set of parameters are not correlated, VIF is 1. If they are correlated R^2 gets larger which produces larger VIF. Marquardt proposed that if VIF is larger than 10, there is too much correlation. Following the limit proposed by Marquardt any parameter having VIF of more than 10 is eliminated from the model. Then, second order terms (quadratic curvilinear regression) and other transformed functions (such as exponential of any characteristics) were adapted in the model and r^2 was maximized. Statistical significance of each factor in the model was tested. Finally assumptions of regression, such as homoscedacity, normality and independence were checked based on residuals and distribution of errors. (Levine, Ramsey and Smidt 2001).

APPENDIX E

ALL PLOTS SHOWING THE EFFECT OF CHARACTERISTICS OF FLY ASHES ON RESILIENT MODULUS

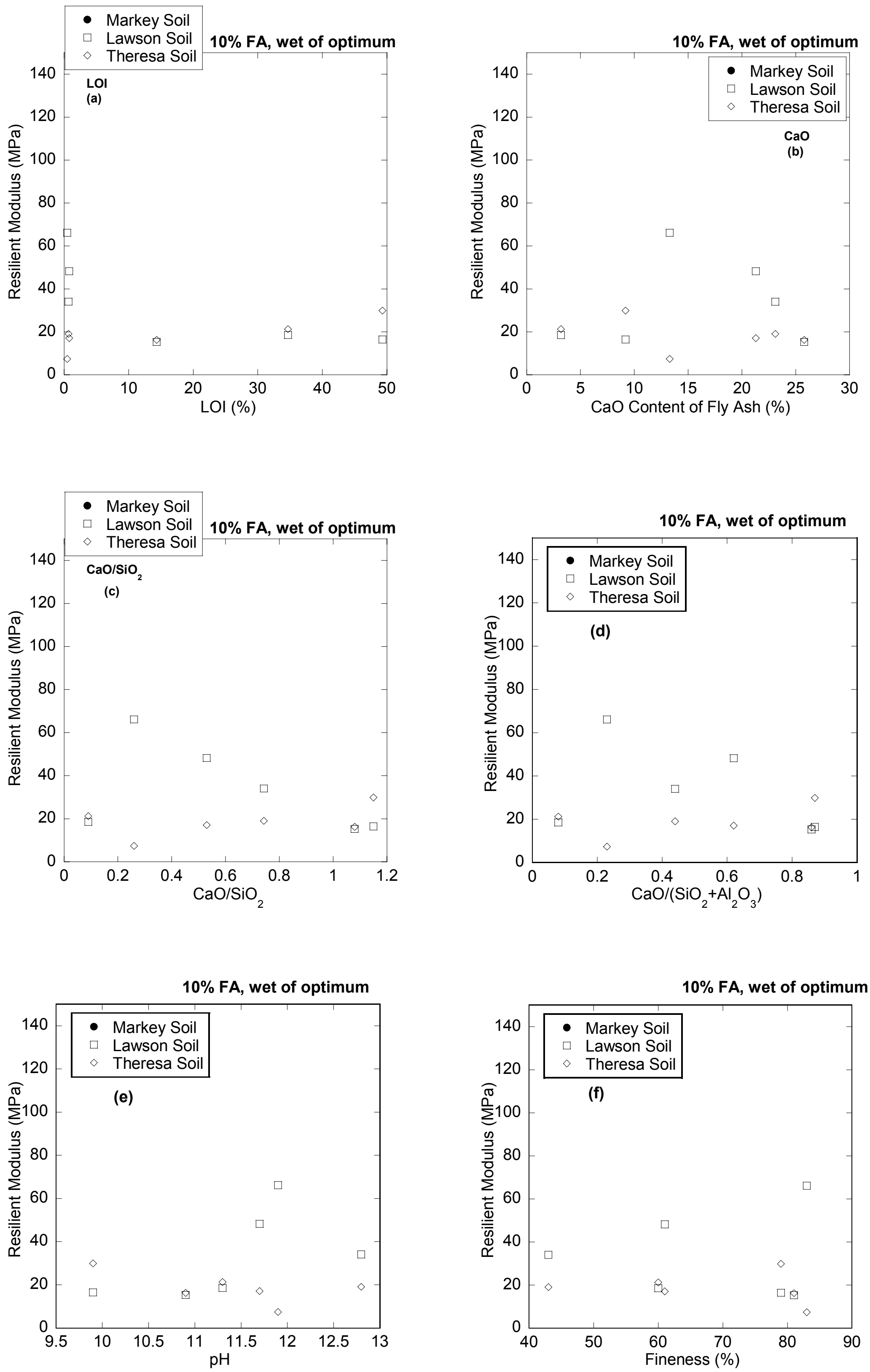


Figure E.1. Variation of resilient modulus as a function of chemical properties of fly ashes (fly ash percentage=10%, moisture state= wet of optimum): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

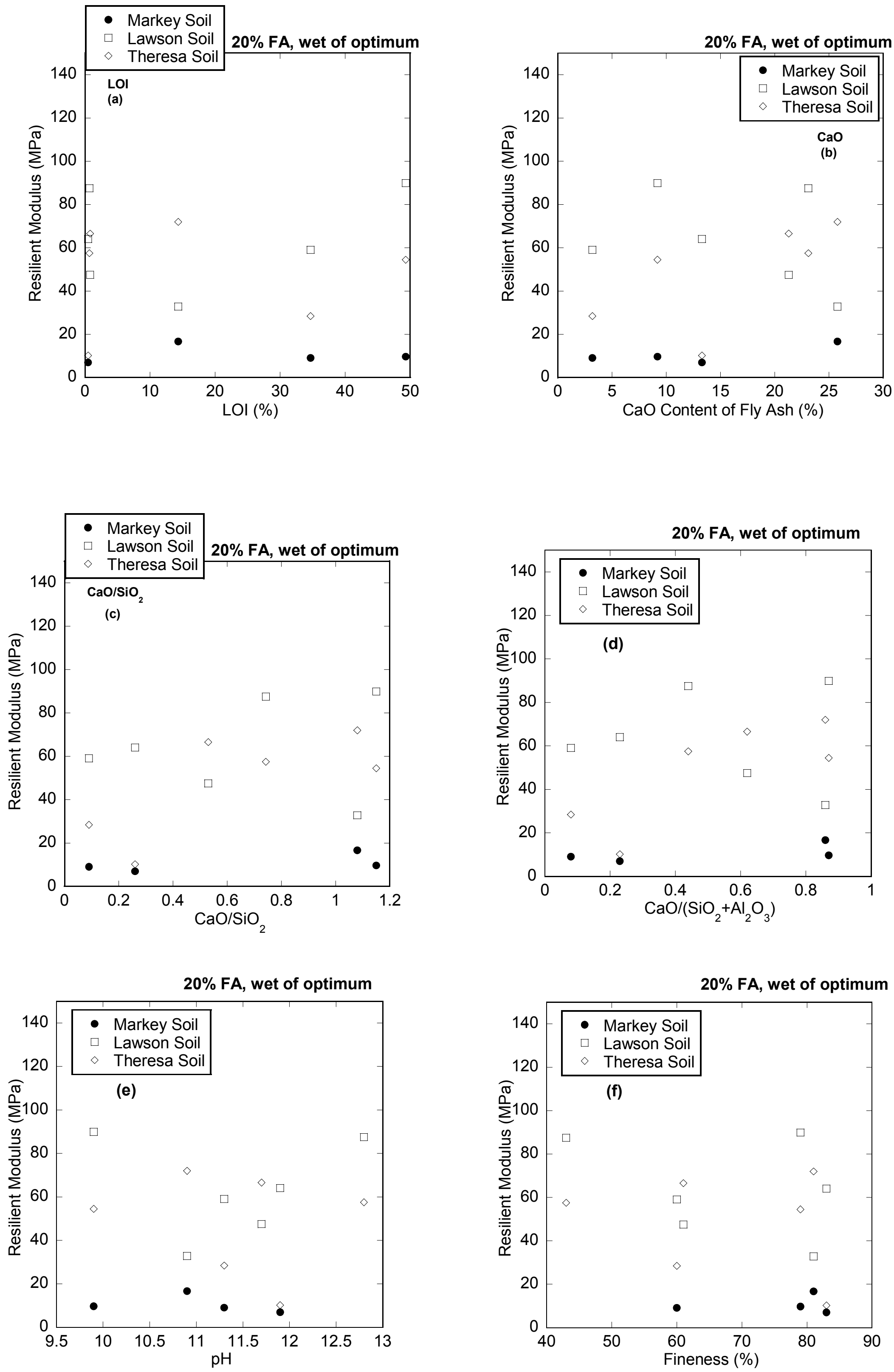


Figure E.2. Variation of resilient modulus as a function of chemical properties of fly ashes (fly ash percentage=20%, moisture state= wet of optimum): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

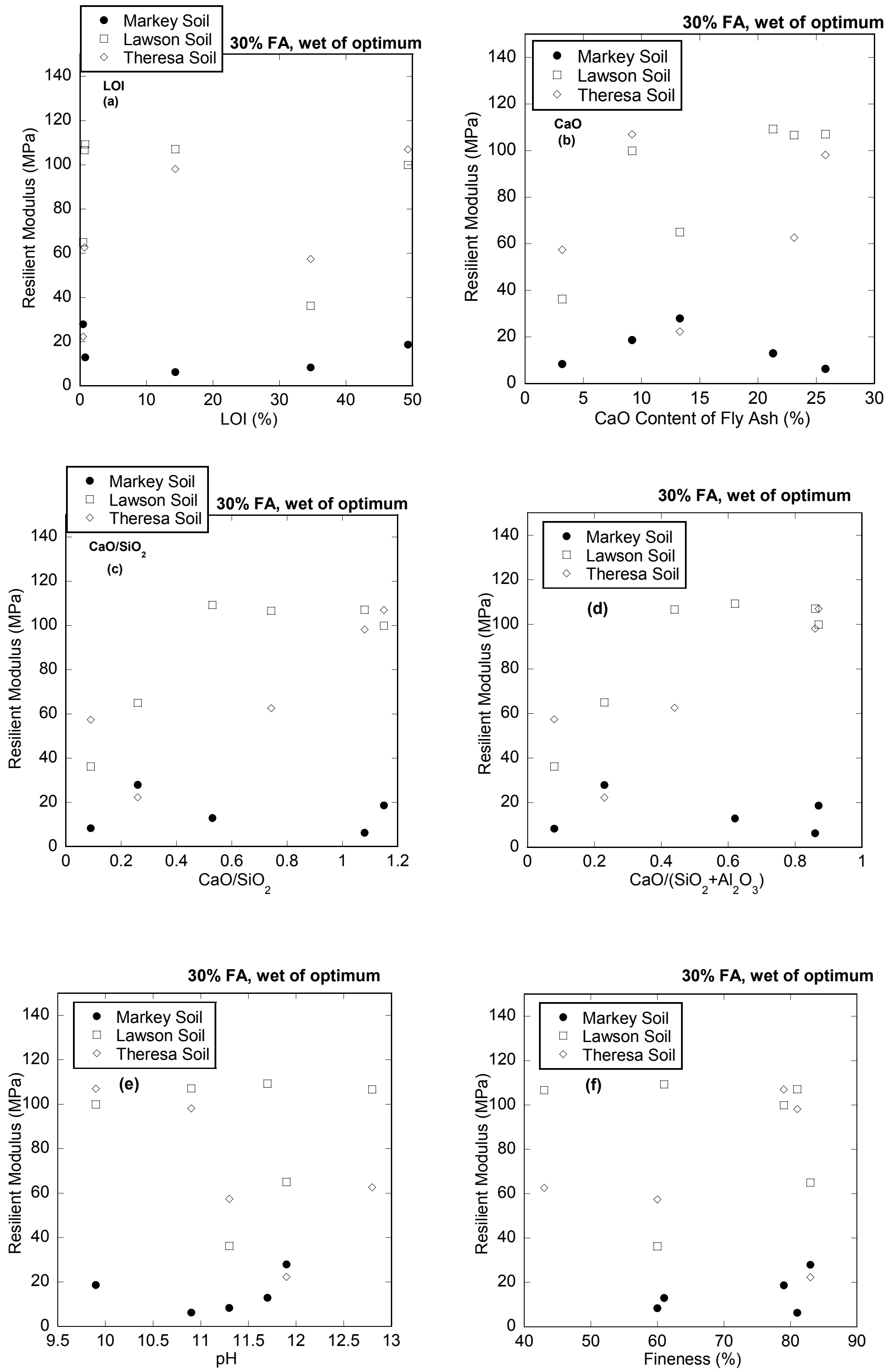


Figure E.3. Variation of resilient modulus as a function of chemical properties of fly ashes (fly ash percentage=30%, moisture state= wet of optimum): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

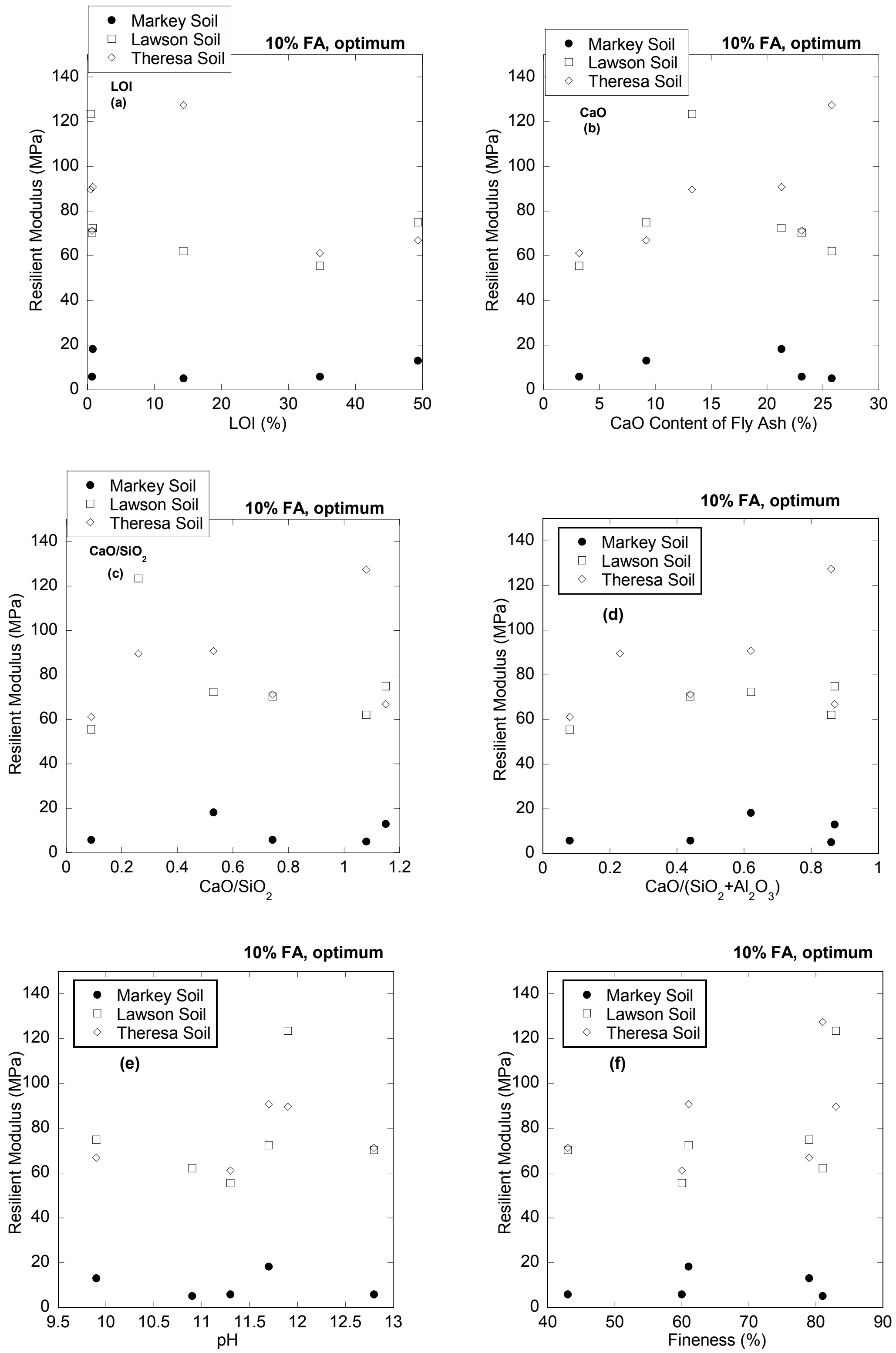


Figure E.4. Variation of resilient modulus as a function of chemical properties of fly ashes (fly ash percentage=10%, moisture state= optimum water content): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

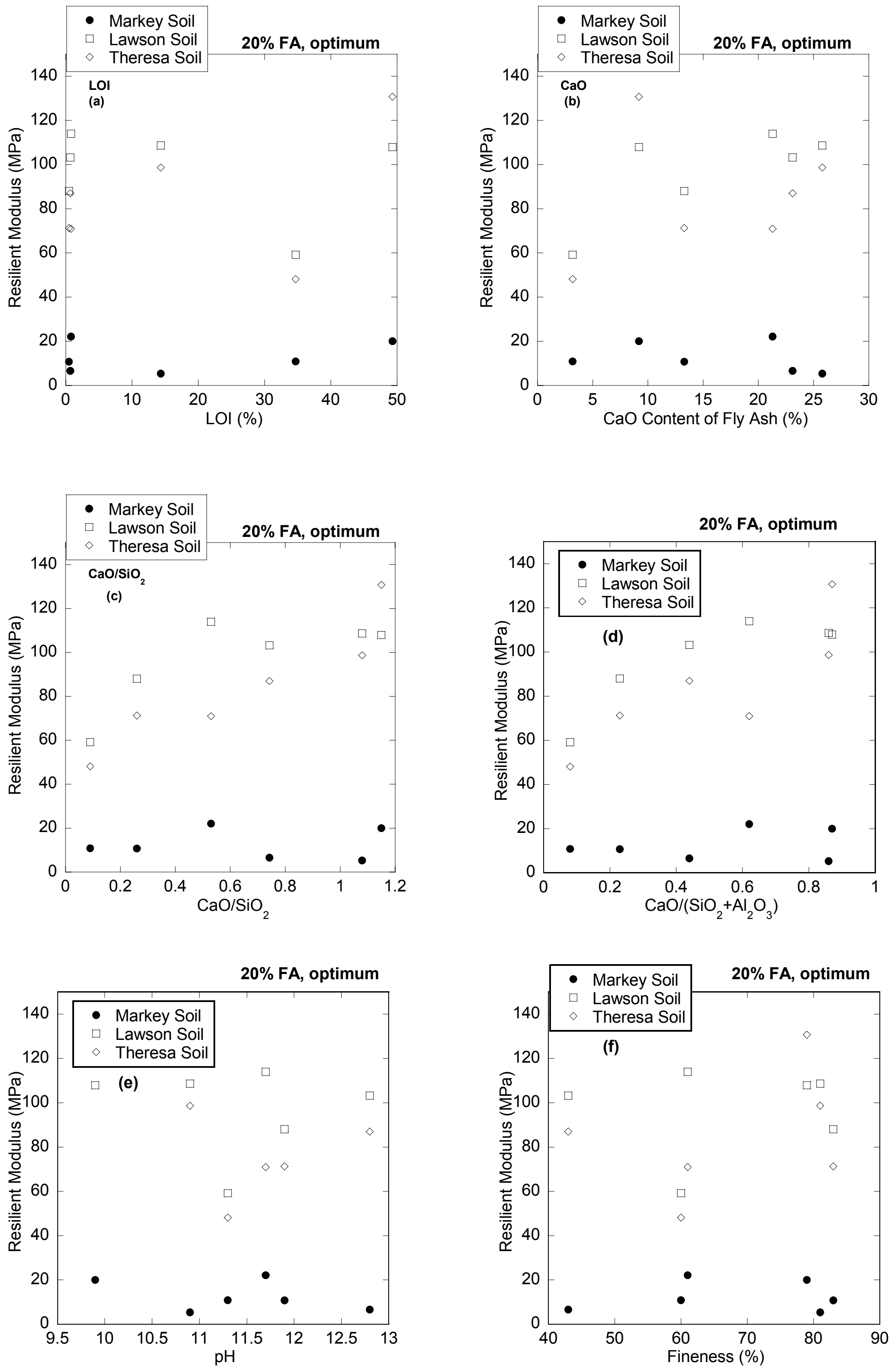


Figure E.5. Variation of resilient modulus as a function of chemical properties of fly ashes (fly ash percentage=20%, moisture state= optimum water content): (a) LOI, (b) CaO content, (c) CaO/SiO_2 Ratio, (d) $CaO/(SiO_2+Al_2O_3)$ ratio, (e) pH, and (f) Fineness of fly ashes, wet of optimum=water content at wet of optimum

APPENDIX F

ALL PLOTS SHOWING THE EFFECT OF CHARACTERISTICS OF SOILS ON RESILIENT MODULUS OF SOIL-FLY ASH MIXTURE

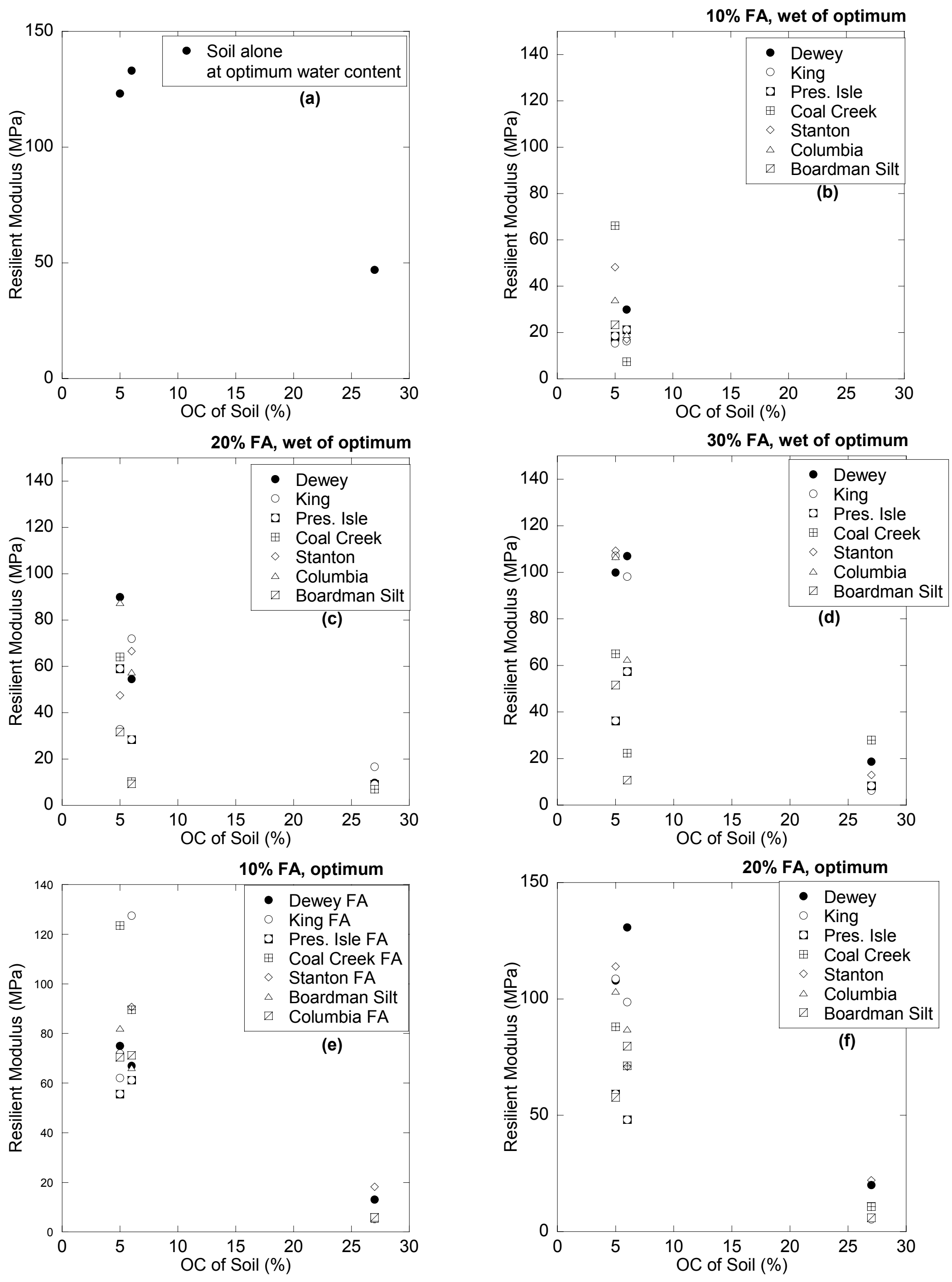


Figure F.1. Variation of resilient modulus of soil-fly ash mixture as a function organic content of the soil and fly ash type: (a) Soil alone, untreated, (b) 10% fly ash at wet of optimum, (c) 20% fly ash at wet of optimum, (c) 30% fly ash at wet of optimum, (d) 10% fly ash at optimum water content, (e) 20% fly ash, optimum water content

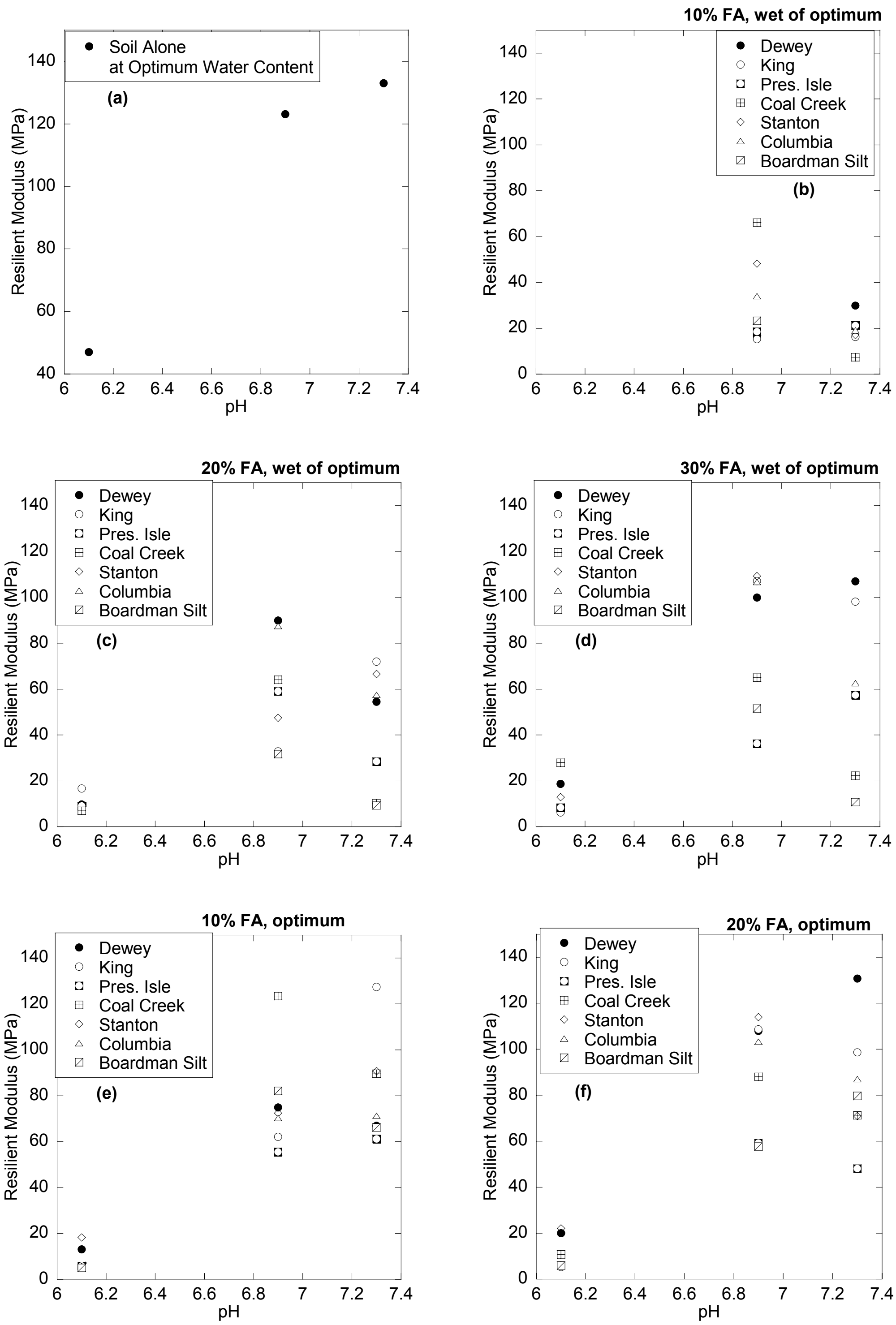


Figure F.2. Variation of resilient modulus of soil-fly ash mixture as a function pH of the soil and fly ash type: (a) Soil alone, untreated, (b) 10% fly ash at wet of optimum, (c) 20% fly ash at wet of optimum, (c) 30% fly ash at wet of optimum, (d) 10% fly ash at optimum water content, (e) 20% fly ash, optimum water content

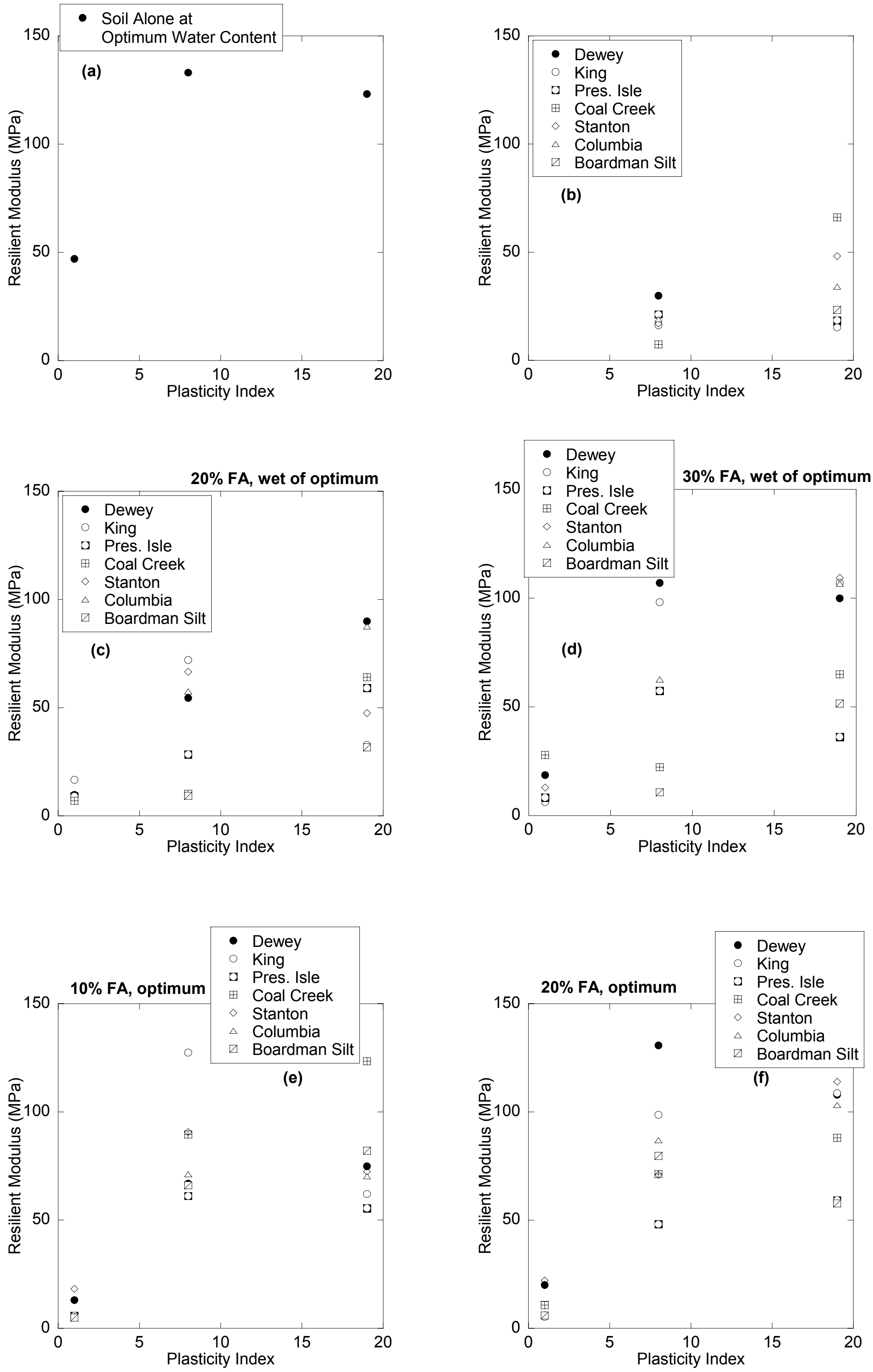
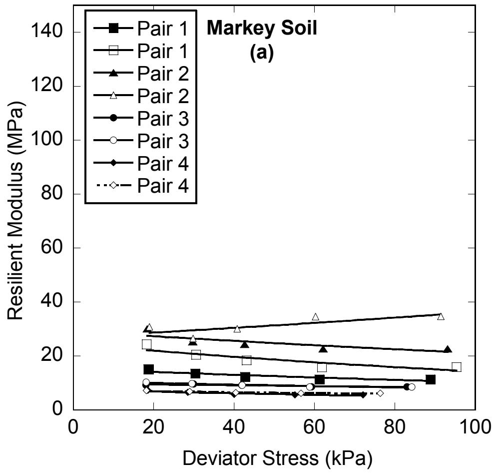
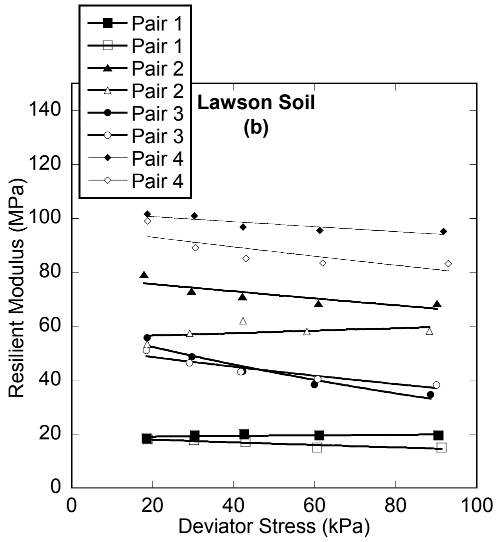


Figure F.3. Variation of resilient modulus of soil-fly ash mixture as a function plasticity index of the soil and fly ash type: (a) Soil alone, untreated, (b) 10% fly ash at wet of optimum, (c) 20% fly ash at wet of optimum, (c) 30% fly ash at wet of optimum, (d) 10% fly ash at optimum water content, (e) 20% fly ash, optimum water content

APPENDIX G

REPRODUCIBILITY OF RESILIENT MODULUS TEST





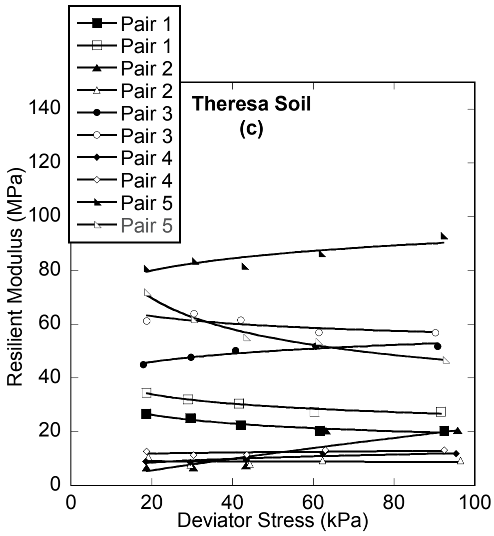


Figure G.1. Reproducibility of resilient modulus test based on tests run on duplicate specimens of (a) markey soil-fly ash, (b) Lawson soil-fly ash, and (c) Theresa soil-fly ash mixtures.

APPENDIX H

RESILIENT MODULUS VERSUS DEVIATOR STRESS GRAPHS

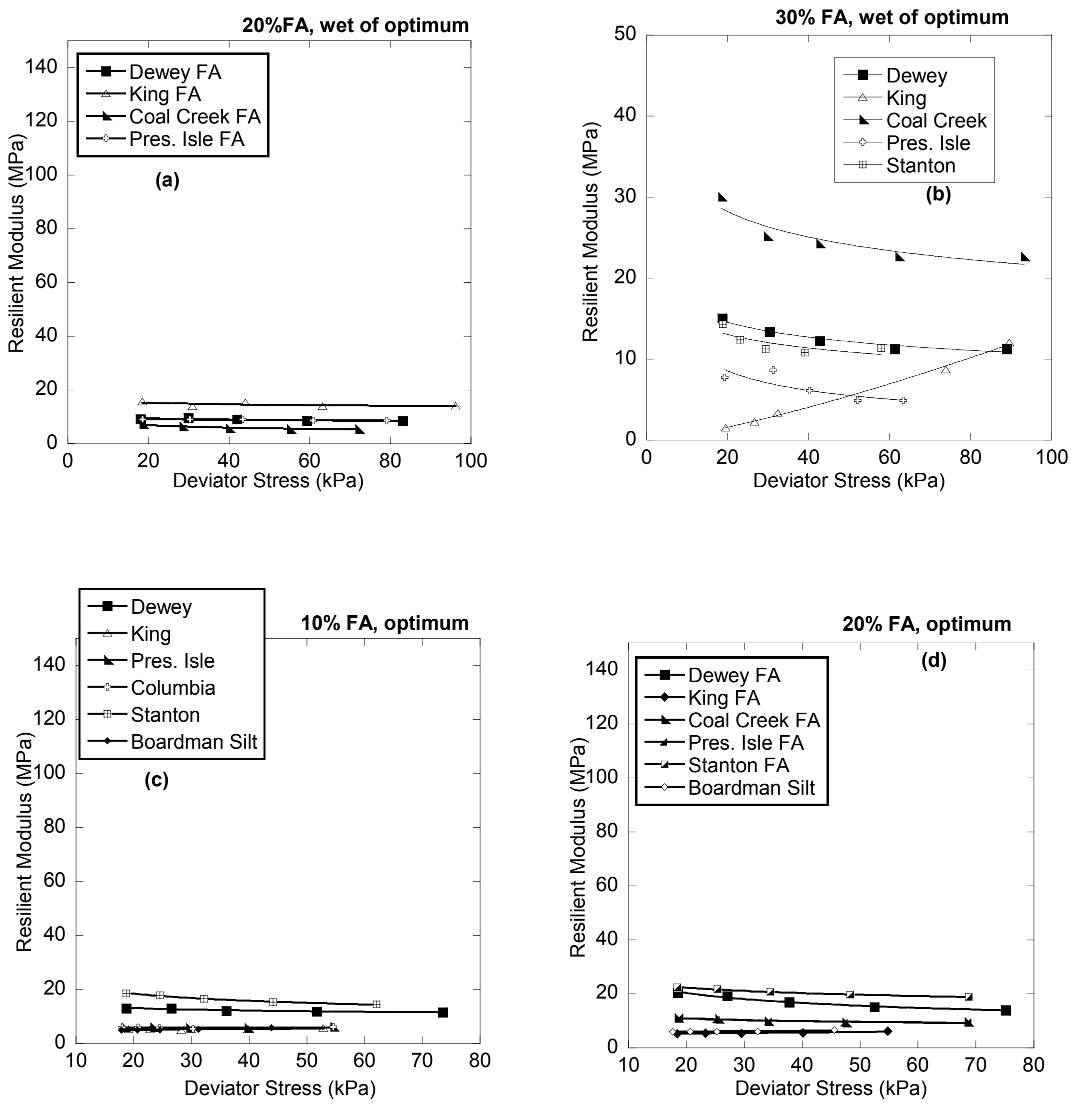


Figure H.1. Resilient modulus versus deviator stress curves for Markey soil-fly ash mixtures: (a) fly ash percentage=20% at wet of optimum, (b) fly ash percentage=30% at wet of optimum, (c) fly ash percentage=10% at optimum water content, and (d) fly ash percentage=20% at optimum water content

*Markey soil specimens mixed with 10% fly ash at wet of optimum were too soft to withstand conditioning stress.

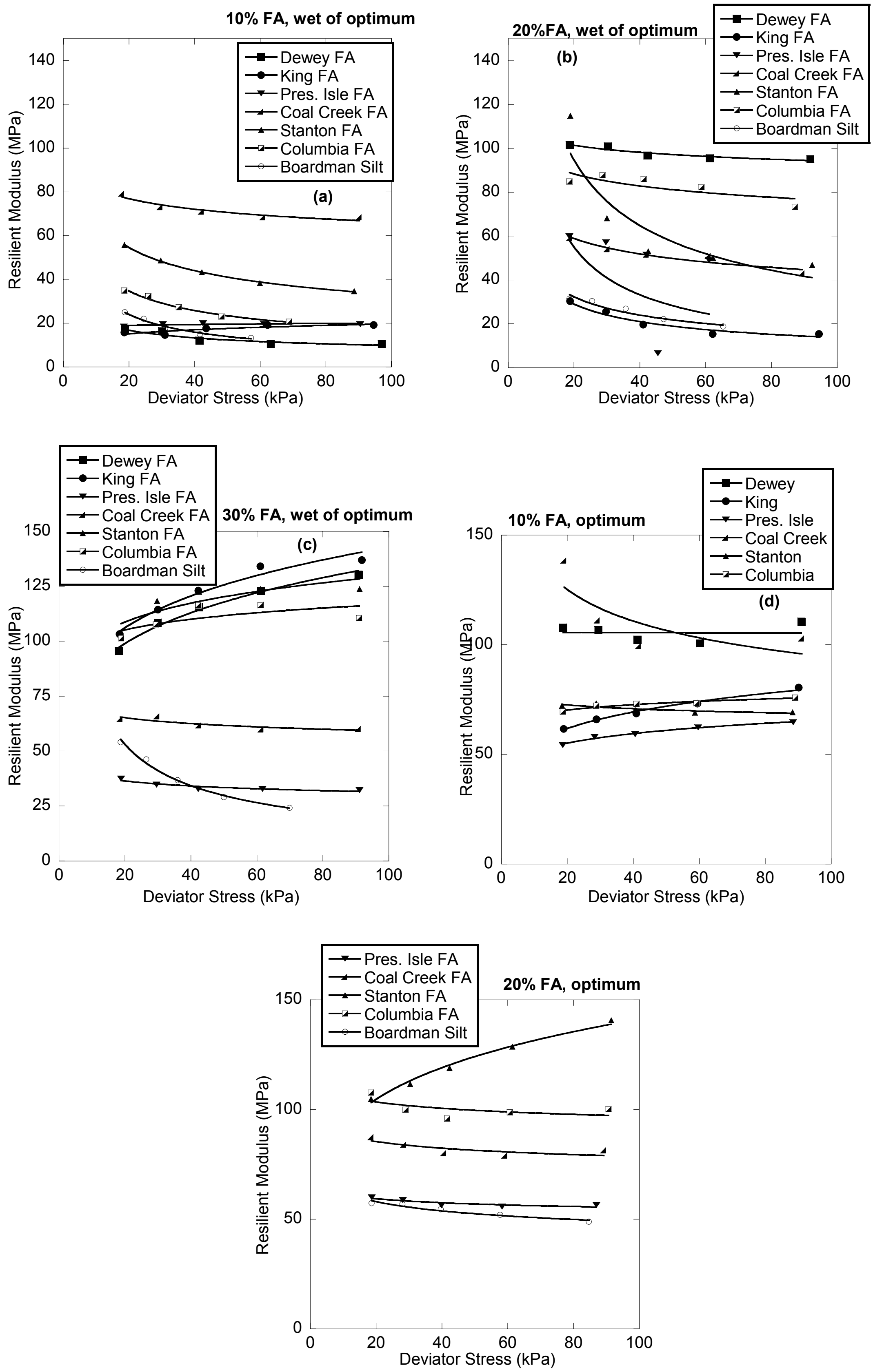


Figure H.2. Resilient modulus versus deviator stress curves for Lawson soil-fly ash mixtures: (a) fly ash percentage=10% at wet of optimum, (b) fly ash percentage=20% at wet of optimum, (c) fly ash percentage=30% at wet of optimum, (d) fly ash percentage=10% at optimum water content, and (e) fly ash percentage=20% at optimum water content

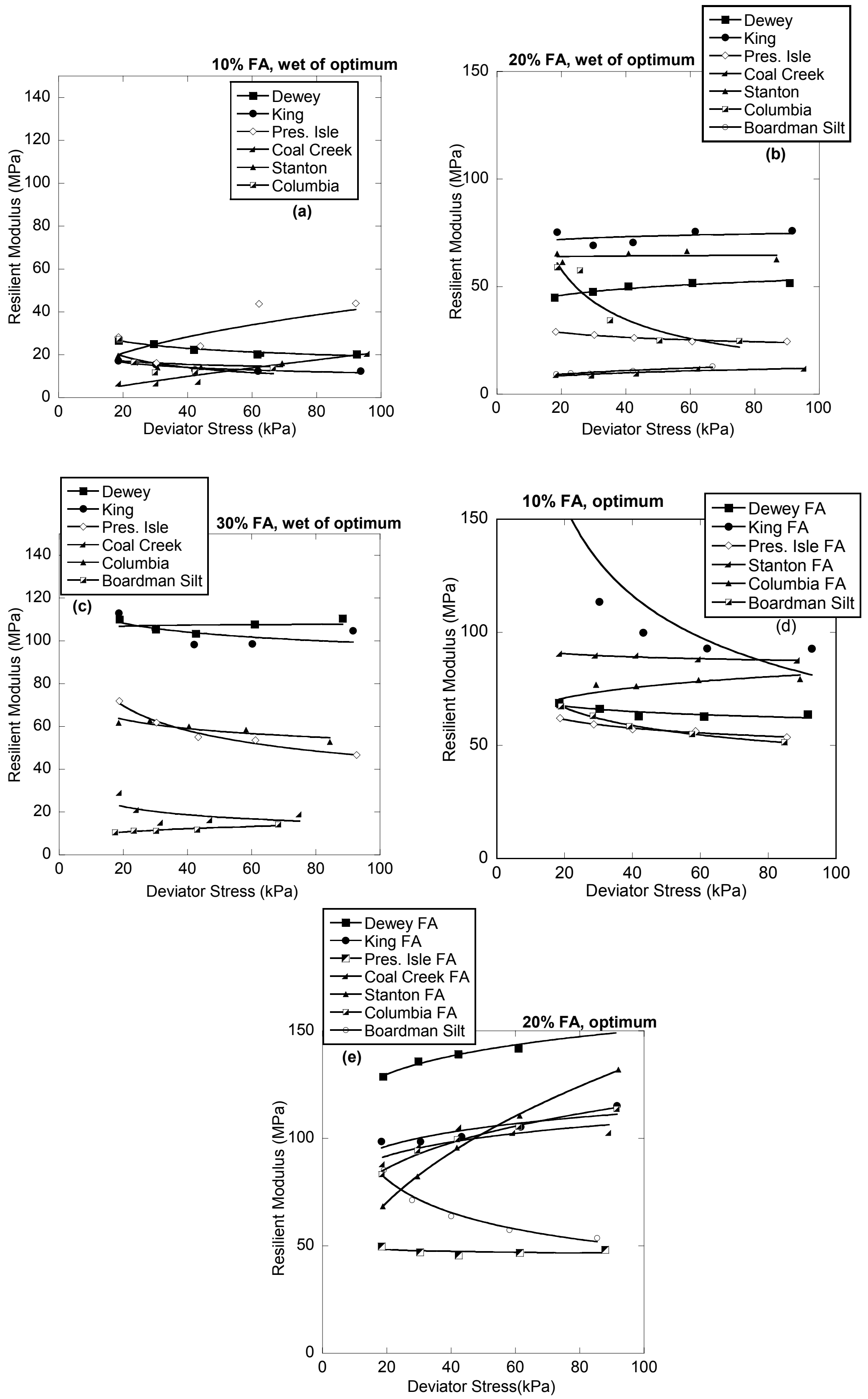


Figure H.3. Resilient modulus versus deviator stress curves for Theresa soil-fly ash mixtures: (a) fly ash percentage=10% at wet of optimum, (b) fly ash percentage=20% at wet of optimum, (c) fly ash percentage=30% at wet of optimum, (d) fly ash percentage=10% at optimum water content, and (e) fly ash percentage=20% at optimum water content

APPENDIX J

RESILIENT MODULUS MODEL COEFFICIENTS

($Mr = K1\ (\sigma_d)^{K2}$)

Table J.1. Resilient modulus model coefficients for specimens of Markey soil-fly ash mixtures

Soil	Fly Ash	Moisture State	Fly Ash Percentage	K1	K2	R^2
Markey	Dewey	Very Wet	20	11.60	-0.0683	0.62
	King	Very Wet	20	17.92	-0.0533	0.35
	Pres. Isle	Very Wet	20	10.04	-0.0321	0.55
	Coal Creek	Very Wet	20	13.20	-0.2120	0.90
	Columbia	Very Wet	20			
	Stanton	Very Wet	20			
	Boardman Silt	Very Wet	20			
	Dewey	Very Wet	30	26.25	-0.1964	0.95
	King	Very Wet	30	0.03	1.3263	0.99
	Pres. Isle	Very Wet	30	35.65	-0.4768	0.64
	Coal Creek	Very Wet	30	47.07	-0.1707	0.87
	Columbia	Very Wet	30			
	Stanton	Very Wet	30	23.74	-0.1962	0.63
	Boardman Silt	Very Wet	30			
	Dewey	Optimum	10	17.60	-0.0990	0.91
	King	Optimum	10	4.04	0.0798	0.38
	Pres. Isle	Optimum	10	5.66	0.0128	0.03
	Coal Creek	Optimum	10			
	Columbia	Optimum	10	5.43	0.0229	0.05
	Stanton	Optimum	10	35.44	-0.2185	0.99
	Boardman Silt	Optimum	10	2.80	0.1900	0.93
	Dewey	Optimum	20	48.01	-0.2871	0.98
	King	Optimum	20	3.66	0.1204	0.75
	Pres. Isle	Optimum	20	15.66	-0.1234	0.81
	Coal Creek	Optimum	20	16.55	-0.1389	0.78
	Columbia	Optimum	20			
	Stanton	Optimum	20	33.55	-0.1362	0.99
	Boardman Silt	Optimum	20	4.67	0.0826	0.70

Table J.2. Resilient modulus model coefficients for specimens of Lawson soil-fly ash mixtures

Soil	Fly Ash	Moisture State	Fly Ash Percent age	K1	K2	R^2
Lawson	Dewey	Very Wet	10	45.80	-0.3353	0.86
	King	Very Wet	10	9.29	0.1631	0.74
	Pres. Isle	Very Wet	10	17.07	0.0347	0.47
	Coal Creek	Very Wet	10	101.54	-0.0928	0.91
	Columbia	Very Wet	10	125.64	-0.4290	0.98
	Stanton	Very Wet	10	138.84	-0.3115	0.99
	Boardman Silt	Very Wet	10	142.65	-0.5948	0.98
	Dewey	Very Wet	20	116.75	-0.0469	0.88
	King	Very Wet	20	117.72	-0.4674	0.95
	Pres. Isle	Very Wet	20	487.05	-0.7278	0.22
	Coal Creek	Very Wet	20	102.11	-0.1835	0.91
	Columbia	Very Wet	20	116.63	-0.0920	0.59
	Stanton	Very Wet	20	487.17	-0.5466	0.87
	Boardman Silt	Very Wet	20	117.26	-0.4304	0.93
	Dewey	Very Wet	30	55.83	0.1910	0.99
	King	Very Wet	30	61.05	0.1845	0.96
	Pres. Isle	Very Wet	30	48.06	-0.0927	0.85
	Coal Creek	Very Wet	30	78.23	-0.0607	0.75
	Columbia	Very Wet	30	86.41	0.0654	0.45
	Stanton	Very Wet	30	78.32	0.1095	0.71
	Boardman Silt	Very Wet	30	352.24	-0.6315	0.99
	Dewey	Optimum	10	106.04	-0.0013	0.00
	King	Optimum	10	37.56	0.1661	0.98
	Pres. Isle	Optimum	10	39.69	0.1096	0.99
	Coal Creek	Optimum	10	212.26	-0.1763	0.67
	Columbia	Optimum	10	60.46	0.0499	0.93
	Stanton	Optimum	10	80.85	-0.0361	0.70
	Boardman Silt	Optimum	10	165.36	-0.2299	0.99
	Dewey	Optimum	20			
	King	Optimum	20			
	Pres. Isle	Optimum	20	67.84	-0.0448	0.74
	Coal Creek	Optimum	20	99.87	-0.0522	0.63
	Columbia	Optimum	20	116.78	-0.0405	0.36
	Stanton	Optimum	20	59.90	0.1863	0.99
	Boardman Silt	Optimum	20	80.48	-0.1092	0.94

Table J.3. Resilient modulus model coefficients for specimens of Theresa soil-fly ash mixtures

Soil	Fly Ash	Moisture State	Fly Ash Percentage	K1	K2	R^2
Theresa	Dewey	Very Wet	10	46.62	-0.1911	0.94
	King	Very Wet	10	32.13	-0.2229	0.89
	Pres. Isle	Very Wet	10	5.47	0.4463	0.58
	Coal Creek	Very Wet	10	0.46	0.8304	0.79
	Columbia	Very Wet	10	76.93	-0.4603	0.53
	Stanton	Very Wet	10	25.53	-0.1339	0.32
	Boardman Silt	Very Wet	10			
	Dewey	Very Wet	20	34.81	0.0928	0.90
	King	Very Wet	20	66.81	0.0248	0.12
	Pres. Isle	Very Wet	20	40.58	-0.1165	0.96
	Coal Creek	Very Wet	20	4.46	0.2160	0.81
	Columbia	Very Wet	20	525.93	-0.7365	0.88
	Stanton	Very Wet	20	62.80	0.0060	0.02
	Boardman Silt	Very Wet	20	4.33	0.2512	0.91
	Dewey	Very Wet	30	105.12	0.0056	0.01
	King	Very Wet	30	128.20	-0.0564	0.39
	Pres. Isle	Very Wet	30	152.10	-0.2608	0.98
	Coal Creek	Very Wet	30	50.83	-0.2707	0.42
	Columbia	Very Wet	30	85.56	-0.1006	0.76
	Stanton	Very Wet	30	62.80	0.0062	0.0152
	Boardman Silt	Very Wet	30	5.85	0.2000	0.88
	Dewey	Optimum	10	78.90	-0.0526	0.71
	King	Optimum	10	561.53	-0.4269	0.81
	Pres. Isle	Optimum	10	80.88	-0.0919	0.98
	Coal Creek	Optimum	10	96.79	-0.0254	0.19
	Columbia	Optimum	10	54.26	0.0895	0.74
	Stanton	Optimum	10	96.80	-0.0223	0.90
	Boardman Silt	Optimum	10	115.12	-0.1822	0.99
	Dewey	Optimum	20	98.79	0.0912	0.97
	King	Optimum	20	72.67	0.0940	0.80
	Pres. Isle	Optimum	20	51.40	-0.0217	0.16
	Coal Creek	Optimum	20	68.32	0.0986	0.66
	Columbia	Optimum	20	49.02	0.1876	0.99
	Stanton	Optimum	20	20.43	0.4120	0.99
	Boardman Silt	Optimum	20	202.51	-0.3061	0.97