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The use of lime sludge for soil stabilization

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The use of lime sludge for soil stabilization

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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DEDICATION

I dedicate this thesis to my parents and my sister who have always supported me and showed me the best path to follow. I found them with me whenever I needed. It is their unconditional love that motivates me to set higher targets.

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NOMENCLATURE

LOE   Loess

LS   Lime sludge

CF   Class C fly ash

FF   Class F fly ash

PC   Portland cement

PI   Plasticity index

UCS   Unconfined compressive strength

F-T   Freeze-thaw

W-D   Wet-dry

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ABSTRACT

Weak subgrade layers can decrease the designed service life of pavements significantly, and building of thicker top layers may be required. Weak local soil can be turned into an effective material by chemical soil stabilization. Class C fly ash (CF), class F fly ash (FF) and Portland cement (PC) have been used for soil stabilization. Fly ash has been used by the concrete industry, and its popularity in industry sometimes causes temporary shortages. PC is known to be the most expensive stabilizer among other stabilizers. In this research, lime sludge (LS) was investigated as an alternative stabilizer due to the benefits of using waste materials and the uncertain future of fly ash and PC. For this purpose, LS was used alone and with other stabilizers for soil stabilization, and unconfined compressive strength (UCS), freeze-thaw (F-T), wet-dry (W-D) tests and swelling test under F-T were conducted.

The UCS test results of the specimens cured up to 90 days showed that LS can be used alone to increase the strength of soil. The UCS test results of 7-day cured specimens pointed out LS can be mixed with CF and FF for further increase in strength. Using LS and PC together decreased the effect of PC because of a low pH environment. F-T test results of 7-day cured specimens showed that relatively higher strength losses were observed in the open system compared to the closed one. In addition, test results showed that there were no considerable benefits of using LS either alone or with other stabilizers on F-T durability. According to the W-D test results, the use of LS decreased the performance of PC and caused failures. Swelling test results under F-T showed that although the use of LS decreased the performance of other stabilizers, an optimum amount of LS (around 12%) could be used alone to reduce the swelling.

CHAPTER 1. INTRODUCTION

According to the Highway Statistics 2014 report published by the U.S. Department of Transportation Federal Highway Administration (FHWA), total public road length is 6,722,347 km (4,177,073 miles) in the U.S. Each year, billions of dollars are spent just to keep pavements in suitable conditions; hence, establishing a long-term development and maintenance plan for pavement systems is a national priority. In the U.S., large volumes of earthen materials are used in pavement constructions each year. These materials can be replaced with suitable waste materials such as highway paving materials, secondary materials and construction debris that are normally thrown in landfills. Reusing waste materials has several benefits such as reducing solid waste disposal costs and landfill requirements, minimizing the consumption of natural resources, obtaining added value from waste materials, and ultimately providing sustainable construction and economic growth.

Designing successful pavement systems is not only based on the quality of the top layers (asphalt or concrete) but also the foundation layers underneath such as base, subbase or subgrade. In fact, the stability of the foundation layers is the main parameter that affects the long-term pavement performance (Little and Nair 2009). In particular, the quality of the subgrade layers plays an essential role in the long-term pavement performance. Weak subgrades can decrease the designed service life of pavements significantly (Milburn and Parsons 2004), and building of thicker base, subbase or surface layers may be required in the presence of structurally poor subgrade layers (Panchal and Avineshkumar 2015). Locally available soils are generally used as the subgrade layers during pavement construction in order to decrease the construction cost. However, this would bring the

quality issue regarding the subgrade layers since the locally available soils may not possess the preferred quality. Granular soils consisting of high amounts of gravel or sand are more suitable for subgrade layers than fine-grained soils containing high amounts of silt or clay (Beeghly 2003). In addition, fine-grained soils tend to be relatively more sensitive to frost action. Permeability and capillarity are the two main mechanisms that affect the resistance of soil against frost action. Permeability of soil controls the movement of fluid flow while capillarity controls the movement of fluids against gravity towards the vadose zone (Coduto 1999). Because of their moderate permeability and capillarity, silty soils are known as frost-susceptible (Rosa 2006). Thus, geotechnical engineering properties of the subgrade layers built with silty soils must be improved to increase the service life of pavements.

There is a variety of improvement techniques that can be used when the engineering properties of local soil are not adequate to carry the loads coming from the upper layers and vehicles (Chauhan et al. 2008). One of the methods is a conventional method called excavation and replacement. It is known to be a very straightforward method; however, replacing the locally available soil with a high-quality material incurs extra construction costs. Thus, it is not always recommended (Abu-Farsakh et al. 2015; Senol et al. 2006). The other method is using stabilizers to improve the engineering properties of local soils. Unsuitable local soil can be turned into a better material by improving its engineering properties via physical or chemical stabilization techniques (Little and Nair 2009). Lime, fly ash and Portland cement are the most widely-used materials in soil stabilization; however, they are not suitable for all soil types. Material availability, local soil type, experience and the desired degree of improvement are the main

selection criteria of stabilizers (Selvi 2015). The Soil Stabilization Index System (SSIS) developed by the U.S. Air Force is one of the methods to select the most suitable stabilizer for specific soil types (Little and Nair 2009) (Figure A in Appendix A).

Hydration, cation exchange and pozzolanic reactions are the main reactions occurring in the stabilized soils in the presence of water. During hydration, CaO from the stabilizer reacts with water and forms $Ca(OH)_2$. Stabilized soil gets drier due to the use of water during hydration, and immediate strength gain occurs. During cation exchange, calcium (Ca^{2+}) present in $Ca(OH)_2$ replaces monovalent cations such as sodium (Na^+) and hydrogen (H^+) which are present in soil. This replacement causes a decrease in double diffuse layer (DDL) thickness which leads to an increase of attraction between soil particles (Zhu and Liu 2008a). This increase in attraction leads to an improvement in the linking between soil particles; thus, strength increases. As time progresses, pozzolanic reactions take place between Ca^{2+} existing in $Ca(OH)_2$ and silica/alumina released from soil (silica/alumina can also be released from the stabilizer). Calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels which have cementitious properties are formed during pozzolanic reactions (Prusinski and Bhattacharja 1999; Mallela et al. 2004). In the use of Portland cement, these gels are also formed during hydration. Further increase in strength is observed because of long-term pozzolanic reactions. These three reactions improve the linking between soil particles and fill up the voids existing in the soil matrix (Zhu and Liu 2008). Hydration and cation exchange reactions are relatively fast and occur immediately in the presence of water. On the other hand, time is required for pozzolanic reactions (Little and Nair 2009).

Fly ash is widely used in various types of geotechnical applications such as improving engineering properties of soil and constructing embankments. It is an end product of coal burning for power generation (Chauhan et al. 2008). Coal source and power generation methods affect the type of fly ash (Little and Nair 2009). There are two main types of fly ashes used for soil stabilization named class C fly ash and class F fly ash according to ASTM C618. Classification of these two fly ashes is based on the amount of CaO they contain (Sahu et al. 2017). Generally speaking, class C fly ash is produced by using western coal sources containing relatively higher amount of Ca^{2+}, and class F fly ash is produced by using eastern coal sources containing relatively less Ca^{2+} (Ferguson 1993). Because of containing relatively less CaO, class F fly ash is typically used with other stabilizers containing relatively higher amounts of CaO such as lime and Portland cement. Although class C fly ash is known to be a relatively less effective stabilizer compared to lime and Portland cement, it can be used alone for soil stabilization. Fly ash has been widely used by cement companies (Robl and McCormick 1997) as a high-performance content or clinker to produce high quality Portland cement (Su 2012). Its popularity in the industry sometimes affects its availability, and causes temporary shortages of the material. Thus, alternative materials should be found for future applications.

Portland cement is known to be a very effective stabilizer due to its very high CaO content. Portland cement contains calcium-silicates and calcium-aluminates, and hydration of these materials generates cementitious materials named calcium-silicate-hydrate (C-S-H) and calcium-alumina-hydrate (C-A-H) (Abu-Farsakh et al. 2015). According to ASTM C150, Portland cement is classified into five types in terms of their properties and areas of use. Type I Portland cement is used for general purpose. Type II and type V Portland

cements are known to be sulfate resistant, and they are used in soils containing considerable amount of sulfate. Type III Portland cement is used if high early strength is intended. Lastly, type IV Portland cement is used when low heat is desired during hydration. Although cement works well with coarse-grained materials such as gravels and sands, it can also be used with fine-grained soils such as silts and clays. In fact, the use of cement to stabilize silty soils gives the most drastic improvements relative to other soil types (Little and Nair 2009). The Portland Cement Association (1992) provides a guidance showing the amount of Portland cement that can be used for different soil types (Table A in Appendix A). Portland cement is known to be the most expensive stabilizer among other conventional calcium-based stabilizers, hence alternative materials should be investigated for future applications.

Lime sludge which is mainly $CaCO_3$ is a waste product of water treatment process in which lime is used to precipitate Ca^{2+} and Mg^{2+} by increasing the pH of raw water. Thousands of tons of lime sludge are generated each year (Yu et al. 2010). Generated lime sludge has been thrown in lagoons and stored there so far. Its disposal and removal add extra costs (7 to 10% of the total treatment cost) to water treatment plants (Baker et al. 2004), i.e., in the water treatment plant located in Ames, IA, around 28,000 wet tons of lime sludge are produced and processed annually, and approximately \$300,000 are spent just for its removal. Since it is well-known that utilization of waste products has a great impact on the development of society, alternative uses of lime sludge have been investigated by researchers (Sahu et al. 2017). Lime sludge was used to treat gases containing SO_x in coal-burning power plants, to reduce the dust problem of unpaved roads,

to produce cement, to construct embankments, and to adjust the pH of farm soils (Baker et al. 2004; Lang 2012; Yu et al. 2010).

Although there has been research conducted about the use of lime sludge in geotechnical applications, there is a limited information available about its use as a stabilizer for soil stabilization. In this research, lime sludge was used as an alternative stabilizer to observe whether it can be used for soil stabilization. The main purpose of the project is increasing the use of lime sludge for soil stabilization to obtain the benefits of reusing waste materials and to fulfill the need for exploring alternative stabilizers because of the uncertain futures of fly ash and PC. For this purpose, lime sludge was mixed with loess soil to observe its suitability for soil stabilization. In addition, it was mixed with class C fly ash, class F fly ash and type I/II Portland cement to observe its effects on the performance of these stabilizers when they are used together to stabilize loess. Atterberg limits, unconfined compressive strength (UCS), freeze-thaw (F-T) and wet-dry (W-D) tests, and swelling test under F-T were conducted. In addition to these tests, pH analysis, X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses were also conducted.

CHAPTER 2. MATERIALS

Loess which is locally available in the State of Iowa was collected from the Loess Hills in Western Iowa (Figure 1). Any root residuals, leaves and foreign materials were removed from the collected loess. Its air-dry moisture content was determined to be in the range of 1.5 to 2%. After air-drying, it was crushed by rubber mallet prior to sieving. Any particles retained on the 3/4 in (19 mm) sieve were disposed. Sieve analysis, hydrometer test (ASTM D422) and Atterberg limits test (BS 1377-2 and ASTM D4318) were conducted. It was determined that the soil contains 0% gravel, 1% sand, 87% silt, and 12% clay-sized particles (Figure 2). Its liquid and plastic limits were determined as 37.3 and 26.9, respectively. In addition, its specific gravity was determined as 2.70. A summary of its index properties is provided in Table 1a. It was classified as inorganic silt (ML) and A-4 soil according to the Unified Soil Classification System (USCS) (ASTM D2487) and American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System, respectively. Its XRD pattern and SEM image are provided in Figures B1 and B2 in Appendix B, respectively. It was determined that loess contains quartz (SiO_2), calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), and soil particles have subangular to angular shapes.

Lime sludge (Figure 4a) was collected from a lagoon operated by the Ames Water Treatment Plant (Figure 3) located in Iowa in relatively wet pellet form with the moisture content range of 15 to 17%. Materials were spread on large trays and solid rock particles were removed by hand. Materials were kept in 5-gallon buckets and buckets were sealed well to keep the initial range of its moisture content. Sieve analysis, hydrometer test (ASTM D422) and Atterberg limits test (BS 1377-2 and ASTM D4318) were conducted.

It was determined that the material contains 0% gravel, 8% sand, 92% silt and 0% clay-sized particles (Figure 2). Atterberg limits test results showed that it had a liquid limit of 43 with a plastic limit of 37. In addition, its specific gravity was determined as 2.30. A summary of its index properties is provided in Table 1a. It was classified as inorganic silt (ML) and A-5 according to the USCS and AASHTO, respectively. Its XRD pattern and chemical components are provided in Figure 5a and Table 1b, respectively. It was determined that lime sludge contains mainly $CaCO_3$. Its SEM image is provided in Figure 6a, and it was determined that it has a crystalline structure.

Class C (Figure 4b) and class F (Figure 4c) fly ashes were obtained from Headwaters Resources and Ash Grove Cement Company, respectively. Initial water contents of class C and class F fly ashes were determined to be 0.3% and 0.1%, respectively. Sieve analysis and hydrometer test (ASTM D422) were conducted. It was determined that class C fly ash contains 0% gravel, 7.4% sand, 89.2% silt and 3.4% clay-sized particles while class F fly ash contains 0% gravel, 12.2% sand, 85.3% silt and 2.5% clay-sized particles (Figure 2). Specific gravity values of class C and class F fly ashes were determined to be 2.7 and 2.47, respectively. Materials were kept in 5-gallon buckets and buckets were sealed to keep their initial moisture contents. Their XRD patterns and chemical components are shown in Figure 5b-c and Table 1b, respectively. It was determined that class C fly ash has relatively higher CaO content (24.31%) than class F fly ash (11.80%). Their SEM images are provided in Figure 6b-c. It was determined that both fly ashes have glassy (amorphous) structure.

Type I/II Portland cement (Figure 4d) was taken from Ash Grove Cement Company. Among previously mentioned Portland cement types, type I/II Portland cement

was selected because of its general usefulness. Its initial water content was determined to be 0.7%, and it was stored under the same conditions as other stabilizers. Its XRD pattern and chemical components are shown in Figure 5d and Table 1b, respectively. It was reported that type I/II Portland cement has the highest CaO content (60-67%). Its SEM image is provided in Figure 6d. It was determined that type I/II Portland cement has a crystalline structure.

CHAPTER 3. METHODS

Specimen Preparation

Specimens are summarized in Table 2. Lime sludge (LS), class C fly ash (CF), class F fly ash (FF), and Portland cement (PC) were mixed with loess at different percentages by dry weight of loess separately. In addition, LS + CF, LS + FF, and LS + PC specimens were prepared to observe whether lime sludge can be used with other stabilizers. 50 mm x 50 mm (2 in x 2 in) cylindrical specimens were prepared at their optimum moisture contents for UCS, F-T and W-D tests, and swelling test under F-T in accordance with a method invented by O'Flaherty et al. (1963). All specimens were compacted with standard Proctor compaction energy. Specimens were wrapped with a plastic film and aluminum foil to keep their moisture contents constant. Specimens were cured for 1 day, 7 days, 28 days and 90 days for UCS tests, and only for 7 days for F-T and W-D tests.

Atterberg Limits Test

Atterberg Limits tests were conducted to determine liquid limits, plastic limits and plasticity indices of the specimens provided in Table 2. Fall cone penetrometer (Figure C2 in Appendix C) method (BS 1377-2) was used to determine liquid limits by multipoint method. Humboldt H-4262 plastic limit device (Figure C2 in Appendix C) was used for the determination of plastic limits and the procedure described in ASTM D4318 was followed. Air-dried loess was sieved through No. 40 sieve and 500 g of the material passing No. 40 sieve was collected. After preparing the specimens, approximately 100 g of water was added to them. Specimens were stored in zip lock bags and they were allowed to mellow for 1 day at room temperature prior to tests.

Standard Proctor Test

Standard Proctor tests were conducted in accordance with ASTM D698 Method A to find relationships between the water contents and dry densities of the specimens provided in Table 2. Automatic Proctor device (Figure C3 in Appendix C) was used for the tests. Specimens were reused and they were not allowed to mellow. Materials were mixed in a dry state, and enough water was added to the dry mixtures to reach the target water content values prior to each test. 5 tests were conducted for each specimen to obtain their compaction curves. Maximum dry unit weight (γ_{dmax}) and optimum moisture content (w_{opt}) values were obtained from the compaction curves.

Unconfined Compressive Strength (UCS) Test

UCS tests were conducted in accordance with ASTM D5102 and D1633. GeoTAC Sigma-1 Automated Load Test System (Figure C4 in Appendix C) was used for the tests. Strain rate and maximum axial strain were selected to be 2%/min and 15%, respectively. Instead of continuing the tests to reach 15% maximum axial strain, tests were ended after the specimens had failed.

Tests were conducted on 1-day, 7-day, 28-day and 90-day cured specimens. In addition, UCS tests were conducted on the specimens subjected to 1, 4, 8, and 12 F-T (both closed and open systems) and W-D cycles. UCS tests were conducted at the end of thawing periods of the specimens subjected to F-T cycles, and after both wetting and drying periods of the specimens subjected to W-D cycles. After each test, moisture contents of the tested specimens were determined to observe their changes.

Freeze-Thaw (F-T) Test

ASTM D560 was adapted for the F-T tests. In addition, closed and open systems were conducted in accordance with the procedure described by Aldaood et al. (2016). For both systems, only 7-day cured specimens were used. In the closed system, plastic film and aluminum foil were not removed from the specimens after the curing to avoid the changes in moisture contents, and sealed specimens were placed in a freezer (Figure D1 in Appendix D). To better simulate the field conditions, open system was also conducted. After the curing, specimens were unwrapped and placed in the freezer with a saturated felt pad having a thickness of 6 mm underneath (Figure D2 in Appendix D). The saturated felt pad was used to simulate the capillary action (Figure D3 in Appendix D). For both systems, specimens were kept in the freezer set to -23±2℃ for 24 hours for the freezing. Then, specimens were thawed at room temperature for 24 hours. In the closed system, specimens were kept in sealed conditions throughout the test. In the open system, water was supplied regularly to keep the felt pads saturated. For both systems, 1, 4, 8 and 12 F-T cycles were applied to the specimens. After reaching the desired number of cycles, specimens were subjected to UCS test. Prior to UCS test, specimens were weighed and after the test, moisture contents of the specimens were determined to observe the changes in moisture contents.

Swelling Test under F-T Cycles

Swelling tests under F-T cycles were conducted in accordance with ASTM D560. The open F-T system was used for 7-day cured specimens. Prior to tests, three locations for both height and diameter measurements were marked on the specimens in order to increase the consistency of the measurements. Only 2 F-T cycles were applied to the

specimens since significant deterioration was observed in the specimens after the 2nd cycle. Measurements were taken after each freezing and thawing period. Volumes of the specimens were calculated to observe the effects of stabilizers on swelling behavior of loess under F-T cycles.

Wet-Dry (W-D) Test

ASTM D559 was adapted for the W-D tests. In analogy to the F-T tests, only 7-day cured specimens were used. Prior to tests, metal pans were filled with potable water and left for at least 3 hours to reach room temperature. After 3 hours, cured specimens were submerged for 5 hours (Figure E1 in Appendix E). After the wetting, specimens were dried at $71\pm2°C$ in an oven for 42 hours (Figure E2 in Appendix E). UCS tests were conducted on the specimens subjected to 1, 4, 8 and 12 W-D cycles in both wet and dry states. Moisture contents of the specimens were determined after each UCS test.

pH Analysis

pH tests were conducted in accordance with ASTM D4972 and Geotechnical Test Method (GTM-24) Procedure B written by New York State Department of Transportation. An Accumet XL20 pH meter was used (Figure F1 in Appendix F). Specimens were dried at room temperature for 2 days prior to tests. After the drying, specimens were crushed and sieved through No. 10 sieve. 10 g of sieved materials were placed in small plastic tubes and 20 g of distilled water was added. Tubes were shaken and let stand for 1 hour (Figure F2 in Appendix F). Prior to tests, the pH meter was calibrated by the three-point calibration method. Buffer solutions having pH 4, 7 and 10 were used for the calibration. Plastic tubes were shaken shortly before the tests and the measurements were taken.

X-Ray Diffraction (XRD) Analysis

XRD analyses were conducted on 7-day cured specimens. Specimens were dried at room temperature first, then sieved through No. 325 sieve prior to tests. Sieved materials were given to the Materials Analysis and Research Laboratory (MARL) of the Iowa State University Office of Biotechnology. A Siemens D 500 diffractometer (Figure G1 in Appendix G) was used for the tests in which a copper (Cu) tube was operated at 45 kV and 30 mA.

Scanning Electron Microscopy (SEM) Analysis

SEM images were taken with 7-day cured specimens. Specimens were crushed thoroughly prior to tests. Test specimens were placed on a specimen holder with carbon tape. Prior to SEM analysis, an Edwards Scancoat Six benchtop sputter coater (Figure G2 in Appendix G) was used to coat the specimens with gold to reduce any charge build-up to a minimum. After the coating, a JEOL JSM-6060 SEM (Figure G3 in Appendix G) was used to take the images.

CHAPTER 4. RESULTS AND ANALYSIS

Results of Atterberg Limits Tests

A summary of Atterberg limits test results is provided in Table 3. Loess had a plasticity index (PI) of 10.4 and it was classified as low plasticity soil according to Burmister (1949). In addition to the classification provided by Burmister (1949), plasticity of soil could be identified by calculating a term called activity (a ratio between PI and % of clay size fraction) which is related to swelling characteristics of soil (Skempton 1953). Activity of loess was calculated as 0.87. Skempton (1953) provides ranges of activity for different clay minerals (1-7 for smectites, 0.5-1 for illite, and around 0.5 for kaolinite). It was concluded that clay minerals in loess were not smectites. Skempton (1953) also provides three more ranges to identify the clays as active (A>1.25), inactive (A<0.75) or normal clays (0.75<A<1.25). It was concluded that the clay content of loess was normal clay. Since it was determined that clay content was normal clay without smectites, no significant volume change is expected to occur when loess is wet.

A correlation between the expansibility and the PI of soil was provided by Skempton (1953). A decrease in PI decreases the activity, and lower activity means smaller changes in volume when soil is wet. Effects of the stabilizer type and content on the PI of loess are provided in Figure 7. While the use of low amount of LS (≤20%) led to negligible changes in the PI of loess, the use of 30-40% of LS slightly decreased it from 10.4 to 9.7 and 9.4, respectively. Relatively more considerable changes in the PI of loess were observed with adding CF, FF or PC to loess. In addition, further decreases in the PI of loess were observed with increases in CF, FF or PC contents. The most drastic decreases in the PI of loess (1.2 to 6.5%) were observed with the use of PC due to its relatively higher CaO

content (60 to 67%); thus, it was concluded that PC is the most effective stabilizer to decrease the expansibility of soil. Decreases in the PI of loess were less in the specimens prepared with FF (0.3 to 1.3%), followed by the specimens prepared with CF (0.8 to 2.2%). It was concluded that FF was not as effective as CF to decrease the PI of loess due to its relatively lower CaO content (11.80%).

The uses of LS with CF or FF to stabilize loess did not lead to further decreases in PI compared to the specimens prepared with only CF or FF (Figure 8a-b). While mixing loess with LS and 2% PC did not cause perceptible changes in PI compared to the single use of 2% PC, addition of LS decreased the effectiveness of 4% PC to reduce the PI (Figure 8c). It was speculated that PC reacted with SO_4 leaching from LS which mitigated the hydration reactions in the soil matrix and yielded ettringite formation instead (Ouhadi and Yong 2008; Wang et al. 2004; Rollings et al. 1999; Rajasekaran 2005).

Results of Standard Proctor Tests

Standard Proctor curves of the specimens are provided in Appendix H, and w_{opt} and γ_{dmax} values are provided in Table 4. w_{opt} and γ_{dmax} of loess were 16.2% and 16.67 kN/m^3, respectively. The use of stabilizers increases the pore water electrolyte concentration and this causes a thinner diffuse double layer (DDL). Decrease in the thickness of DDL causes flocculation of soil particles. This flocculation withstands the compaction effort and leads to lower γ_{dmax} and higher w_{opt} (Hussain and Dash 2010).

Adding 4-8% LS to loess did not cause significant changes in γ_{dmax} values, but w_{opt} values increased. It was speculated that the use of 4-8% LS were not enough to initiate the flocculation of soil particles. The concept provided by Hussain and Dash (2010) was observed in the test results of the specimens prepared with higher LS contents ($\geq$12%). In

addition, test results of the specimens prepared with CF or FF demonstrated the same concept; γ_{dmax} values decreased and w_{opt} values increased with adding the stabilizers to loess. The specimens prepared with CF showed relatively higher increases in w_{opt} (2 to 4% more increase) and higher decreases in γ_{dmax} (0.6 to 1% more decrease) compared to the specimens prepared with FF. This result was attributed to hydration reactions occurring quickly between the Ca^{2+} released from stabilizers and silica/alumina released from loess and stabilizers in the presence of water. CF has higher CaO content (24.31%) than FF (11.80%); thus, the specimens prepared with CF showed relatively higher changes in γ_{dmax} and w_{opt} than the specimens prepared with FF.

Similar results were also observed in the specimens prepared with 2, 4 and 8% of PC. The changes in w_{opt} and γ_{dmax} in the specimens prepared with PC were relatively higher (0.6 to 4% more increase in w_{opt} and 1 to 3.6% more decrease in γ_{dmax}) than the specimens prepared with CF because PC contains the highest amount of CaO (60 to 67%). An unexpected change in the compaction curve was observed in the specimen prepared with 12% PC. Adding 12% PC to loess led to increases in w_{opt} and γ_{dmax} compared to the specimens prepared with less amount of PC (≤8%) It is explained by ACI Committee (1997) that the use of high amount of PC can cause an increase in γ_{dmax} due to its relatively higher specific gravity (around 3.15) than soil (2.60-2.80).

Results of Unconfined Compressive Strength (UCS) Tests

Duplicate UCS tests were conducted on the specimens, and the average of these duplicates were calculated and recorded. Effects of stabilizer type, stabilizer content, curing period and the use of LS with other stabilizers on the UCS test results were

investigated. Summaries of the UCS test results of all specimens are provided in Table 5 (strengths in kPa) and Table 6 (% change in strength).

Effect of stabilizer type on UCS test results

Comparison of the UCS test results of the specimens prepared with 4, 8 and 12% of each stabilizer is provided in Figure 9. The specimens prepared with LS showed the lowest increases in the strength of loess due to its lack of CaO content. The highest increase in strength (48%) within the specimens prepared with LS was observed in 90-day cured specimen prepared with 12% LS. Even the highest increase in strength within the specimens prepared with LS (48%) was almost 1/3 of the increase in strength in 90-day cured specimen prepared with 12% FF (139%).

The highest increases in strength were observed in the specimens prepared with PC. The lowest and the highest increases in strength were observed with 1-day cured specimen prepared with 4% PC (540%) and with 90-day cured specimen prepared with 12% PC (6053%), respectively. Even the lowest increase in strength within the specimens prepared with PC (540%) was relatively higher than increases in the specimens prepared with other stabilizers due to the high CaO content of PC (60 to 67%). An XRD pattern and SEM image of the 7-day cured specimen prepared with 4% PC are provided in Figures 10b and 11b, respectively. No ettringite formation was detected. It was concluded from the SEM image that PC bonds well with loess.

The use of CF provided the second highest increases in strength. This result was attributed to higher CaO content of CF (24.31%) compared to FF (11.80%) and LS (no CaO content was observed. It was reported by Lang (2012) that LS contains 3.5% CaO). XRD pattern and SEM image of 7-day cured specimen prepared with 12% CF are provided

in Figures 10a and 11a, respectively. No ettringite formation was detected, and it was concluded from the SEM image that the bonding between loess and CF was not as good as the bonding between loess and PC. It was concluded that CaO content of stabilizer plays an important role in strength gain.

Effects of stabilizer content on UCS test results

Comparison of the UCS test results of the specimens prepared with different stabilizer contents are provided in Figure 12. Overall, the use of higher amounts of stabilizers caused higher increases in strength as expected. This result was attributed to a statement that the amount of CaO in the mixture increases as the stabilizer content increases. In addition, the amount of alumina and silica released from stabilizer for long-term pozzolanic reactions (if the pH of the mixture is suitable) increases as the stabilizer content increases. It is stated by Nawaz et al. (2016) that higher short-term gains in strength are observed with the use of fly ash containing higher CaO content. With the use of higher amount of stabilizer, more CaO could get in contact with silica and alumina released from soil in the short-term. In the long-term, more CaO can react with more silica and alumina released from stabilizer. These increases in the amount of chemical reactions provide better improvements in the engineering properties of soil.

Effect of curing period on UCS test results

UCS test results of the specimens at different curing periods are provided in Figure 12. Consistent increases in strengths were observed in all specimens, and it was concluded that chemical reactions continued throughout 90 days. It was observed that there was a direct proportion between the strength gain and curing period. The lowest strength values were observed in 1-day cured specimens whereas the highest values were observed in 90-

day cured ones. Increases in the strength of loess after 1 day of curing were attributed to hydration reactions occurring between the stabilizer and loess immediately in the presence of water. Moisture content and temperature of the mixture affect the continuity of hydration and pozzolanic reactions. Moisture content of the mixture should be sufficient for the hydration reactions, and temperature should be at optimum, and should not vary a lot throughout the curing for the continuity of pozzolanic reactions (Makusa 2012). In addition, release of silica and alumina from the soil and stabilizer increases in the presence of high pH environment (Keller 1999). Thus, continuity of the pozzolanic reactions was attributed to an existence of a suitable environment such as adequate water content, pH and temperature in the mixtures throughout 90 days.

Effect of mixing LS with other stabilizers on UCS test results

UCS test results of the specimens prepared with LS + CF, LS + FF and LS + PC are provided in Figure 13. 30 and 40% of LS by dry weight of loess were used in the mixtures. XRD pattern and SEM image of the specimen prepared with 40% LS are provided in Figures 14a and 15a, respectively. Lime sludge crystals were observed in the SEM image and it was concluded that the bonding between loess and LS were not as good as the bonding between loess-CF and loess-FF. Strength increases in the specimens prepared with LS + CF (125 to 168%) were relatively higher than the specimens prepared with CF (63 to 76%) (Figure 13a). XRD pattern and SEM image of the specimen prepared with 40% LS + 12% CF are provided in Figures 14b and 15b, respectively. No ettringite formation was detected. In addition, it was observed from the SEM image that CF bound well with loess in the presence of LS. Hence, it was concluded that the use of CF is still effective in the presence of LS to stabilize loess, and these two materials can be mixed if

further increase in strength is intended. Like the specimens prepared with LS + CF, further increases in strength were observed in the specimens prepared with LS + FF (73 to 100%) compared to the specimens prepared with FF (41 to 47%) (Figure 13b). Although the specimens prepared with LS + FF did not give high increases in strength compared to the specimens prepared with LS + CF, it was concluded that FF is still effective in the presence of LS to stabilize loess. It was also concluded that the use of LS with FF may not be suitable if higher increases in strength are desired for stabilization.

Considerable decreases in the strength gain rate were observed in the specimens prepared with LS + PC (118 to 400%) compared to specimens prepared with PC (530 to 1030%) (Figure 13c). XRD pattern and SEM image of the specimen prepared with 40% LS + 4% PC are provided in Figures 14c and 15c. No ettringite formation was detected. Hence, previously mentioned speculation regarding the ettringite formation was negated. It was concluded by comparing the SEM images of the specimen prepared with 4% PC (Figure 11b) and specimen prepared with 40% LS + 4% PC (Figure 15c) that the bonding between loess and PC was not good in the presence of LS. It was concluded that the use of LS with PC decreased the effectiveness of PC. It was previously mentioned that more silica-alumina are released from soil and stabilizer in the presence of high pH environment (Keller 1999). It was speculated that the use of LS led to a low pH environment for PC which reduced the release of silica-alumina during pozzolanic reactions and caused decrease in strength gain rate.

Results of Freeze-Thaw Tests

Summaries of the UCS test results of the specimens subjected to F-T cycles (closed and open systems) are provided in Tables 7-10. In addition, Figures 16-19 are provided to observe the effect of F-T cycles on UCS test results and moisture contents of the specimens.

Effect of closed F-T cycles on the UCS test results

In all 7-day cured specimens prepared with LS, CF, FF or PC, the most drastic decreases in strengths were observed after the 1st cycle (7 to 38%) (Figure 16). Again, in all specimens, increases in strengths were observed between the 1st-4th cycles (2 to 43%), and 8th-12th cycles (1 to 52%) whereas no significant changes were observed between the 4th-8th cycles (2% gain or loss). It was concluded from these results that ongoing curing processes sometimes dominated the damaging effect of F-T cycles and caused increases in strengths accordingly. The highest increases in strengths were observed in the specimens prepared with PC between previously mentioned cycles (24 to 43% between 1st-4th cycles, and 15 to 52% between 8th-12th cycles) (Figure 16f). Second highest increases in strengths were observed in the specimens prepared with CF (27 to 38% between 1st-4th cycles, and 8 to 12% between 8th-12th cycles) (Figure 16d). It was concluded that CaO content of the stabilizer and increase in strength were directly proportional. After 12 cycles, final strengths of all specimens were higher than their initial strengths except the specimens prepared with higher amount of LS ($\geq$20%) (around 10% decrease) (Figure 16c). It was concluded that there was an optimum LS content (around 12%) that could be mixed with loess to increase its durability.

Effect of mixing LS with other stabilizers on the UCS test results after closed F-T cycles

Final strengths of the specimens prepared with LS + CF and LS + FF after 12 cycles were lower than their initial ones (1 to 6% for LS + CF, 5 to 12% for LS + FF mixtures) (Figure 18a-b). However, it was observed that final strengths of these specimens were still higher (6 to 17%) than the final strengths of the specimens prepared with CF or FF (Table 7). It was concluded that the use of LS with CF or FF is still effective under F-T effect to increase the strength of loess. However, no significant increases in strengths due to the ongoing curing were observed in the specimens prepared with LS + CF and LS + FF (Figure 18a-b) compared to the increases observed between 1st–4th and 8th–12th cycles in the specimens prepared with CF or FF (Figure 16d-e). It was concluded that the use of LS with CF or FF increased initial 7-day cured strengths, but then reduced the effectiveness of the stabilizers under F-T effect.

Lower final strengths were observed in the specimens prepared with LS + 2% PC (17 to 22% less than initial) whereas higher final strengths were observed in specimens prepared with LS + 4% PC (1 to 5% higher than initial) (Figure 18c). It was observed that the use of higher PC content with LS increased the durability of loess. It was previously mentioned that the effectiveness of PC reduced in the presence of LS in the soil matrix. However, the use of higher amount of PC increased the hydration and pozzolanic reactions which caused increases in strengths.

Effect of open F-T cycles on the UCS test results

Like observed in the closed system, the most significant decreases in strengths were observed after the 1st cycle (21 to 93%) in 7-day cured specimens prepared with LS, CF, FF or PC (Figure 16). Systematical decreases in strengths after each predetermined cycle

were observed except between 1st-4th cycles of the specimens prepared with 4, 8 and 12% PC (Figure 16f). Increases in strengths (17 to 29%) were observed in these mixtures. It was concluded that ongoing curing processes dominated the damaging effect of F-T cycles between 1st-4th cycles in those specimens.

All final strengths of the specimens after 12 cycle were below 10 kPa (around 95% decrease in the strengths) except the specimens prepared with PC. It was concluded that the use of LS, CF or FF to stabilize loess did not improve its durability in the open system (Figure 16b-e). It was observed that the use of higher amount of PC provided better durability (Figure 16f). Hence, it was concluded that there was a direct proportion between the amount of PC and the durability of loess.

Effect of mixing LS with other stabilizers on the UCS test results after open F-T cycles

When LS was mixed with CF or FF to stabilize loess, more drastic decreases in strengths were observed after the 1st cycle (around 87%) (Figure 18a-b) compared to the decreases in the specimens prepared with CF or FF (around 48%) (Figure 16d-e). It was concluded that no matter how high initial 7-day cured strengths are, existence of LS in the soil matrix decreased the durability. It was concluded that existence of LS in the soil matrix decreased stabilities of the specimens against the change in moisture contents during the open F-T test, and caused absorbing higher amount of water, i.e., moisture contents of the specimens prepared with LS + CF were 39 to 41% (Figure 19a) whereas specimens prepared with CF had moisture contents of around 35% (Figure 17d). Same trend (decrease in durability) was also observed in the specimens prepared with LS + PC (Figure 18c). In addition to the previously mentioned speculation regarding the low pH environment caused by the presence of LS, it was speculated that absorption of higher amount of water in the

presence of LS in the soil matrix caused decrease in durability of the specimens prepared with LS + PC, i.e., moisture contents of the specimens prepared with 40% LS + 4% PC were 31.4% to 41% (Figure 19c) whereas the specimens prepared with 4% PC had moisture contents of 17.6 to 32.1% (Figure 17f).

Comparison of closed and open F-T cycles

Overall, higher strengths were observed in the closed system compared to the open system (Figures 16 and 18), and it was observed that open system was more destructive than the closed system. No considerable changes in moisture contents of the specimens were observed in the closed system (1 to 3% after 12 cycle); however, high changes in moisture contents of the specimens were observed in the open system (44 to 163%) (Figures 17 and 19).

In the closed system, it was observed that ongoing curing processes sometimes dominated the damaging effect of F-T cycles, and increases in strengths were observed at some points in all specimens. However, in the open system, significant decreases in strengths were observed until a specific point without any increase in strengths afterwards (except the specimens prepared with 4, 8 and 12% PC) (Figures 16 and 18). This result was attributed to that relatively higher moisture contents observed in the open system (Figures 17 and 19) mitigated the positive effects of the curing processes. Most of the specimens turned into a mud after certain number of cycles in the open system, and very low strength values (less than 5 kPa) were observed because of relatively higher moisture contents.

Results of the Wet-Dry Tests

A summary of the UCS test results of the specimens subjected to W-D cycles is provided in Table 11. In addition, Figure 20 is provided to observe the effect of W-D cycles on the UCS test results and moisture contents of the specimens.

Effect of the W-D cycles on the UCS test results

All specimens except the specimens prepared with PC failed during the 1st wetting. The specimens prepared with 2-4% PC failed during the 2nd and 6th wettings, respectively, and the specimens prepared with 8-12% PC did not fail until the 12th cycle. It was concluded that the stabilizer type (related to CaO content) and stabilizer content are the two main factors that affect the durability of soil against the W-D cycles.

It was observed that there were increases in strengths between 1st-4th cycles in the specimens prepared with 8% PC (54%) and 12% PC (75%) (Figure 20). It was concluded that ongoing curing processes dominated the damaging effect of the W-D cycles and led to increases in strengths accordingly. In addition, it was concluded that increases in the amount of PC increased the durability of loess against the W-D cycles. Strengths of the specimens in the wet and dry conditions showed that strengths in the dry condition were relatively higher, and the shapes of the trends of change in strengths were like each other.

Effect of mixing LS with other stabilizers on the UCS test results after W-D cycles

It was previously observed that the specimens prepared with LS + CF and LS + FF had higher 7-day cured strengths than the specimens prepared with CF or FF (Figure 13a-b). However, the specimens prepared with LS + CF and LS + FF failed during the 1st wetting. It was concluded that even higher 7-day cured strengths obtained in the specimens

prepared with LS + CF and LS + FF were not enough for the specimens to withstand the destructive effect of the W-D cycles.

Although the specimens prepared with 2 and 4% PC stayed stable until the 2nd and 6th cycles, respectively, all the specimens prepared with LS + PC failed during the 1st wetting (except the specimen prepared with 30% LS + 4% PC. It failed during the 2nd wetting). Hence, it was concluded that the existence of LS reduced the effectiveness of PC against the W-D cycles. This result was attributed to a decrease in the quality of the bonding between loess and PC in the presence of LS (Figure 11b for 4 PC and Figure 15c for 40 LS + 4 PC). Thus, it was concluded that there is no need to mix LS with CF or FF to increase the durability against the W-D cycles, and it should not be used with PC in the areas where W-D cycles are an issue.

Results of Swelling Tests under Open F-T Cycles

A summary of the swelling test results under open F-T cycles is provided in Table 12. In addition, test results are shown in Figures 21 and 22.

Effects of stabilizer type and content on swelling of soil

It was observed that the use of 12% LS gave the highest improvement (12% change in volume) after 2 cycles within the specimens prepared with LS (Figure 21a-b). This result was attributed to that there was an optimum LS content that should be used to improve the durability of loess. Higher LS contents (>12%) caused higher volume changes accordingly. It was speculated that an increase in LS content increased the water intake capacity of the specimens (Figure 17b-c) and higher volume changes were observed when higher amount of water froze. Only the specimens prepared with 12% CF or FF showed lower changes in volume compared to the changes observed in loess (Figure 21c-d). Relatively better

improvements were observed in the specimens prepared with PC (Figure 21e). Even the use of 2% PC improved the swelling characteristic of loess (around 1.3% increase in volume). Shrinkage was observed in the specimens prepared with 4, 8 and 12% PC. This result was attributed to material characteristics of PC. It was speculated that higher hydration rate of PC due to its higher CaO content (60 to 67%) used higher amount of water existing in the soil matrix, and this caused a decrease in moisture content and drying shrinkage was observed. In short, the use of PC showed better improvements against swelling. The use of LS showed the lowest performance and the same trend was observed in the specimens prepared with CF or FF.

Effect of mixing LS with other stabilizers on swelling

No certain trend was observed in the specimens prepared with LS + CF and LS + FF (Figure 22a-b). Significant changes in volumes of the specimens were observed when LS and PC were used together to stabilize loess, i.e., increases in volumes were around 15% higher in the specimens prepared with LS + 2% PC compared to the specimens prepared with 2% PC (Figure 22c). It was concluded that the use of LS with PC decreased the effectiveness of PC to improve the swelling behavior of loess. This result was attributed to previously mentioned speculation regarding the low pH environment in the specimens prepared with LS + PC caused by LS.

<div align="center">

Results of pH Analysis

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A summary of the pH test results is provided in Table 13. In addition, pH test results are shown in Figures 23-25.

Effect of stabilizer type on pH

Amount of the Ca^{2+} in the soil matrix affects the pH. Since PC contains the highest amount of CaO (60 to 67%), it was expected to observe the highest pH values in the specimens prepared with PC. It was observed that the use of PC to stabilize loess always provided the highest pH values (10 to 12) after all curing periods, as expected due to its highest CaO content (60 to 67%) (Figure 23). The use of CF to stabilize loess provided the second highest pH values (8.5 to 9.2). Lowest pH values (8.23 to 8.98) were observed in the specimens prepared with LS due to its lack of CaO content (0-3.5%).

Effect of stabilizer content on pH

It was concluded for all specimens that increases in stabilizer contents increased the pH values accordingly (Figure 23). Increase in PC content provided the highest increases in the pH values (17.4 to 41%) compared to the pH of loess (8.51). No significant difference in the increasing trends was observed in the specimens prepared with CF or FF. However, specimens prepared with LS showed the lowest rate of increase in pH. It was speculated that CaO content of the stabilizer was the main reason of different increasing trends since it was previously mentioned that amount of the Ca^{2+} in the soil matrix affects the pH.

Effect of curing period on pH

It was expected that the pH values would decrease with an increase in curing period due to the principles of Ca^{2+} saturation and stabilization (Chen and Lin 2009). Ca^{2+} content in the soil matrix affects the pH and decrease in its content because of hydration and pozzolanic reactions decrease the pH. There was a decreasing trend in all specimens with an increase in curing period (Figure 24). Up to 7 days of curing, increases in pH values

were observed. It was speculated that the release of Ca^{2+} from the stabilizer in the presence of water continued up to 7 days of curing. After 7 days, most of the Ca^{2+} was released and formed calcium silicate and calcium aluminate cements. Thus, after 7 days of curing, pH values decreased gradually up to 90 days of curing.

Effect of mixing LS with other stabilizers on pH

When LS was mixed with CF, decreases in pH values were observed at a rate of 1 to 3% compared to the specimens prepared with CF only (Figure 25a). On the other hand, 1 to 3% increases in the pH values were observed in the specimens prepared with LS + FF compared to the specimens prepared with FF alone (Figure 25b). The most drastic changes in pH values (around 14% decrease) were observed in the specimens prepared with LS + PC (Figure 25c).

There should be a suitable pH environment for stabilizers to release silica and alumina for long-term pozzolanic reactions. It was concluded that the use of LS did not change the pH of the soil matrix significantly (1 to 3% increase or decrease) for CF and FF (Figure 25a-b). However, the existence of LS changed the pH of the soil matrix for PC significantly (around 14% decrease) in the specimens prepared with LS + PC (Figure 25c). It was previously speculated that a low pH environment for PC in the presence of LS caused a decrease in the rate of increase in strength and a decrease in durability in LS + PC specimens. A low pH environment was observed in the specimens prepared with LS + PC. It was concluded that a low pH environment (14% decrease in pH compared to single use of PC) decreased the effectiveness of PC by mitigating the release of silica and alumina from loess and PC (in calcium-silicate and calcium-aluminate form), which reduced the short-term hydration and long-term pozzolanic reactions.

CHAPTER 5. CORRELATIONS

Correlation between UCS at Different Curing Periods

All linear correlation coefficients of determination (r-squared – R^2) values between 1-day vs 7-day, 7-day vs 28-day, and 28-day vs 90-day cured strengths are higher than 0.99 (Figure 26). It was concluded that there is a linear relationship between the strengths at different curing periods. Hydration and pozzolanic reactions are the main reasons of the improvements in engineering properties of soil. Hydration reactions between soil and stabilizer start immediately in the presence of water, and calcium hydroxide ($Ca(OH)_2$) is produced. Further increases in strength are observed due to time dependent pozzolanic reactions. Hence, longer curing periods provide higher strengths up to a point which pozzolanic reactions are ended.

Correlation between UCS and PI

An attempt was made to find a relationship between UCS test results and plasticity indices. Correlations are provided in Figure 27. A 2nd degree polynomial relationship was fit to the two parameters. The lowest R^2 value was determined to be 0.96. Hence, it was concluded that there is a correlation between the strength results and plasticity indices. Higher strength values are expected in the specimens showing lower plasticity indices. An increase in stabilizer content or the use of stabilizers having relatively higher CaO contents cause more significant decreases in PI and increases in strength of soil.

Correlation between UCS and pH

Higher pH values are expected in order to obtain better soil stabilization. There should be a suitable pH environment for stabilizers to be effective. In most cases, pH values higher than or around 12 are expected for long-term pozzolanic reactions. pH plays an

important role in the dissolution of silica and alumina from the soil and stabilizer. Higher dissolution of alumina and silica provides greater increases in strength in the long-term due to pozzolanic reactions. An attempt was made to correlate UCS and pH tests results (Figure 28). All R^2 values were determined to be around 0.98. Hence, it was concluded that there is a 2nd degree polynomial relationship between UCS and pH. Better stabilizer, the one containing the highest amount of CaO, provides higher pH values and higher strengths accordingly.

Correlation between pH and PI

As mentioned previously, there are correlations between UCS-PI, and UCS-pH. Another attempt was made to correlate pH and PI tests results and correlations are shown in Figure 29. The lowest R^2 values for quadratic relationships were determined to be 0.89. Hence, it was concluded that there is a 2nd degree polynomial relationship between pH and PI. Better stabilizer decreases the PI and increases the pH accordingly. It is expected that lower PI values should bring higher pH values.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Increasing the use of waste materials in pavement constructions helps industry to reduce the costs due to the disposal of waste materials, to control possible contaminations of surrounding areas, to create new income sources and to conserve energy and sources of other commonly-used materials. Fly ash and PC have been widely used for soil stabilization. However, the uncertain futures of these materials demand finding alternative waste materials such as LS. In this research, a laboratory study was conducted to observe the usability of lime sludge in stabilization of loess which is locally available in Iowa. Lime sludge obtained from the Ames Water Treatment Plant located in Iowa was used alone and mixed with previously mentioned stabilizers to stabilize loess in terms of strength and durability. For this purpose, UCS, F-T, swelling under F-T and W-D tests were conducted. These tests were also supported by conducting pH, XRD and SEM analyses. The observations are summarized as follows:

1. Within the specimens prepared with a single stabilizer, the use of stabilizers having relatively higher CaO contents and the use of higher amounts of stabilizers provided better improvements in the PI and strength of loess. While increases in the amounts of CF, FF and PC provided greater decreases in the PI and greater increases in the strength of loess, only the use of high amount of LS (>20%) provided considerable improvements.

2. Higher strength values were observed in the specimens having longer curing periods. Hydration and pozzolanic reactions occurring between loess and stabilizers

in the presence of water provided short-term and long-term strength gains, respectively.

3. While open F-T tests were more destructive than the closed ones, the most drastic decreases in strengths were observed after the 1st cycle in both systems. In the closed system, all the strength values of the specimens prepared with a single stabilizer after 12 F-T cycles were higher than the initial ones except the specimens prepared with high LS content (>12%). In the open system, all the final strength values were lower than the initial ones. The use of PC provided the best durability in both systems.

4. W-D cycles were more destructive than open F-T cycles, and only the specimens prepared with PC did not fail after the 1st wetting. Ongoing curing processes dominated the damaging effect of W-D cycles in the specimens prepared with high PC content (≥8%) and led to increases in strengths accordingly. Increase in the amount of PC increased the durability of loess against W-D cycles.

5. While single uses of PC to stabilize loess showed the best improvements against swelling under F-T, the uses of LS provided the lowest improvements. The use of 12% LS gave the best improvement within the specimens prepared with LS. Relatively higher moisture contents were observed in the specimens prepared with higher amounts of LS (>12%) and this result was attributed to an increase in the water intake capacity of the specimens due to LS.

6. The use of stabilizers having relatively higher CaO contents provided higher pH values. In addition, increases in stabilizer contents increased the pH values

accordingly. These results were attributed to an increase in Ca^{2+} released from stabilizers due to increases in CaO and stabilizer contents.

7. Increases in pH values were observed in all specimens up to 7 days of curing because of ongoing release of Ca^{2+} from stabilizers. After 7 days, gradual decreases in the pH values were observed because of a decrease in free Ca^{2+} due to pozzolanic reactions.

8. While using LS + CF and LS + FF to reduce the PI of loess did not provide further decreases in PI compared to the specimens prepared with only CF or FF, further increases in 7-day cured strengths were observed. Higher 7-day cured strengths were observed due to a suitable pH environment in LS + CF and LS + FF specimens. Although higher 7-day cured strengths were observed, existence of LS decreased the effectiveness of CF and FF against F-T cycles and decreased the durability. In addition, the use of LS with CF and with FF did not improve the durability against W-D cycles. No certain trend was observed in the specimens prepared with LS + CF and LS + FF regarding swelling under F-T.

9. The use of LS with PC decreased the effect of PC to improve the PI and strength of loess due to the low pH environment caused by the presence of LS. Lower 7-day cured strengths were observed in the specimens prepared with LS + PC compared to the specimens prepared with PC. The existence of LS also reduced the effectiveness of PC against open and closed F-T cycles. The use of LS with PC again reduced the durability against W-D cycles compared to the specimens prepared with PC. All specimens failed after the 1st wetting. The use of LS with PC decreased the effectiveness of PC to improve the swelling behavior of loess.

Recommendations

Based on the results of this research, it is recommended that:

1. Advanced chemical analysis of the release of silica and alumina from loess at different pH environments needs to be conducted to understand their release mechanisms, and to verify the formation of hydration gels as speculated in the manuscript.

2. More specimens should be prepared with LS contents between 12 and 20% by dry weight of loess to obtain its optimum value for the best improvements against F-T and swelling.

3. The use of LS should be investigated to stabilize other types of soils such as clayey soils having higher cohesion, higher plasticity, lower permeability and less frost-susceptibility compared to loess soil.

4. Some buffer solutions could be found and used to compensate the lower pH values in the specimens prepared with LS + PC compared to the specimens prepared with PC alone to increase the release of silica and alumina.

5. The clay content of loess could be increased by mixing it with a clayey soil to decrease its frost-susceptibility and increase its durability against F-T and W-D cycles.

6. The water intake capacity of LS and the changes in this capacity of the specimens prepared with different LS contents should be investigated. In addition, the effects of different water intake capacities could be observed under open F-T cycles.

7. LS could be used to stabilize expansive clays such as bentonite to observe its effects on the swelling behaviors of the soil.

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TABLES

Table 1a. Index properties of the materials

Material	C_u	C_c	W_{opt} (%)	γ_{dmax} (kN/m^3)	LL (%)	PI (%)	Gravel Content (%)	Fine Content (<75 μm) (%)	Classification	
									USCS	AASHTO
LOE	2.74	0.67	16.2	16.67	37.3	10.4	0	99	ML	A-4
LS	6.12	0.99	-	-	43	6	0	92	ML	A-5
CF	3.43	1.39	-	-	-	-	0	93	-	-
FF	2.57	1.32	-	-	-	-	0	88	-	-
PC	-	-	-	-	-	-	-	-	-	-

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 1b. Chemical compositions of the materials

Material	G_s	LOI (%)	CaO (%)	CaCO$_3$ (%)	SO$_3$ (%)	SiO$_2$ (%)	Al$_2$O$_3$ (%)	MgO (%)
LOE	2.7	-	-	-	-	-	-	-
LS	2.3	-	0-3.5	>60	-	-	-	-
CF	2.7	0.16	24.31	-	0.81	39.01	21.23	5.31
FF	2.47	0	11.8	-	0.45	57.06	18.82	2.89
PC	-	-	60-67	-	1.3-3	17-25	3-8	0.1-4

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 2. Legend of the specimens and their compositions

Specimen Description	LS (%)	CF (%)	FF (%)	PC (%)
LOE	0	0	0	0
4 LS	4	0	0	0
8 LS	8	0	0	0
12 LS	12	0	0	0
20 LS	20	0	0	0
30 LS	30	0	0	0
40 LS	40	0	0	0
4 CF	0	4	0	0
8 CF	0	8	0	0
12 CF	0	12	0	0
4 FF	0	0	4	0
8 FF	0	0	8	0
12 FF	0	0	12	0
2 PC	0	0	0	2
4 PC	0	0	0	4
8 PC	0	0	0	8
12 PC	0	0	0	12
30 LS + 8 CF	30	8	0	0
30 LS + 12 CF	30	12	0	0
30 LS + 8 FF	30	0	8	0
30 LS + 12 FF	30	0	12	0
30 LS + 2 PC	30	0	0	2
30 LS + 4 PC	30	0	0	4
40 LS + 8 CF	40	8	0	0
40 LS + 12 CF	40	12	0	0
40 LS + 8 FF	40	0	8	0
40 LS + 12 FF	40	0	12	0
40 LS + 2 PC	40	0	0	2
40 LS + 4 PC	40	0	0	4

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement. The numbers following LS, CF, FF, and PC indicate the percentages of materials by dry weight of loess.

Table 3. Atterberg limits test results

Specimen Description	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
LOE	37.3	26.9	10.4
4 LS	36.7	26.6	10.1
8 LS	36.4	26.3	10.1
12 LS	36.9	26.8	10.1
20 LS	36.7	26.7	10
30 LS	37.2	27.5	9.7
40 LS	37.4	28	9.4
4 CF	37.7	28.1	9.6
8 CF	37.8	28.9	8.9
12 CF	38.1	30	8.2
4 FF	37.7	27.6	10.1
8 FF	37.6	27.9	9.7
12 FF	37.7	28.6	9.1
2 PC	40.8	31.6	9.2
4 PC	41.9	35.8	6.1
8 PC	42.3	37.6	4.7
12 PC	42.9	39	3.9
30 LS + 8 CF	38.3	29.4	8.9
30 LS + 12 CF	38.5	29.9	8.6
30 LS + 8 FF	37.7	28.3	9.4
30 LS + 12 FF	38	28.3	9.7
30 LS + 2 PC	37.8	28.8	9.1
30 LS + 4 PC	40	32.5	7.5
40 LS + 8 CF	38.3	29.5	8.8
40 LS + 12 CF	38.9	30.7	8.2
40 LS + 8 FF	37.9	28.6	9.3
40 LS + 12 FF	38	28.7	9.3
40 LS + 2 PC	38	28.4	9.5
40 LS + 4 PC	39.9	32.1	7.8

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 4. Summary of standard Proctor test results

Specimen Description	w_{opt} (%)	γ_{dmax} (kN/m^3)
LOE	16.2	16.67
4 LS	16.8	16.65
8 LS	17.7	16.68
12 LS	18.3	16.48
20 LS	18.5	16.29
30 LS	18.8	16.09
40 LS	19.4	15.79
4 CF	17.2	16.51
8 CF	17.7	16.46
12 CF	18.5	16.32
4 FF	16.9	16.62
8 FF	17.2	16.56
12 FF	17.9	16.50
2 PC	17	16.02
4 PC	17.3	15.99
8 PC	18.3	15.87
12 PC	19.2	16.15
30 LS + 8 CF	17.4	16.24
30 LS + 12 CF	18	16.12
30 LS + 8 FF	17.7	16.15
30 LS + 12 FF	18.2	16.06
30 LS + 2 PC	17.3	16.37
30 LS + 4 PC	18.2	16.26
40 LS + 8 CF	18.3	16.02
40 LS + 12 CF	18.6	15.90
40 LS + 8 FF	18.5	15.95
40 LS + 12 FF	18.6	15.90
40 LS + 2 PC	18.2	16.02
40 LS + 4 PC	18.8	15.74

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 5. UCS test results of cured specimens (in kPa)

Specimen Description	Unconfined Compressive Strength (kPa)			
	1-Day Cured	7-Day Cured	28-Day Cured	90-Day Cured
LOE	94.87	-	-	-
4 LS	105.48	107.41	120.38	132.66
8 LS	104.43	108.81	115.83	136.45
12 LS	109.43	111.84	121.62	140.1
20 LS	-	135.60	-	-
30 LS	-	146.78	-	-
40 LS	-	166.95	-	-
4 CF	121.4	135.82	171.68	197.4
8 CF	136.48	155.07	226.84	255.18
12 CF	145.64	167.12	316.19	336.95
4 FF	105.09	122.36	135.55	175.33
8 FF	115.08	134.02	164.65	194.16
12 FF	125.17	139.15	194.16	227.04
2 PC	-	598.3	-	-
4 PC	607.07	1072.26	2583.74	3449.59
8 PC	791.24	1527.64	3197.65	4801.79
12 PC	1073.58	2056.84	4119.41	5837.72
30 LS + 8 CF	-	213.99	-	-
30 LS + 12 CF	-	237.66	-	-
30 LS + 8 FF	-	164.14	-	-
30 LS + 12 FF	-	177.82	-	-
30 LS + 2 PC	-	206.01	-	-
30 LS + 4 PC	-	504.52	-	-
40 LS + 8 CF	-	220.04	-	-
40 LS + 12 CF	-	254.01	-	-
40 LS + 8 FF	-	174.66	-	-
40 LS + 12 FF	-	190.18	-	-
40 LS + 2 PC	-	207.76	-	-
40 LS + 4 PC	-	444.32	-	-

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 6. UCS test results of cured specimens (in % change)

Specimen Description	Change in Unconfined Compressive Strength (%)			
	1-Day Cured	7-Day Cured	28-Day Cured	90-Day Cured
LOE	0.00	-	-	-
4 LS	11.18	13.22	26.89	39.83
8 LS	10.07	14.70	22.09	43.82
12 LS	15.87	17.88	28.2	47.67
20 LS	-	42.93	-	-
30 LS	-	54.71	-	-
40 LS	-	75.97	-	-
4 CF	27.96	43.16	80.96	108.07
8 CF	43.85	63.45	139.1	168.97
12 CF	53.51	76.16	233.28	255.16
4 FF	10.77	28.97	42.88	84.81
8 FF	21.3	41.27	73.55	104.65
12 FF	31.93	46.67	104.65	139.32
2 PC	-	530.64	-	-
4 PC	539.88	1030.22	2623.4	3536.05
8 PC	734.01	1510.21	3270.49	4961.34
12 PC	1031.61	2068.02	4242.08	6053.27
30 LS + 8 CF	-	125.55	-	-
30 LS + 12 CF	-	150.51	-	-
30 LS + 8 FF	-	73.01	-	-
30 LS + 12 FF	-	87.43	-	-
30 LS + 2 PC	-	117.14	-	-
30 LS + 4 PC	-	431.79	-	-
40 LS + 8 CF	-	131.93	-	-
40 LS + 12 CF	-	167.74	-	-
40 LS + 8 FF	-	84.1	-	-
40 LS + 12 FF	-	100.46	-	-
40 LS + 2 PC	-	118.99	-	-
40 LS + 4 PC	-	367.28	-	-

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 7. UCS test results of the specimens subjected to F-T cycles (closed)

Specimen Description	Unconfined Compressive Strength (kPa) - Closed System				
	7-Day Cured	After 1 Cycle	After 4 Cycles	After 8 Cycles	After 12 Cycles
LOE	94.87	94.46	93.91	93.08	92.39
4 LS	107.41	93.98	101.77	102.59	108.45
8 LS	108.81	97.49	111.90	111.01	116.66
12 LS	111.84	101.97	119.69	118.25	123.21
20 LS	135.60	119.62	118.80	123.69	122.73
30 LS	146.78	129.90	132.72	129.69	130.93
40 LS	166.95	140.10	150.24	150.58	151.89
4 CF	135.82	111.07	141.41	133.90	147.48
8 CF	155.07	129.07	177.40	169.54	190.36
12 CF	167.12	145.69	200.98	205.33	222.63
4 FF	122.36	100.25	118.38	116.25	123.69
8 FF	134.02	111.83	128.17	127.97	135.00
12 FF	139.15	117.90	143.82	142.58	144.38
2 PC	598.30	372.59	514.62	491.32	567.03
4 PC	1072.26	853.71	1222.17	1179.62	1533.12
8 PC	1527.64	1420.11	1960.73	1948.05	2630.14
12 PC	2056.84	1901.92	2348.15	2321.19	3520.60
30 LS + 8 CF	213.99	182.44	184.30	188.36	201.67
30 LS + 12 CF	237.66	213.46	221.80	222.56	235.39
30 LS + 8 FF	164.14	145.76	145.69	143.69	144.51
30 LS + 12 FF	177.82	156.65	159.34	162.10	162.58
30 LS + 2 PC	206.01	176.44	157.34	151.41	160.65
30 LS + 4 PC	504.52	442.99	434.92	442.30	507.39
40 LS + 8 CF	220.04	193.40	198.57	205.19	222.98
40 LS + 12 CF	254.01	225.32	227.66	234.63	247.94
40 LS + 8 FF	174.66	150.10	154.17	153.62	154.24
40 LS + 12 FF	190.18	172.37	176.44	180.02	180.99
40 LS + 2 PC	207.76	193.60	170.65	161.27	172.64
40 LS + 4 PC	444.32	397.28	393.28	400.24	467.53

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 8. Moisture contents of the specimens subjected to F-T cycles (closed)

Specimen Description	Moisture Content (%) - Closed System				
	7-Day Cured	After 1 Cycle	After 4 Cycles	After 8 Cycles	After 12 Cycles
LOE	16.2	16.3	16.3	16.1	16.3
4 LS	16.5	16.6	16.3	16.3	15.9
8 LS	17.4	17.2	17.1	17.4	17.8
12 LS	18.3	18	17.9	18.2	18.3
20 LS	18.3	18	18.2	17.9	17.9
30 LS	18.7	18.3	18.6	18.4	18.1
40 LS	19.1	18.8	18.5	18.7	19.1
4 CF	16.6	16.4	16.6	16.3	16.7
8 CF	15.4	15.3	15	15.3	15.3
12 CF	15.5	15.7	14.9	15.1	14.9
4 FF	16.4	16.2	15.9	16.1	15.9
8 FF	15.8	15.5	15.3	15.6	15.7
12 FF	16.1	15.9	15.6	16.2	15.9
2 PC	16	15.4	15.5	15.7	15.8
4 PC	15.6	15.5	15.8	15.2	15.1
8 PC	16	16.4	16.2	16	16.4
12 PC	16.2	16.8	16.4	16.6	16.2
30 LS + 8 CF	16.8	16.8	16.4	17.1	17
30 LS + 12 CF	16.3	16.1	16.5	16.1	16.6
30 LS + 8 FF	16.6	16.2	16.8	16.7	16.9
30 LS + 12 FF	16.4	16.1	16.7	16.1	16.8
30 LS + 2 PC	16.1	16.5	16.6	16.3	16.8
30 LS + 4 PC	14.5	14.8	15.1	14.6	15.2
40 LS + 8 CF	16.7	16.3	17.1	17.2	17.4
40 LS + 12 CF	16.4	16.1	16.4	17	16.8
40 LS + 8 FF	17.3	16.8	17.9	17.8	17.8
40 LS + 12 FF	17.6	17.2	18.3	18	18
40 LS + 2 PC	16.1	15.9	17	16.8	16.4
40 LS + 4 PC	18.5	17.9	19	18.7	19

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 9. UCS test results of the specimens subjected to F-T cycles (open)

Specimen Description	Unconfined Compressive Strength (kPa) - Open System				
	7-Day Cured	After 1 Cycle	After 4 Cycles	After 8 Cycles	After 12 Cycles
LOE	94.87	6.41	5.52	4.83	2.07
4 LS	107.41	18.41	7.72	6.89	4.14
8 LS	108.81	19.44	7.93	7.03	4.83
12 LS	111.84	19.99	7.58	7.24	5.52
20 LS	135.60	32.34	8.00	6.89	4.14
30 LS	146.78	32.54	8.55	6.96	4.83
40 LS	166.95	38.61	6.96	7.24	4.83
4 CF	135.82	53.30	16.55	13.24	6.89
8 CF	155.07	72.05	28.48	18.96	9.65
12 CF	167.12	95.15	39.09	21.30	11.72
4 FF	122.36	48.13	16.89	10.55	5.52
8 FF	134.02	59.43	23.44	10.41	6.89
12 FF	139.15	79.43	35.37	12.41	6.21
2 PC	598.30	269.31	209.53	51.92	36.68
4 PC	1072.26	586.81	757.39	604.26	508.90
8 PC	1527.64	1095.99	1373.16	1296.15	1069.31
12 PC	2056.84	1626.47	1900.40	1762.23	1542.08
30 LS + 8 CF	213.99	27.58	12.69	6.89	4.14
30 LS + 12 CF	237.66	39.09	17.65	11.03	6.89
30 LS + 8 FF	164.14	18.00	12.27	6.89	4.14
30 LS + 12 FF	177.82	21.99	15.86	9.65	4.83
30 LS + 2 PC	206.01	22.61	9.65	6.89	4.14
30 LS + 4 PC	504.52	216.56	137.90	98.73	35.92
40 LS + 8 CF	220.04	29.16	13.79	9.65	6.89
40 LS + 12 CF	254.01	37.51	13.86	11.38	8.27
40 LS + 8 FF	174.66	18.00	9.65	7.58	3.45
40 LS + 12 FF	190.18	23.79	11.03	5.52	4.14
40 LS + 2 PC	207.76	24.82	11.03	5.52	4.00
40 LS + 4 PC	443.32	176.78	117.21	86.87	41.02

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 10. Moisture contents of the specimens subjected to F-T cycles (open)

Specimen Description	Moisture Content (%) - Open System				
	7-Day Cured	After 1 Cycle	After 4 Cycles	After 8 Cycles	After 12 Cycles
LOE	16.2	26.7	30.1	32.4	34.5
4 LS	16.8	27.86	30.41	33.01	35.51
8 LS	17.7	29.12	32.44	34.54	36.1
12 LS	18.3	30.5	32.89	34.1	35.97
20 LS	18.3	30.6	34.9	37.6	38.7
30 LS	18.7	32.6	36.1	38.6	39.6
40 LS	19.1	33.3	36.5	39.9	41.2
4 CF	16.6	22.9	28.8	32.4	35.87
8 CF	15.4	20.6	25.76	29.34	35.45
12 CF	15.5	19.9	26.2	29.9	34.12
4 FF	16.4	23.8	28.4	29.1	32.4
8 FF	15.8	24.9	29.3	31.4	33.1
12 FF	16.1	18.7	24.2	28	33.8
2 PC	16	21.7	28.2	36.6	40.2
4 PC	15.6	17.6	22.5	28.5	32.1
8 PC	16	18.9	21.7	25.8	28.2
12 PC	16.2	18.4	20.1	22.2	23.4
30 LS + 8 CF	16.8	32	35.8	38.1	40.7
30 LS + 12 CF	16.3	30.8	34.9	37.4	40.1
30 LS + 8 FF	16.6	31.1	35.4	39.3	42.1
30 LS + 12 FF	16.4	32.8	36.4	38.9	41.5
30 LS + 2 PC	16.1	33.4	36.2	38.7	41.1
30 LS + 4 PC	14.5	30.4	33.8	35.9	38.2
40 LS + 8 CF	16.7	29.4	34.3	36.4	39.1
40 LS + 12 CF	16.4	29	33.8	36.1	38.7
40 LS + 8 FF	17.3	31	34.4	37.6	40.9
40 LS + 12 FF	17.6	31.4	35.2	37.9	40.4
40 LS + 2 PC	16.1	33.2	36.8	39.2	40.6
40 LS + 4 PC	18.5	31.4	34	35.5	41

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 11. UCS test results of the specimens subjected to W-D cycles

Specimen Description	Unconfined Compressive Strength (kPa)				
	7-Day Cured at w_{opt} (Dry)	After 1 Cycle Wet (Dry)	After 4 Cycles Wet (Dry)	After 8 Cycles Wet (Dry)	After 12 Cycles Wet (Dry)
2 PC	598.3 (1794.98)	358.18 (1129.04)	-	-	-
4 PC	1072.26 (2359.00)	752.79 (1539.78)	520.87 (1224.26)	-	-
8 PC	1527.64 (4201.10)	1128.12 (3365.50)	1740.36 (4566.78)	1556.49 (3904.79)	983.19 (2466.53)
12 PC	2056.84 (5759.17)	1823.08 (5646.50)	3190 (7831.75)	2678.95 (7372.48)	2332.98 (6420.33)
30 LS + 4 PC	504.52 (1720.55)	318.72 (1061.65)	-	-	-

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 12. Swelling test results under F-T cycles

Specimen Description	Change in Volume (%)	
	1st Freezing	2nd Freezing
LOE	3.11	15.09
4 LS	8.10	15.78
8 LS	8.65	14.09
12 LS	9.36	11.86
20 LS	8.08	15.64
30 LS	9.03	16.60
40 LS	10.29	17.13
4 CF	4.16	15.81
8 CF	4.70	16.59
12 CF	1.93	11.92
4 FF	6.63	17.02
8 FF	3.98	16.52
12 FF	1.75	14.08
2 PC	1.23	1.33
4 PC	-0.79	-0.03
8 PC	-0.76	-0.25
12 PC	-0.92	-0.32
30 LS + 8 CF	3.97	13.49
30 LS + 12 CF	3.58	13.92
30 LS + 8 FF	4.52	20.97
30 LS + 12 FF	2.96	16.77
30 LS + 2 PC	3.17	15.58
30 LS + 4 PC	0.36	6.21
40 LS + 8 CF	8.13	18.74
40 LS + 12 CF	3.99	13.35
40 LS + 8 FF	4.85	16.99
40 LS + 12 FF	4.36	15.30
40 LS + 2 PC	3.68	14.37
40 LS + 4 PC	8.34	10.09

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.

Table 13. pH test results

Specimen Description	Curing Condition			
	1-Day	**7-Day**	**28-Day**	**90-Day**
LOE	8.51	-	-	-
4 LS	8.45	8.61	8.56	8.23
8 LS	8.65	8.78	8.71	8.30
12 LS	8.72	8.98	8.88	8.54
20 LS	-	9.18	-	-
30 LS	-	9.22	-	-
40 LS	-	9.25	-	-
4 CF	8.72	8.84	8.78	8.49
8 CF	9.01	8.87	8.95	8.64
12 CF	9.17	9.09	9.18	8.90
4 FF	8.67	8.70	8.67	8.51
8 FF	8.74	8.77	8.72	8.54
12 FF	8.82	8.84	8.77	8.59
2 PC	-	10.16	-	-
4 PC	11.30	11.07	10.71	9.99
8 PC	11.67	11.86	11.57	11.11
12 PC	11.81	12.00	11.82	11.29
30 LS + 8 CF	-	8.79	-	-
30 LS + 12 CF	-	8.81	-	-
30 LS + 8 FF	-	8.89	-	-
30 LS + 12 FF	-	8.79	-	-
30 LS + 2 PC	-	8.83	-	-
30 LS + 4 PC	-	9.89	-	-
40 LS + 8 CF	-	8.78	-	-
40 LS + 12 CF	-	8.86	-	-
40 LS + 8 FF	-	9.06	-	-
40 LS + 12 FF	-	8.95	-	-
40 LS + 2 PC	-	8.80	-	-
40 LS + 4 PC	-	9.42	-	-

LOE: loess, LS: lime sludge, CF: class C fly ash, FF: class F fly ash, PC: type I/II Portland cement.
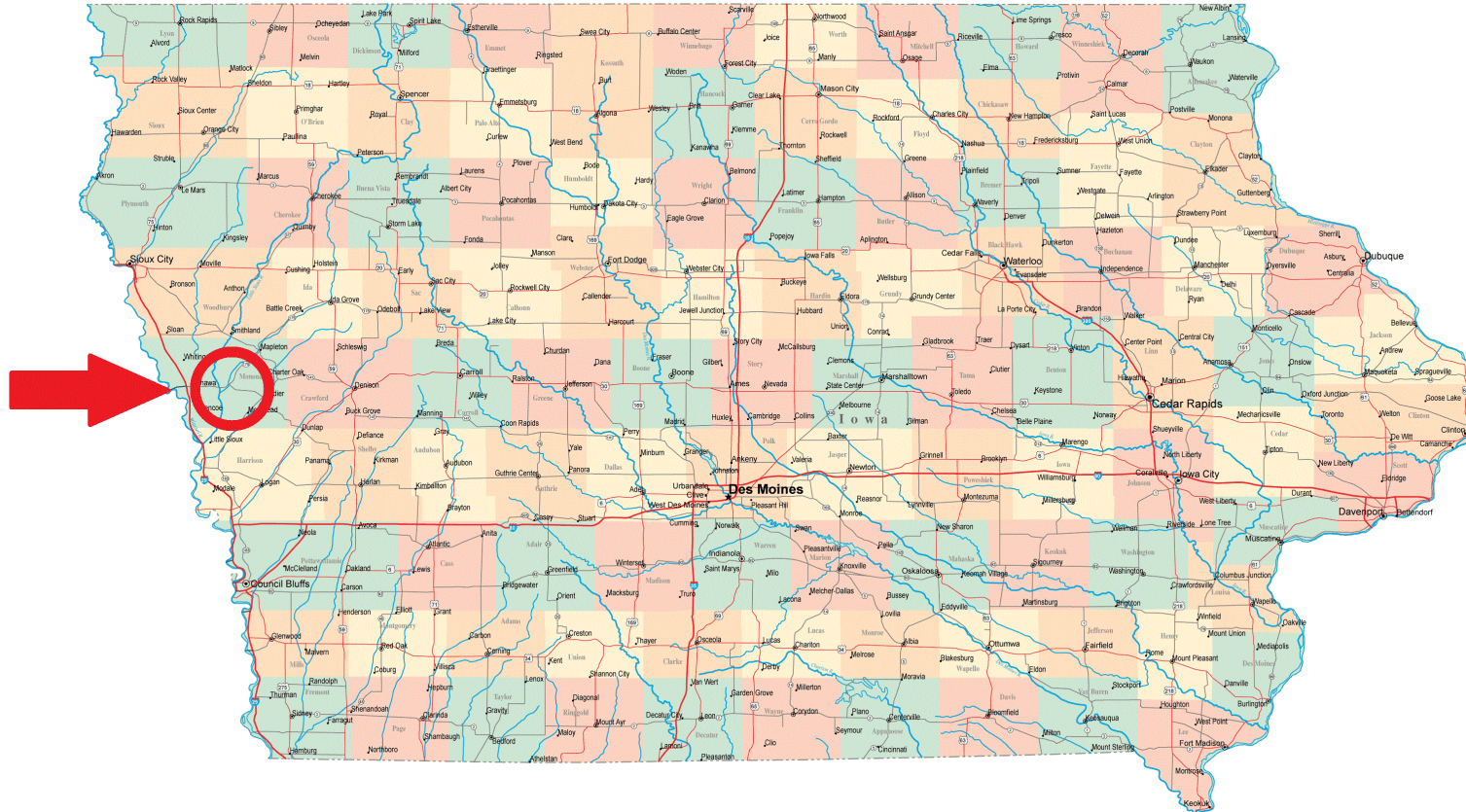
Figure 1. Location of the loess source in the State of Iowa
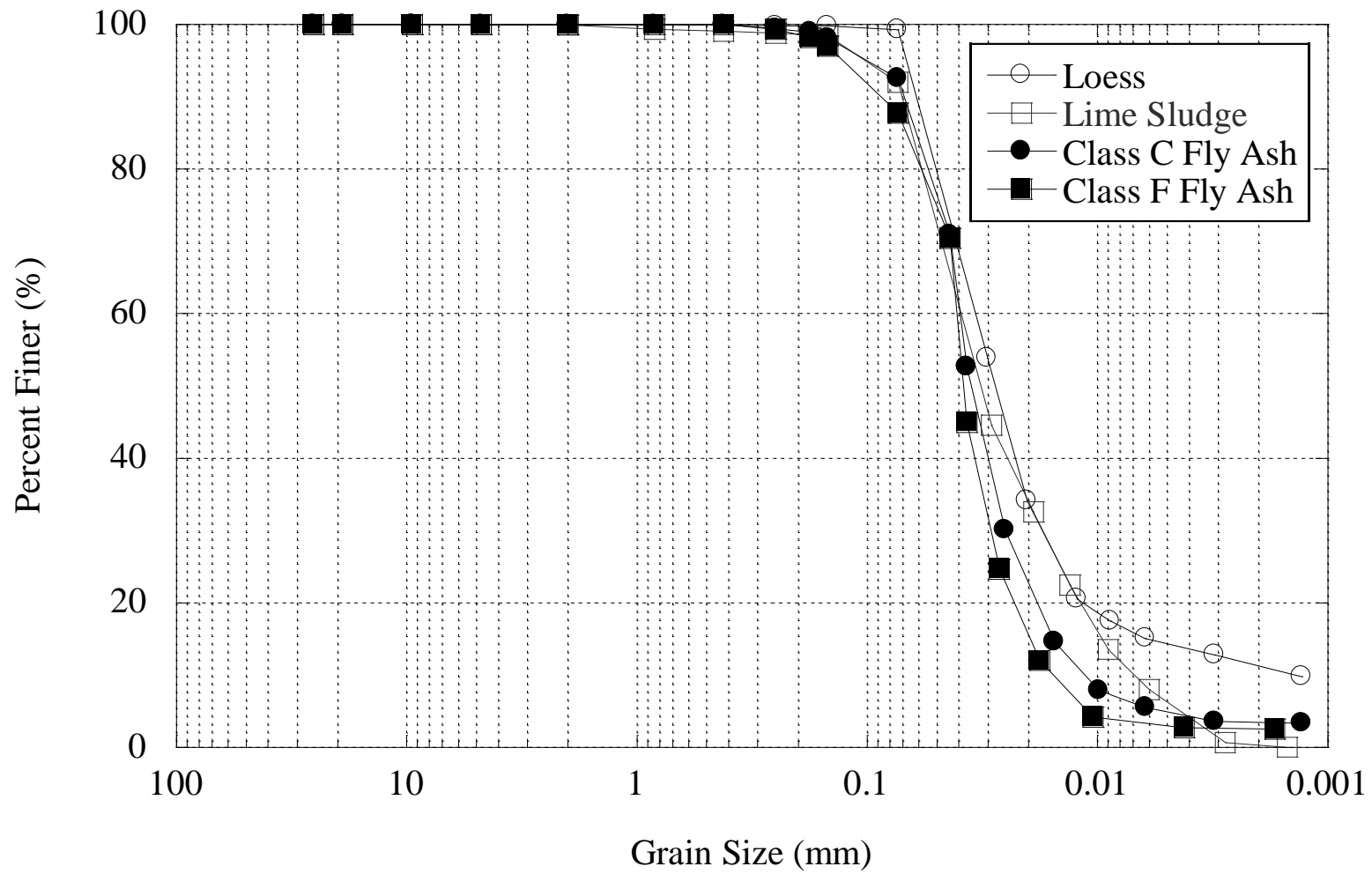
Figure 2. Particle size distribution of the materials

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Figure 3. Lime sludge lagoon operated by Ames Water Treatment Plant
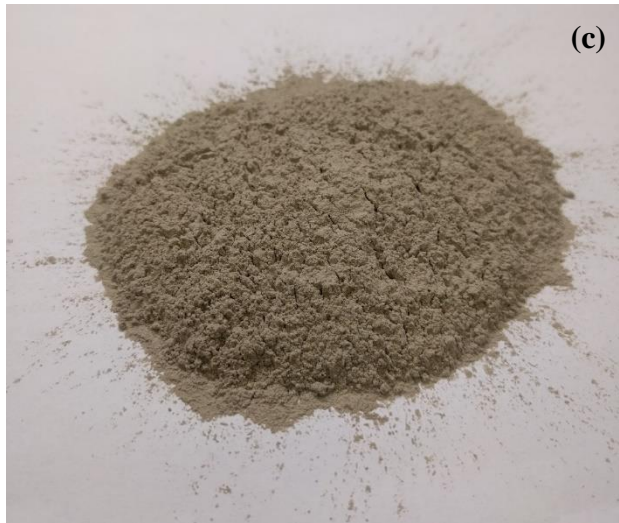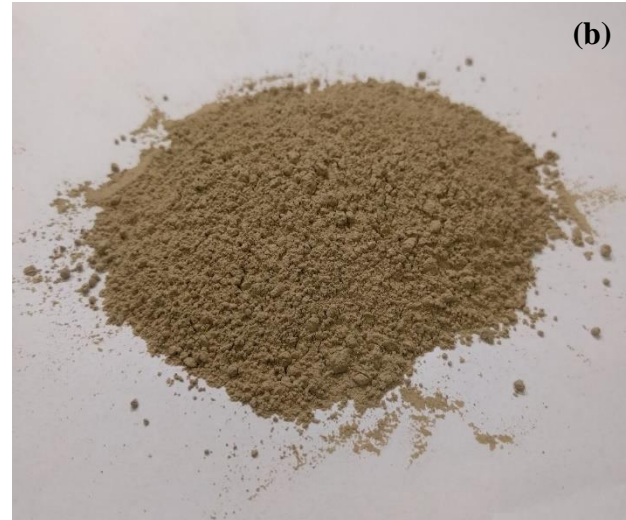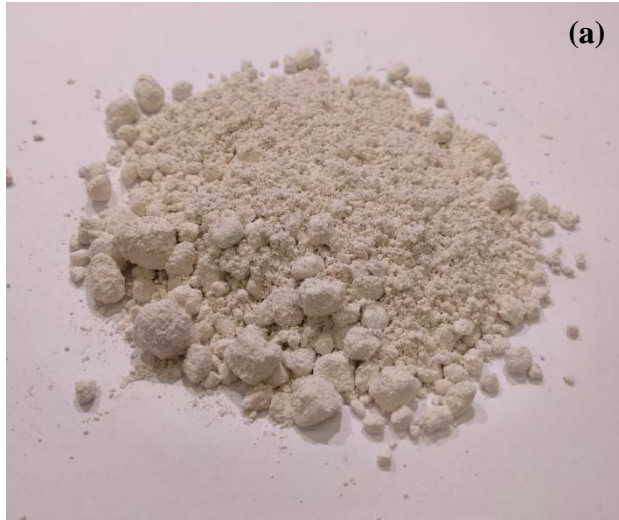
Figure 4. The stabilizers **(a)** LS **(b)** CF **(c)** FF **(d)** PC
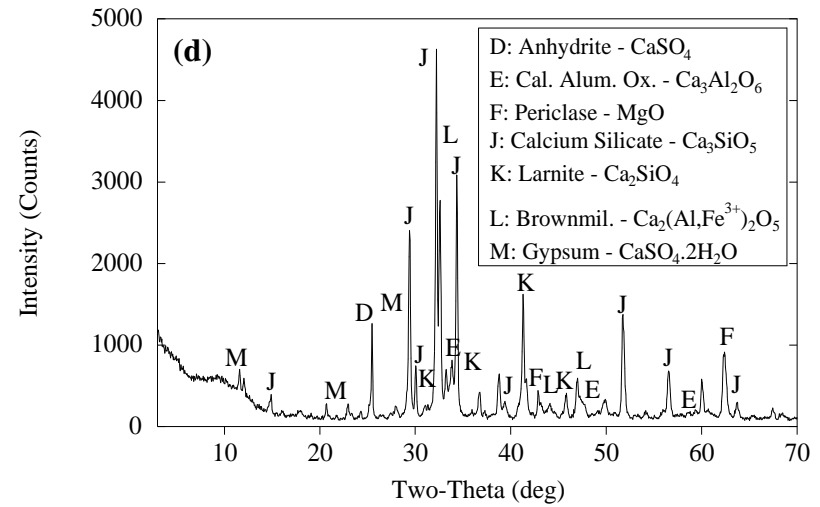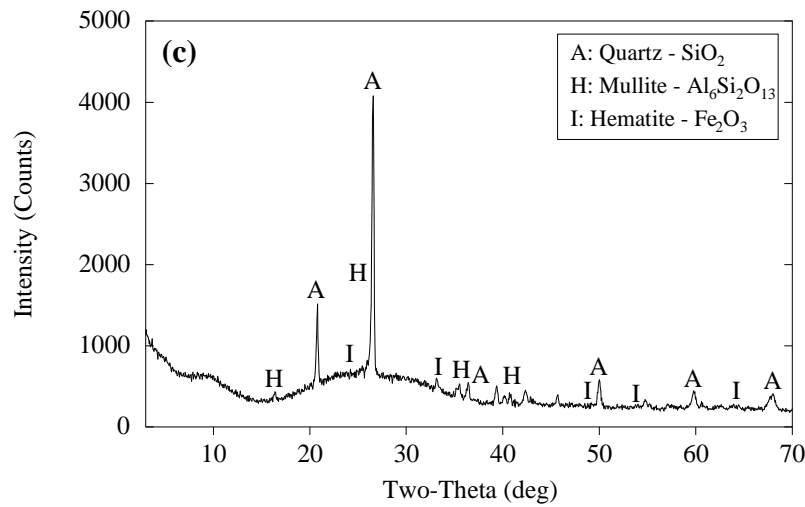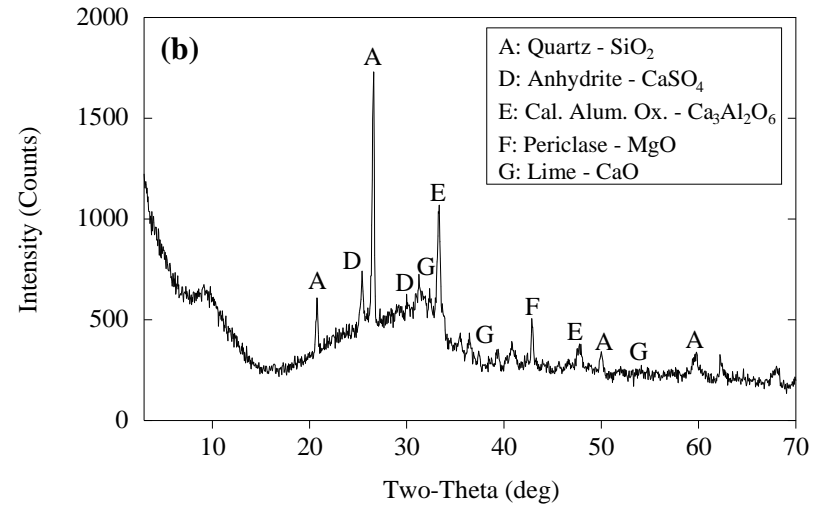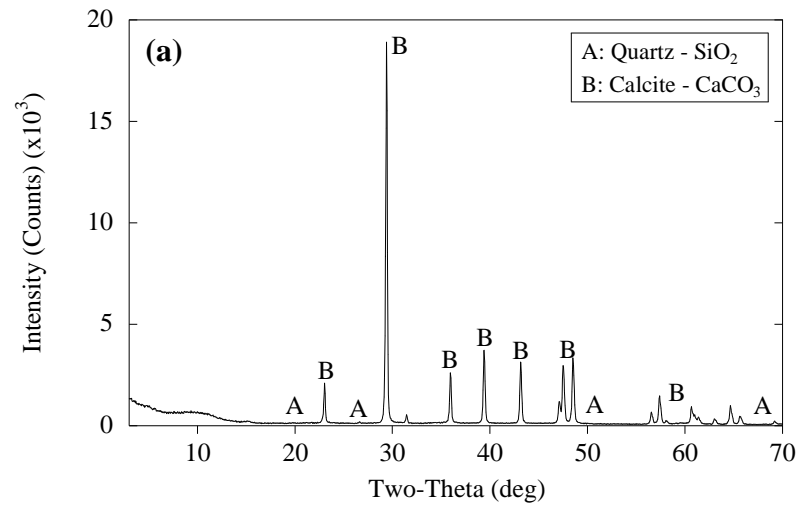
Figure 5. XRD patterns of **(a)** LS **(b)** CF **(c)** FF **(d)** PC
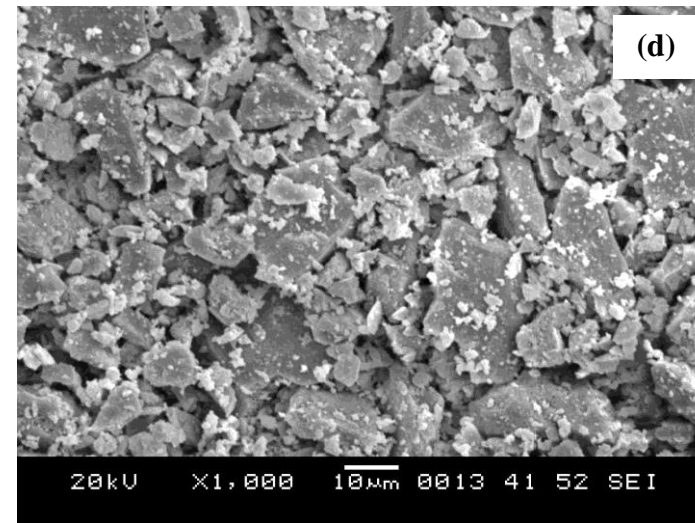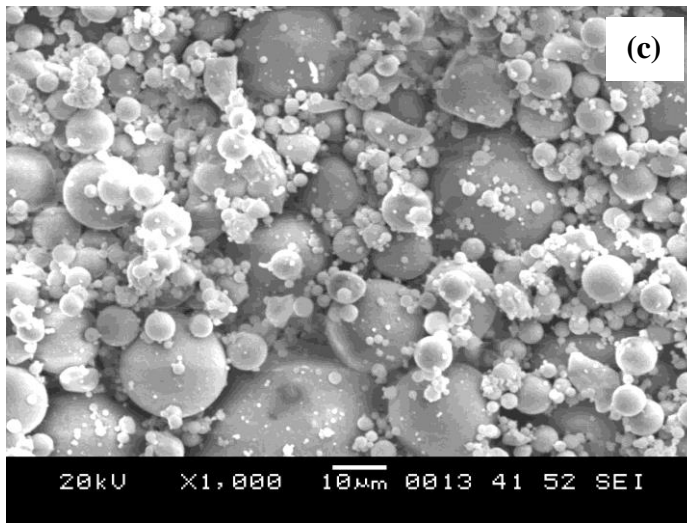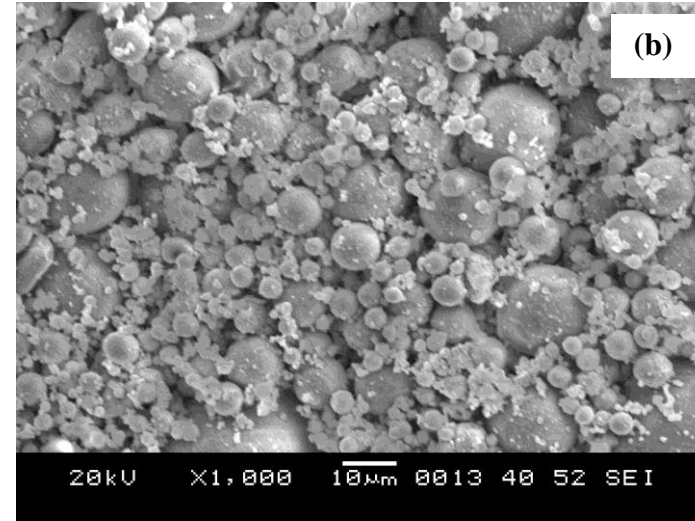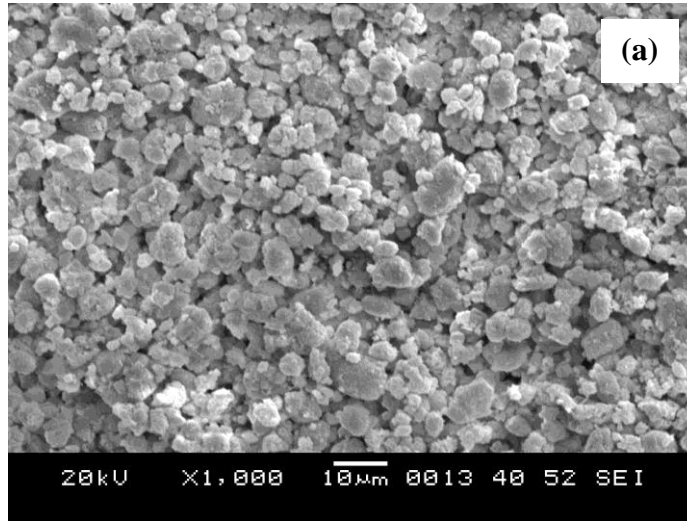
Figure 6. SEM images of **(a)** LS **(b)** CF **(c)** FF **(d)** PC
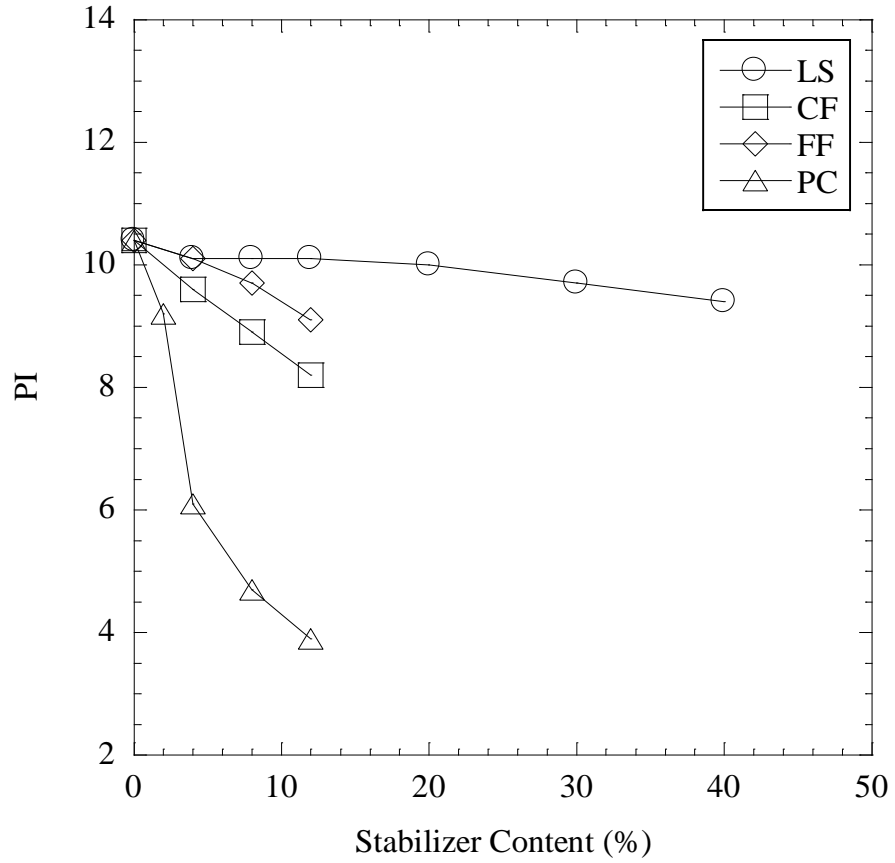
Figure 7. Effects of stabilizer type and content on PI
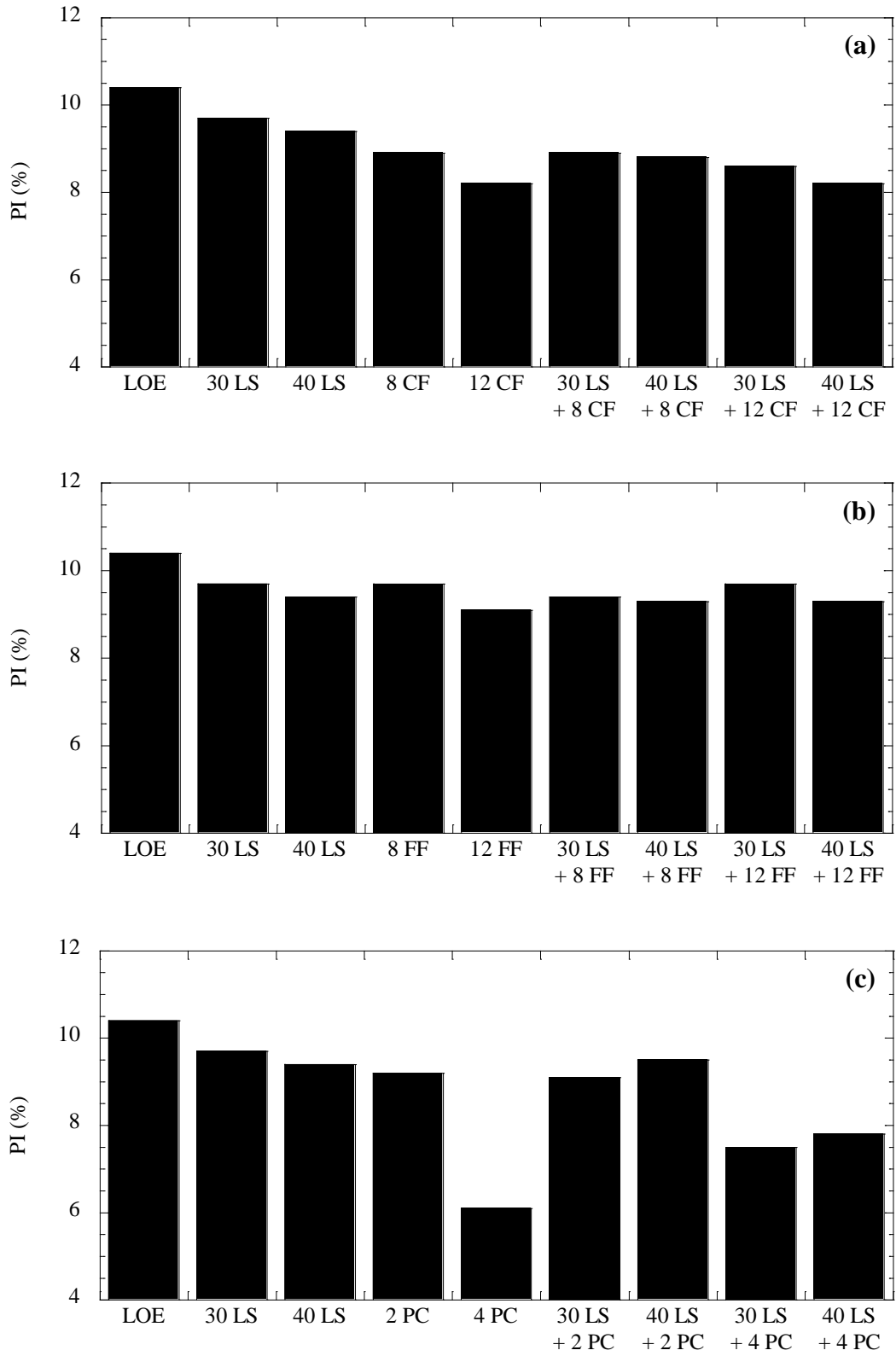
Figure 8. PI values of **(a)** LS + CF **(b)** LS + FF **(c)** LS + PC
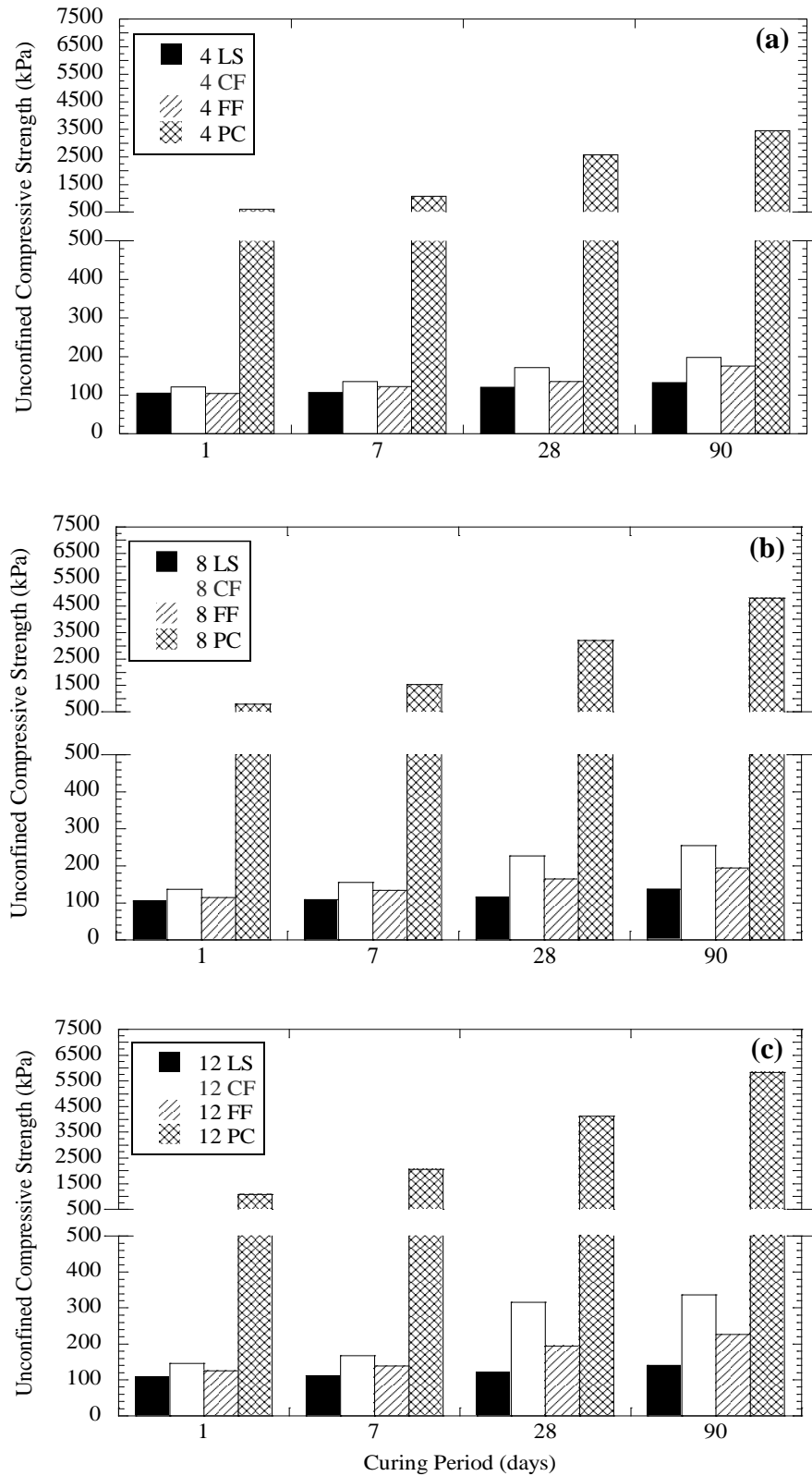
Figure 9. Strengths of the specimens prepared with **(a)** 4% **(b)** 8% **(c)** 12% of stabilizers
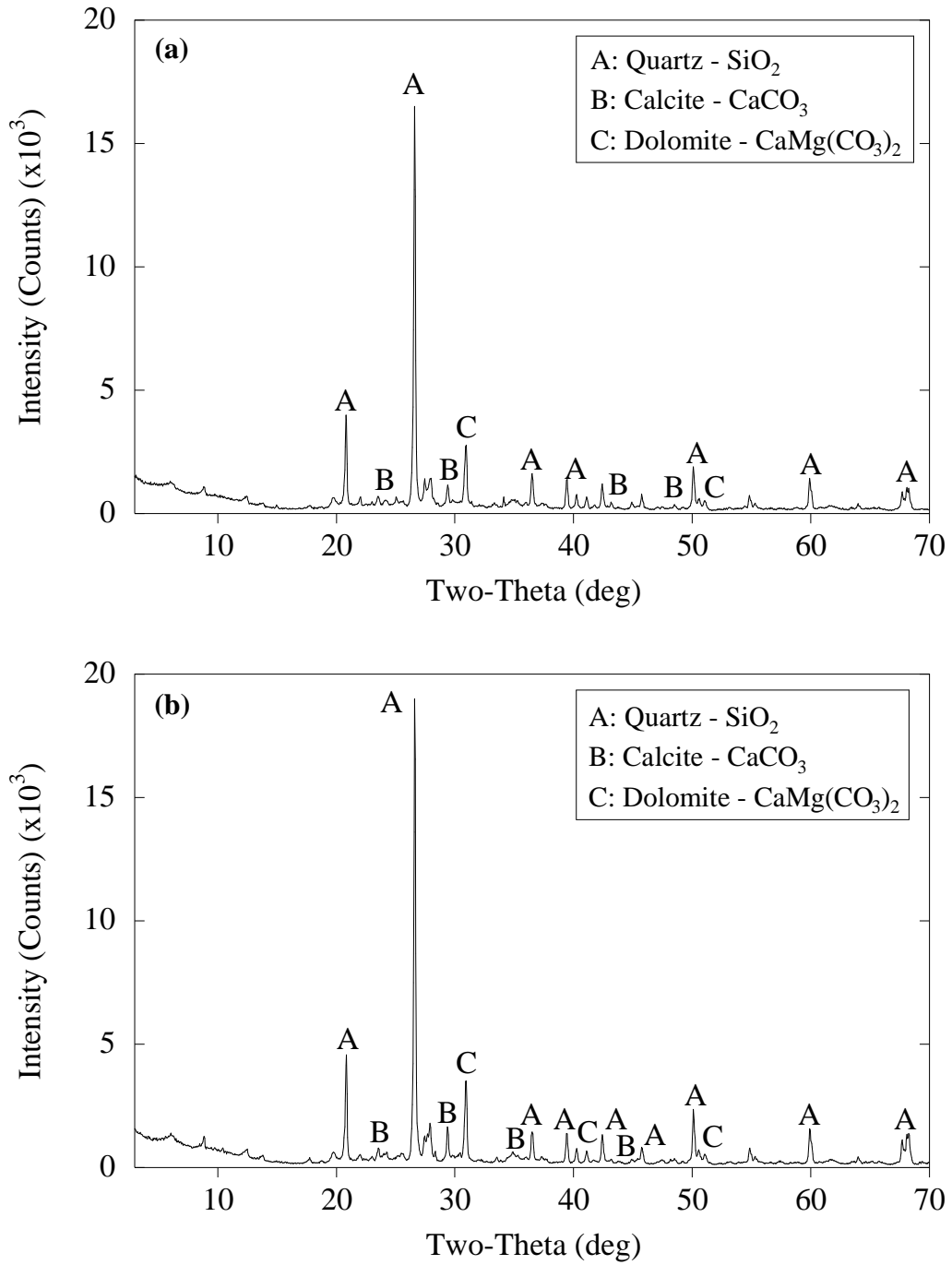
Figure 10. XRD patterns of **(a)** 12 CF **(b)** 4 PC
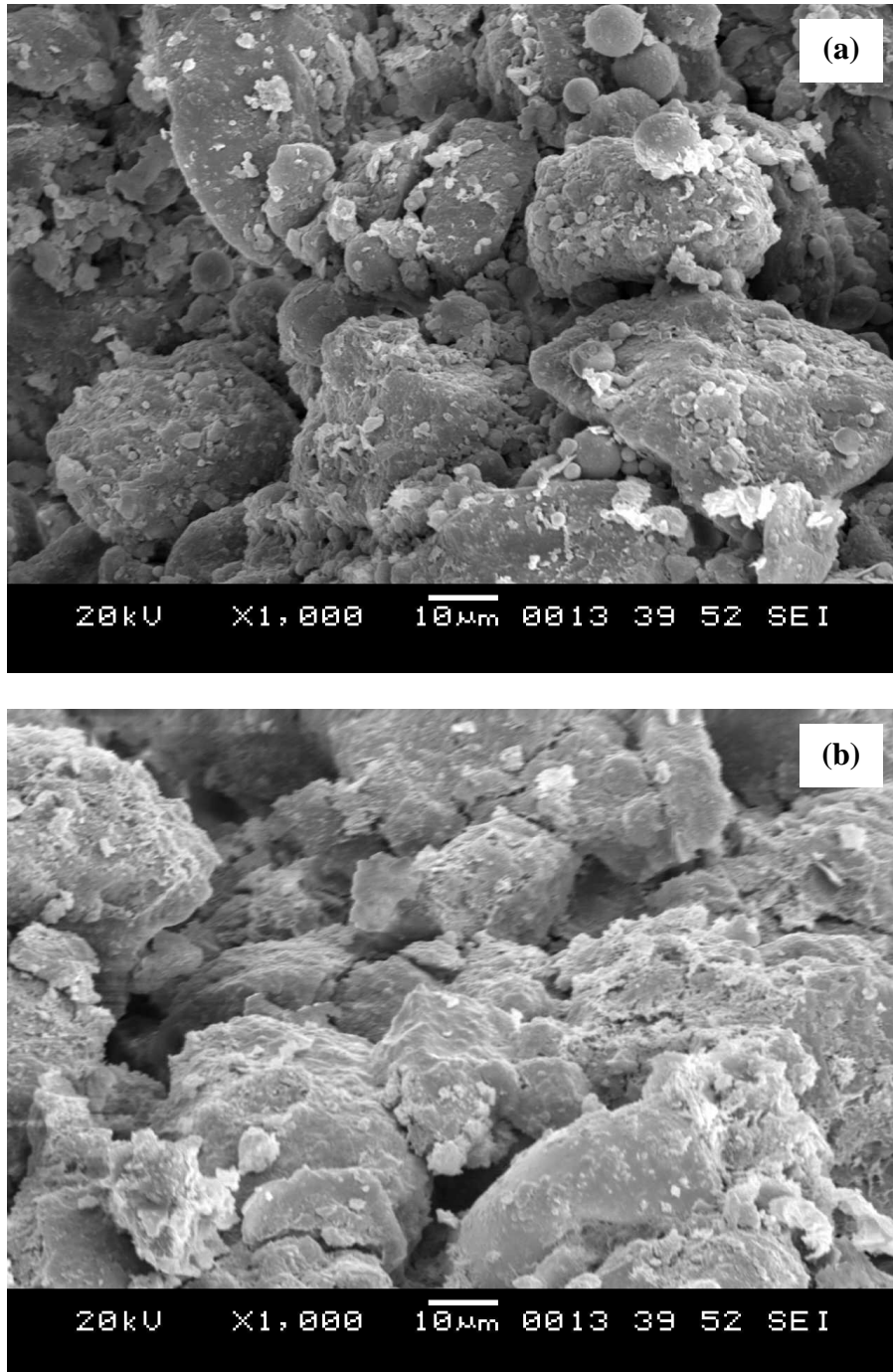
Figure 11. SEM images of **(a)** 12 CF **(b)** 4 PC
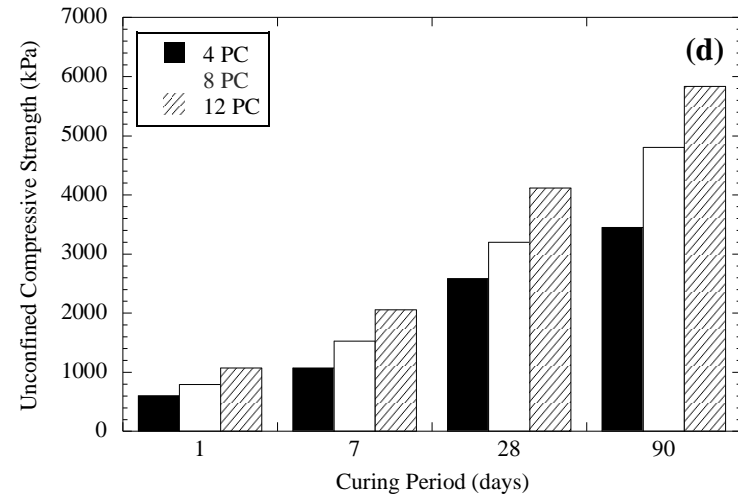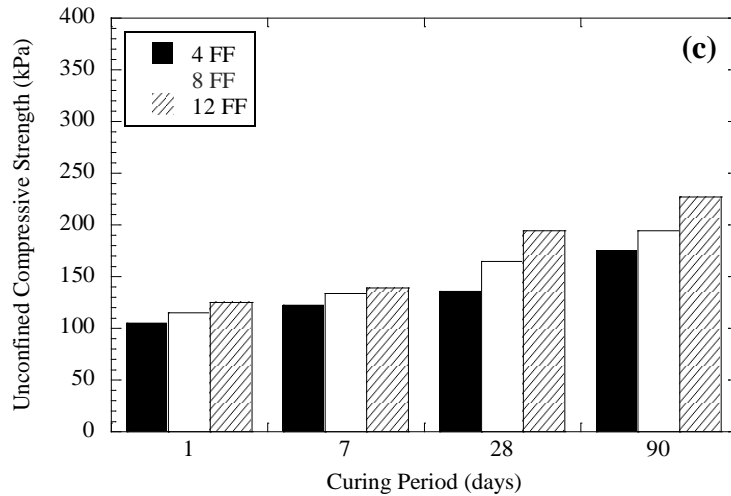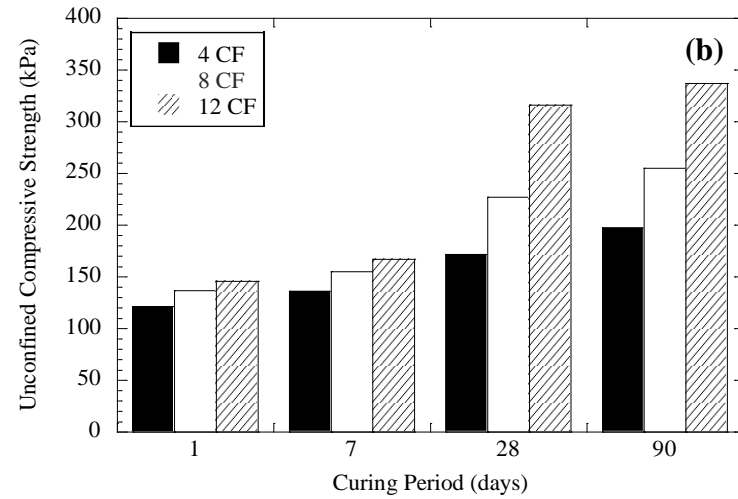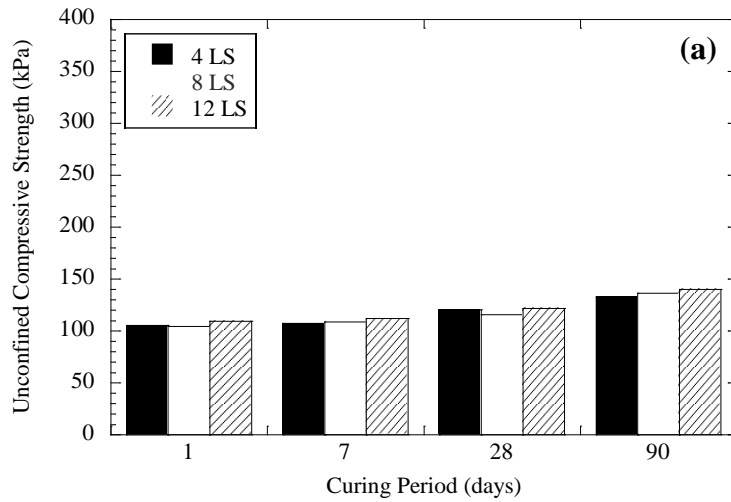
Figure 12. UCS test results of **(a)** LS **(b)** CF **(c)** FF **(d)** PC at different curing periods
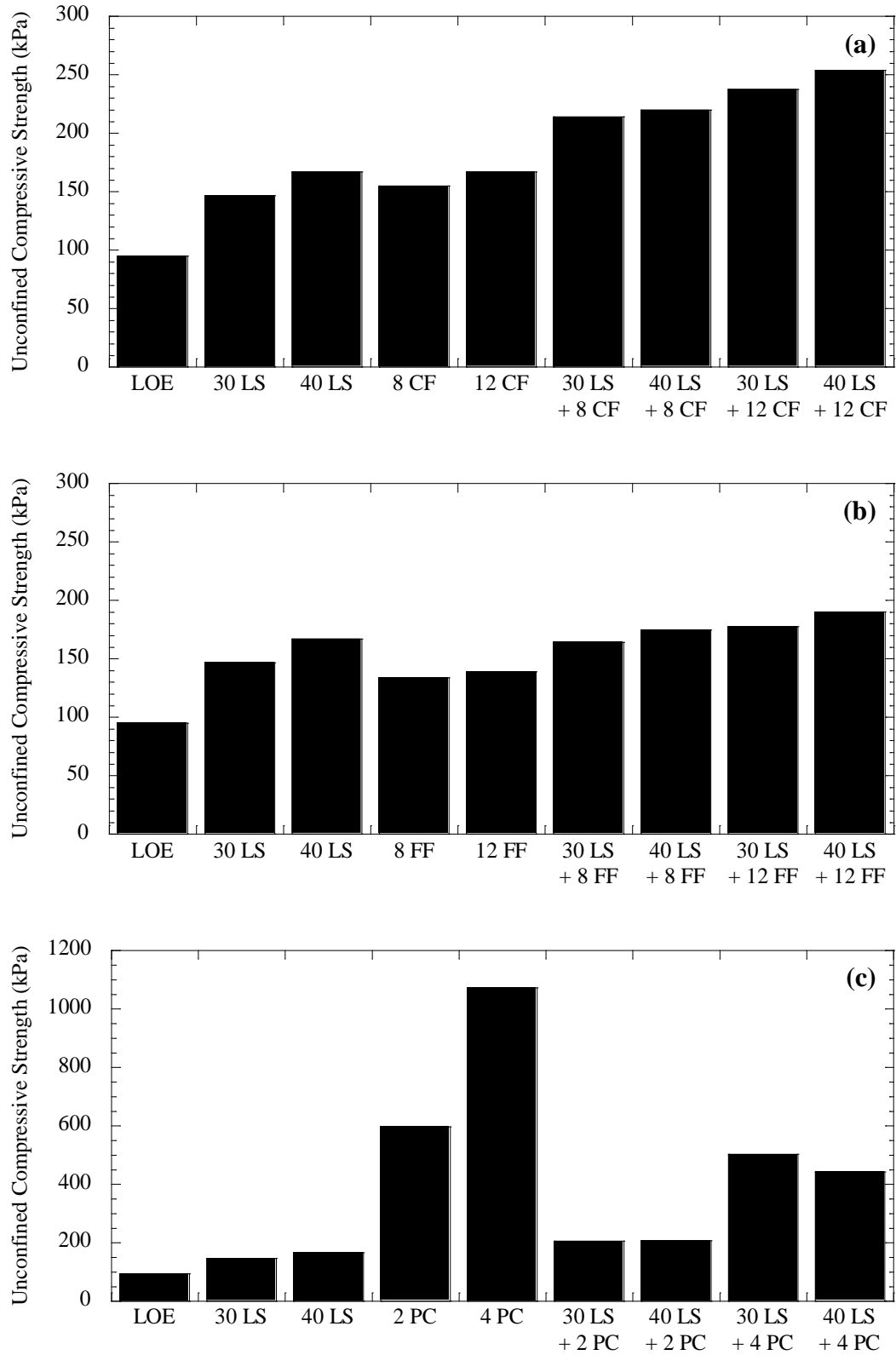
Figure 13. UCS test results of **(a)** LS + CF **(b)** LS + FF **(c)** LS + PC
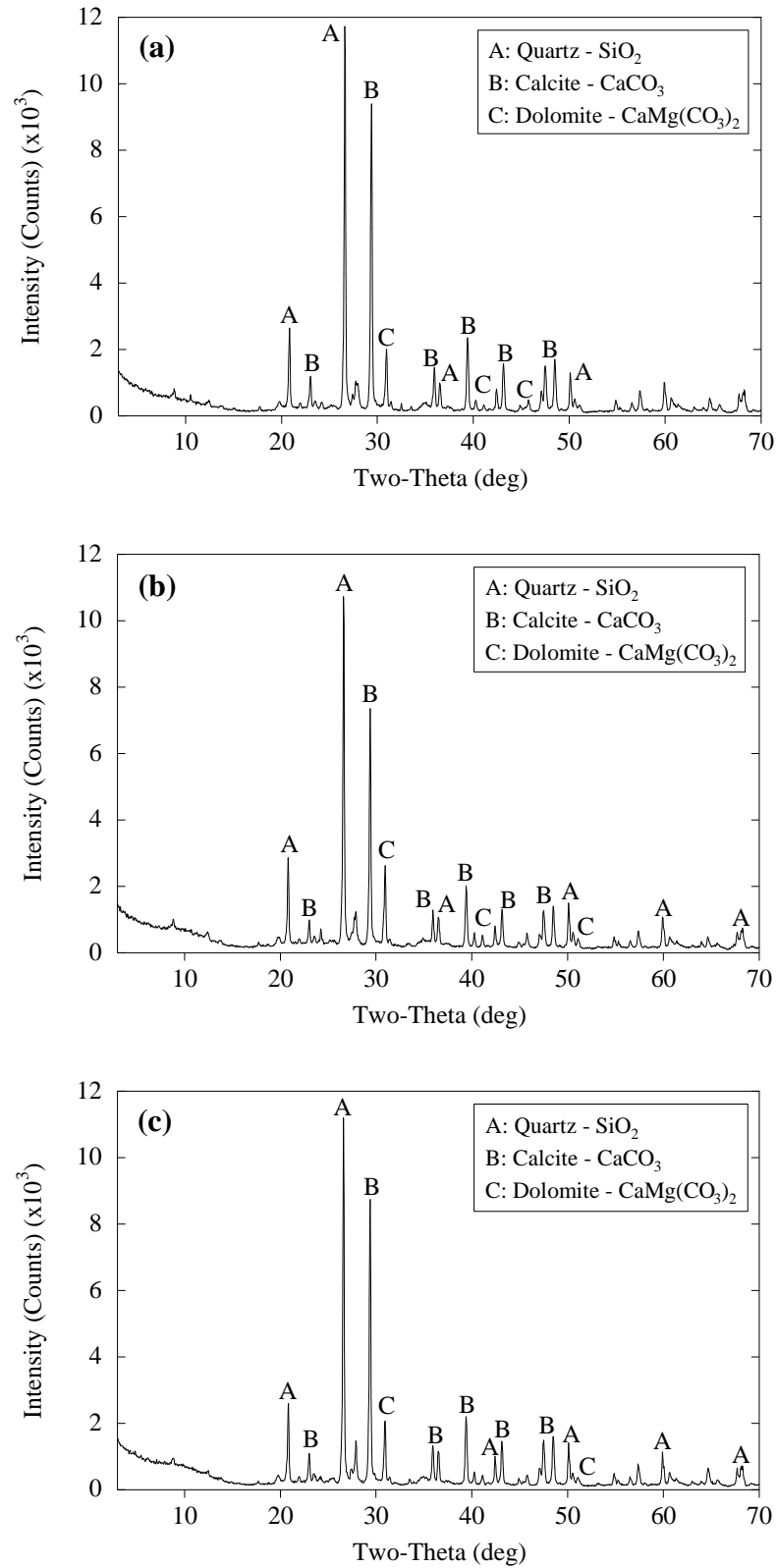
Figure 14. XRD patterns of **(a)** 40 LS **(b)** 40 LS + 12 CF **(c)** 40 LS + 4 PC
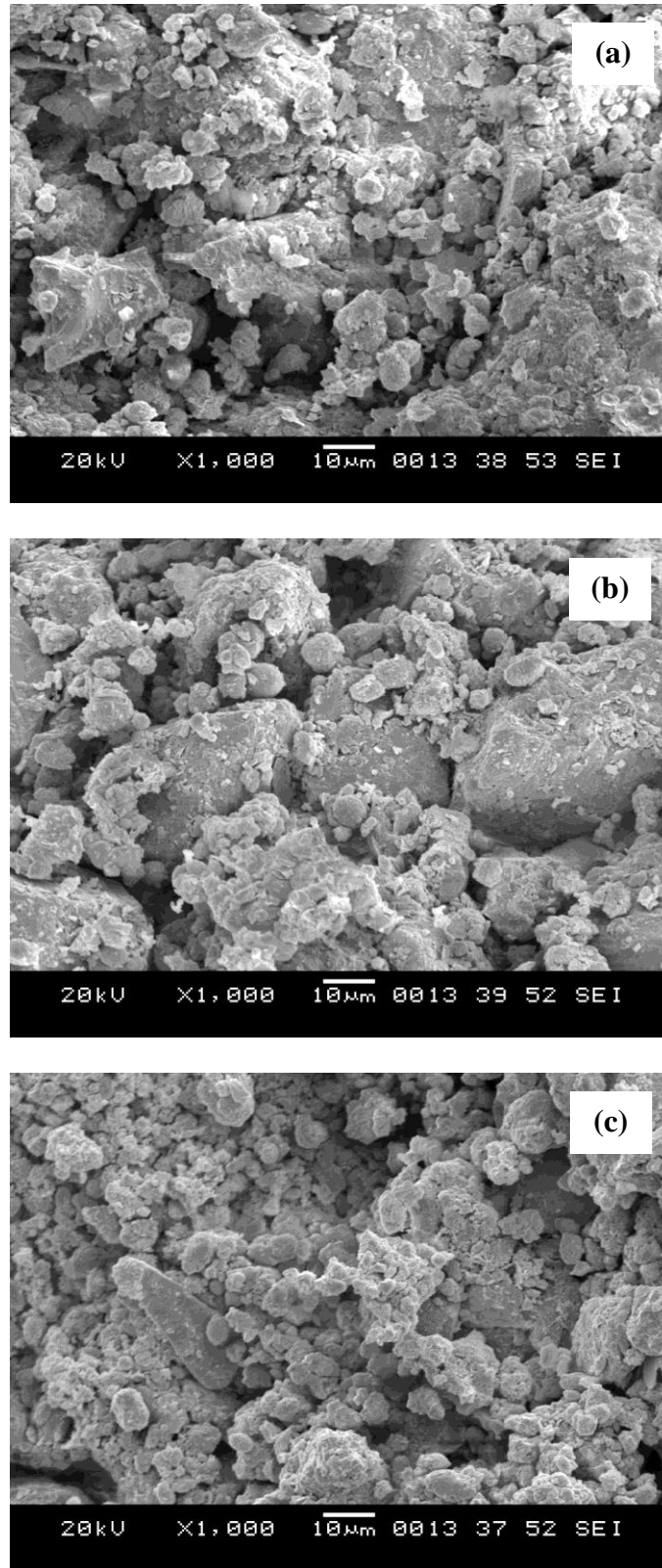
Figure 15. SEM images of **(a)** 40 LS **(b)** 40 LS + 12 CF **(c)** 40 LS + 4 PC
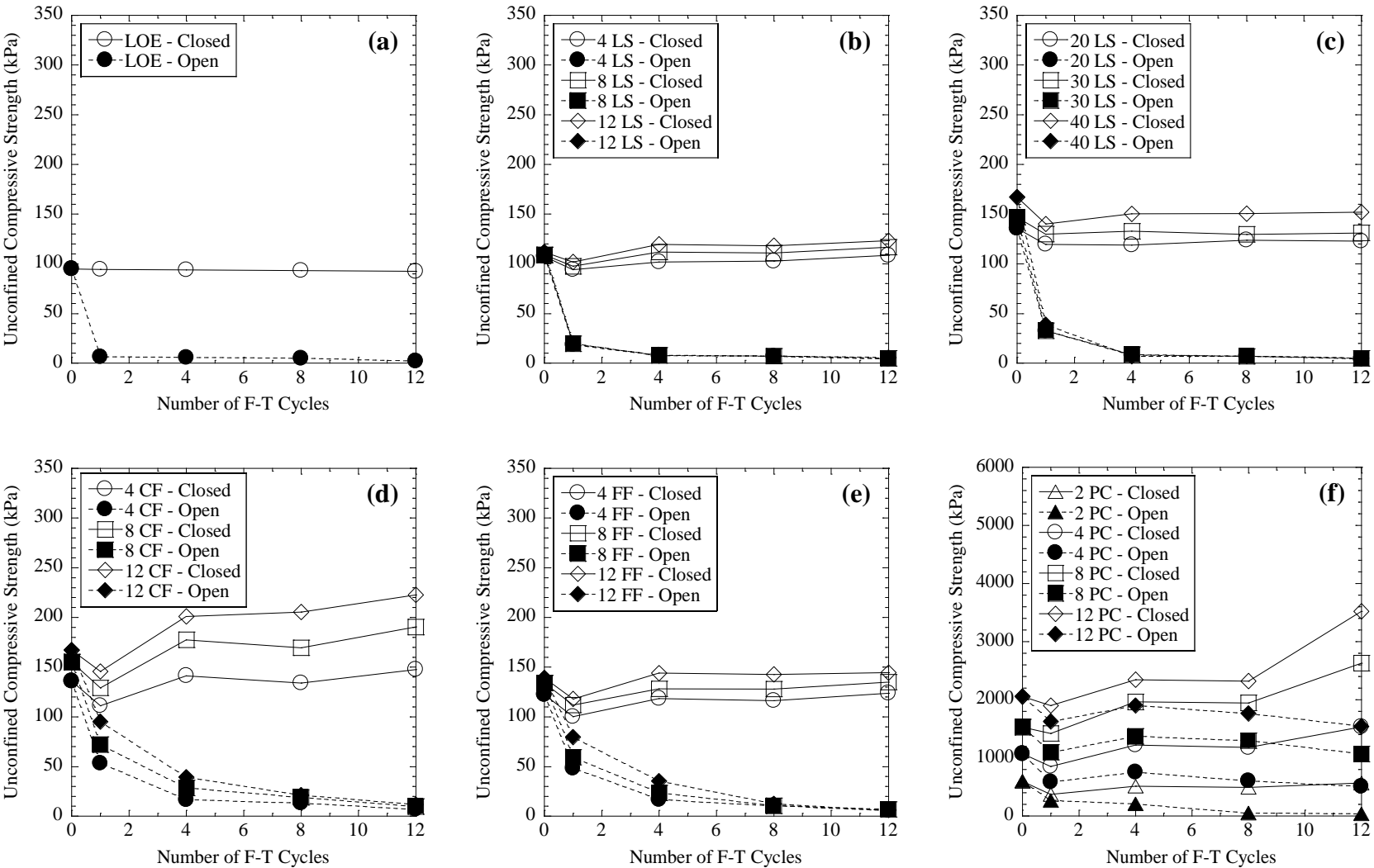
Figure 16. UCS test results of **(a)** LOE **(b-c)** LS **(d)** CF **(e)** FF **(f)** PC subjected to F-T
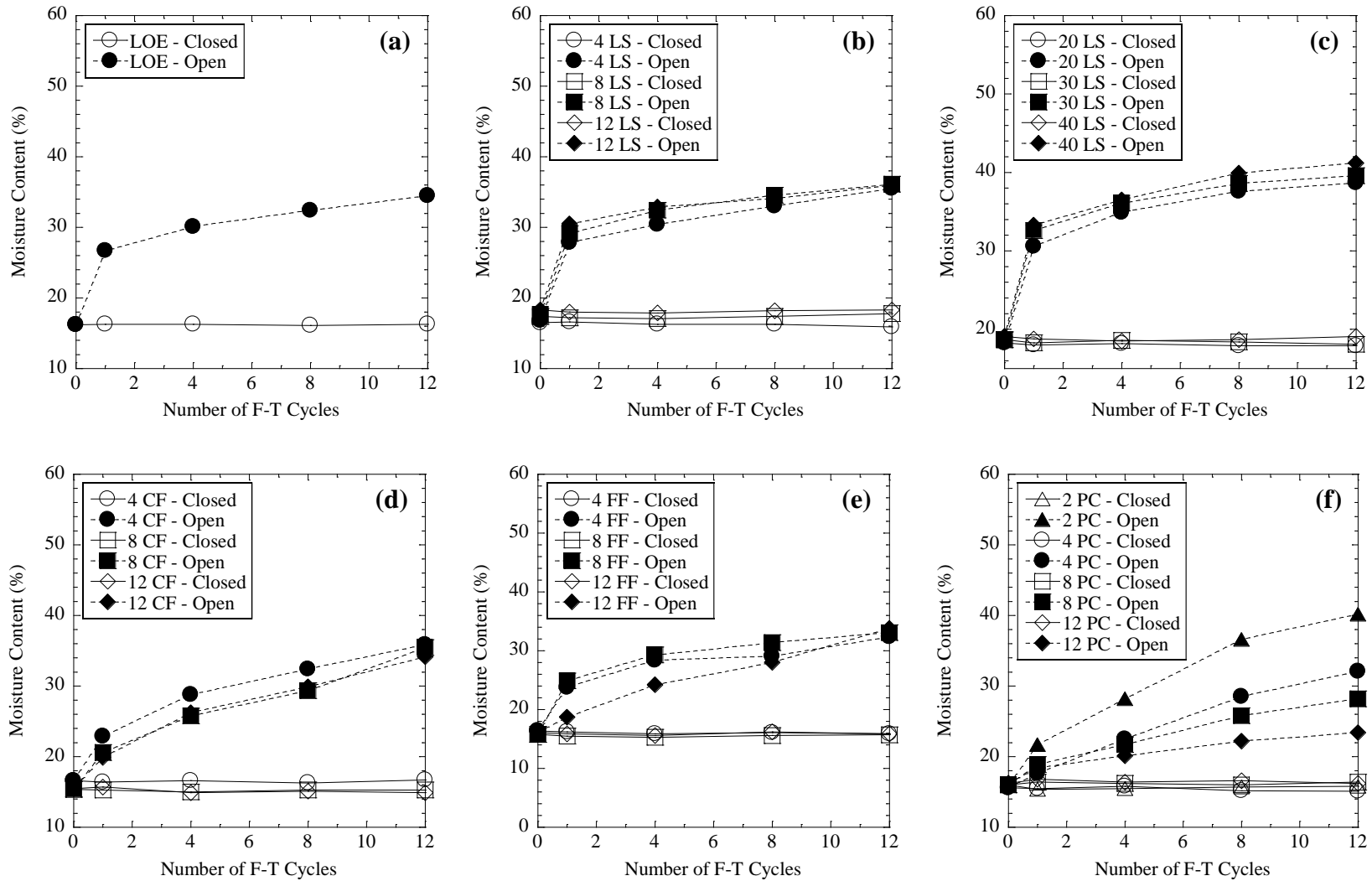
Figure 17. Moisture contents of **(a)** LOE **(b-c)** LS **(d)** CF **(e)** FF **(f)** PC subjected to F-T
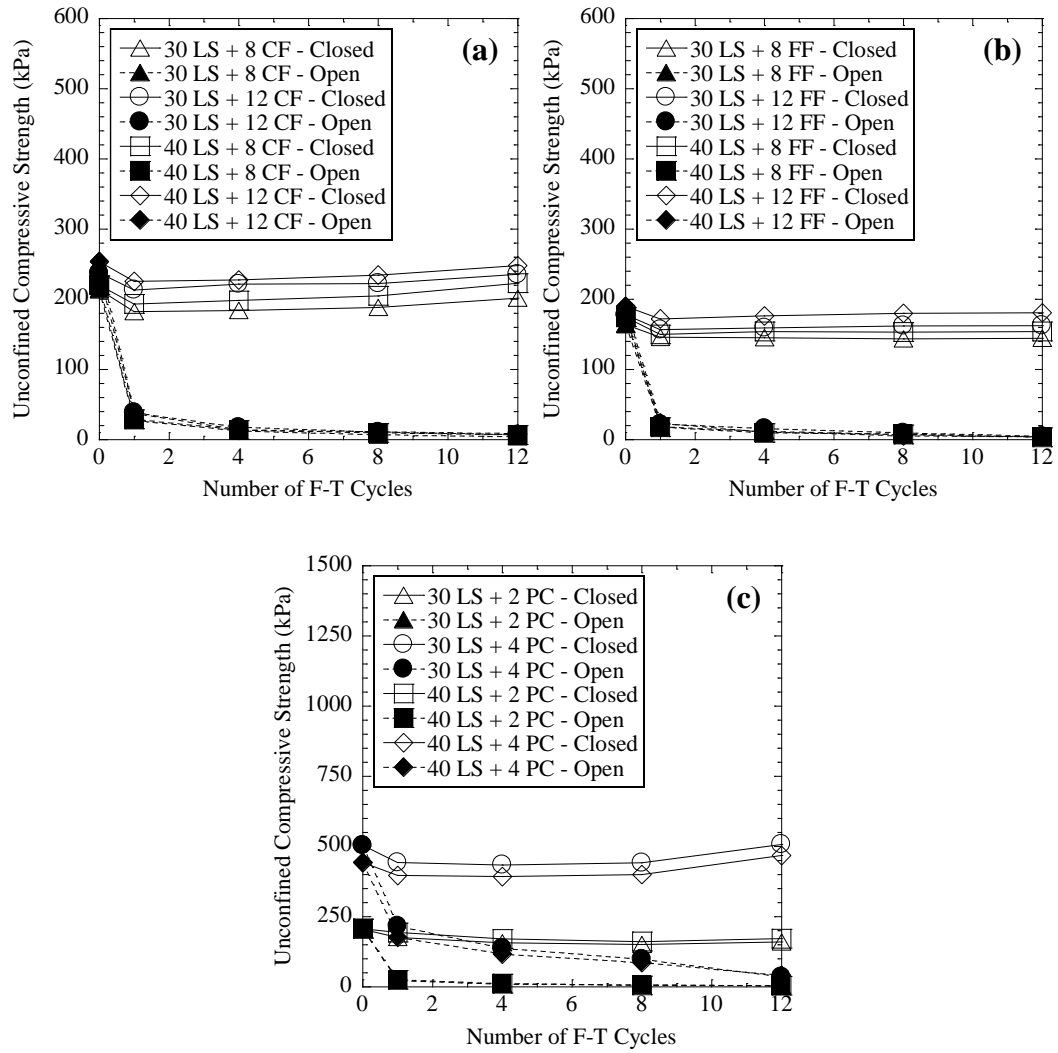
Figure 18. UCS test results of **(a)** LS + CF **(b)** LS + FF **(c)** LS + PC subjected to F-T
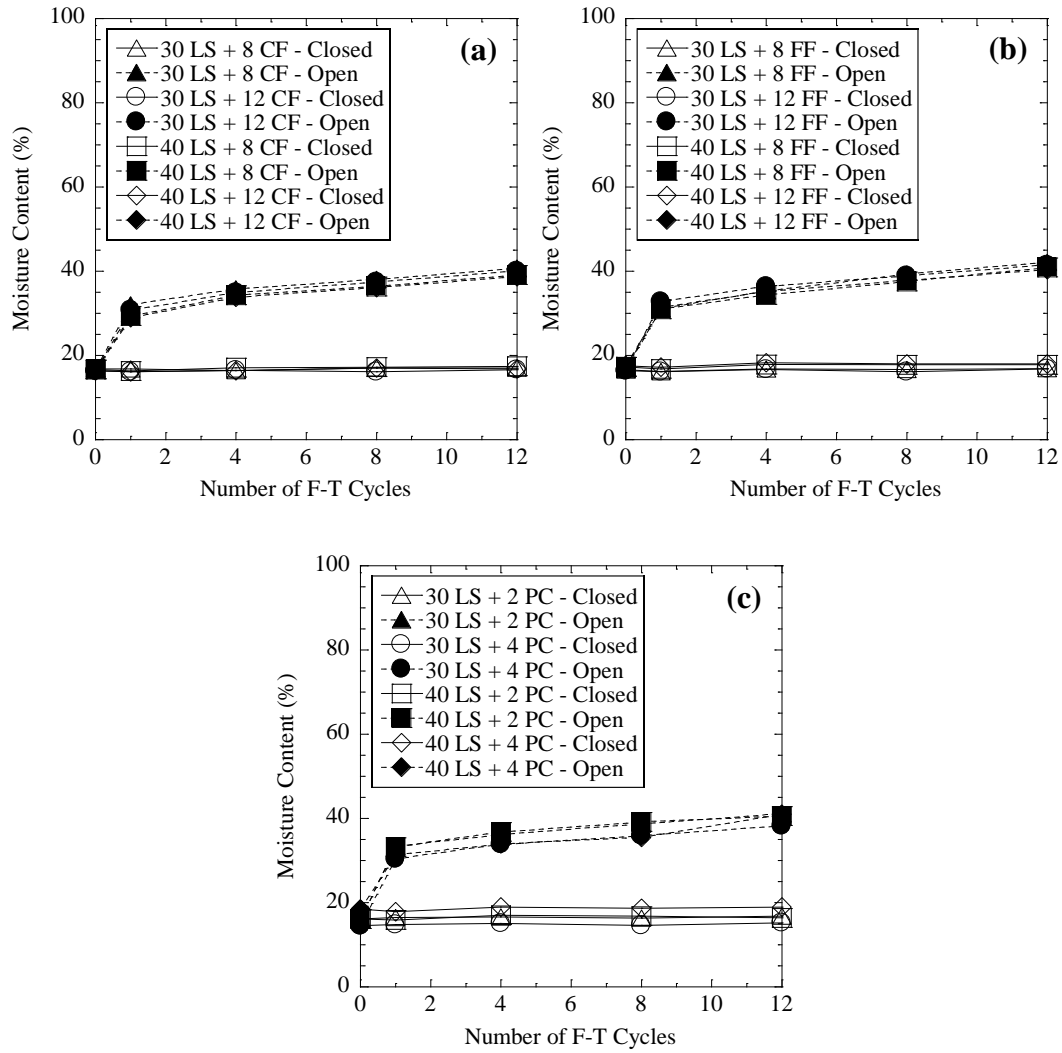
Figure 19. Moisture contents of **(a)** LS + CF **(b)** LS + FF **(c)** LS + PC subjected to F-T
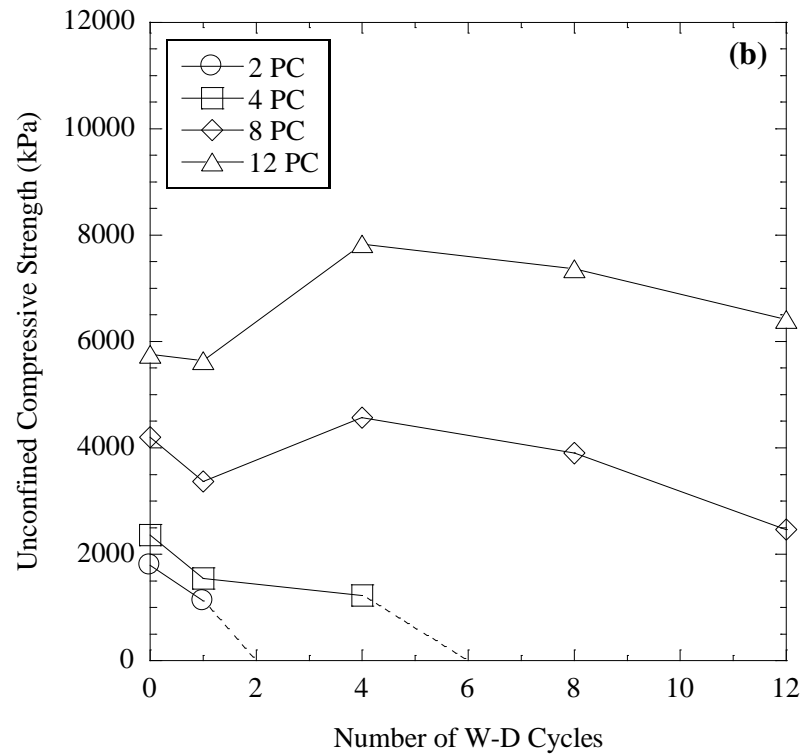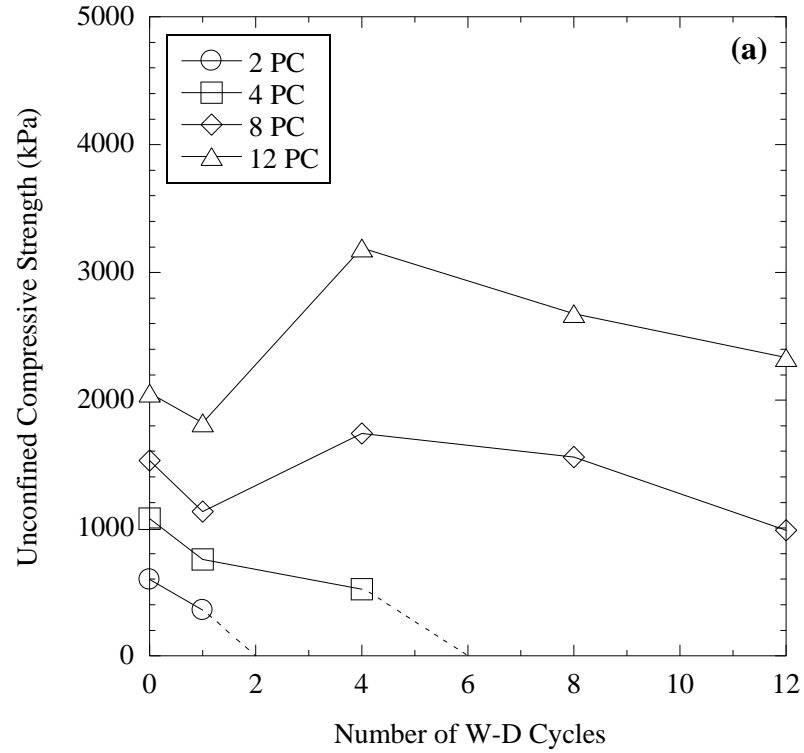
Figure 20. UCS test results of the specimens subjected to W-D **(a)** wet **(b)** dry conditions
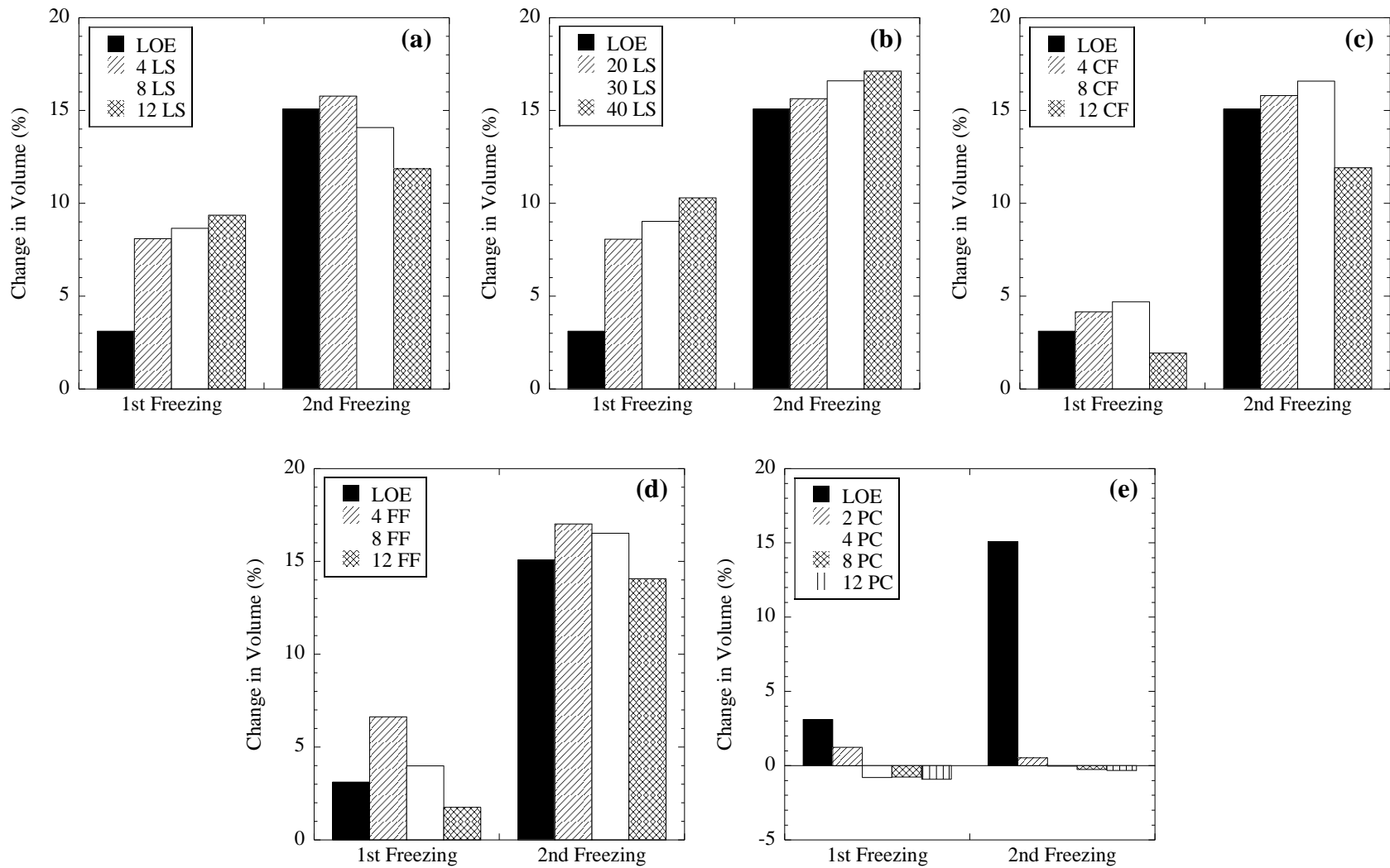
Figure 21. Swelling test results of **(a-b)** LS **(c)** CF **(d)** FF **(e)** PC
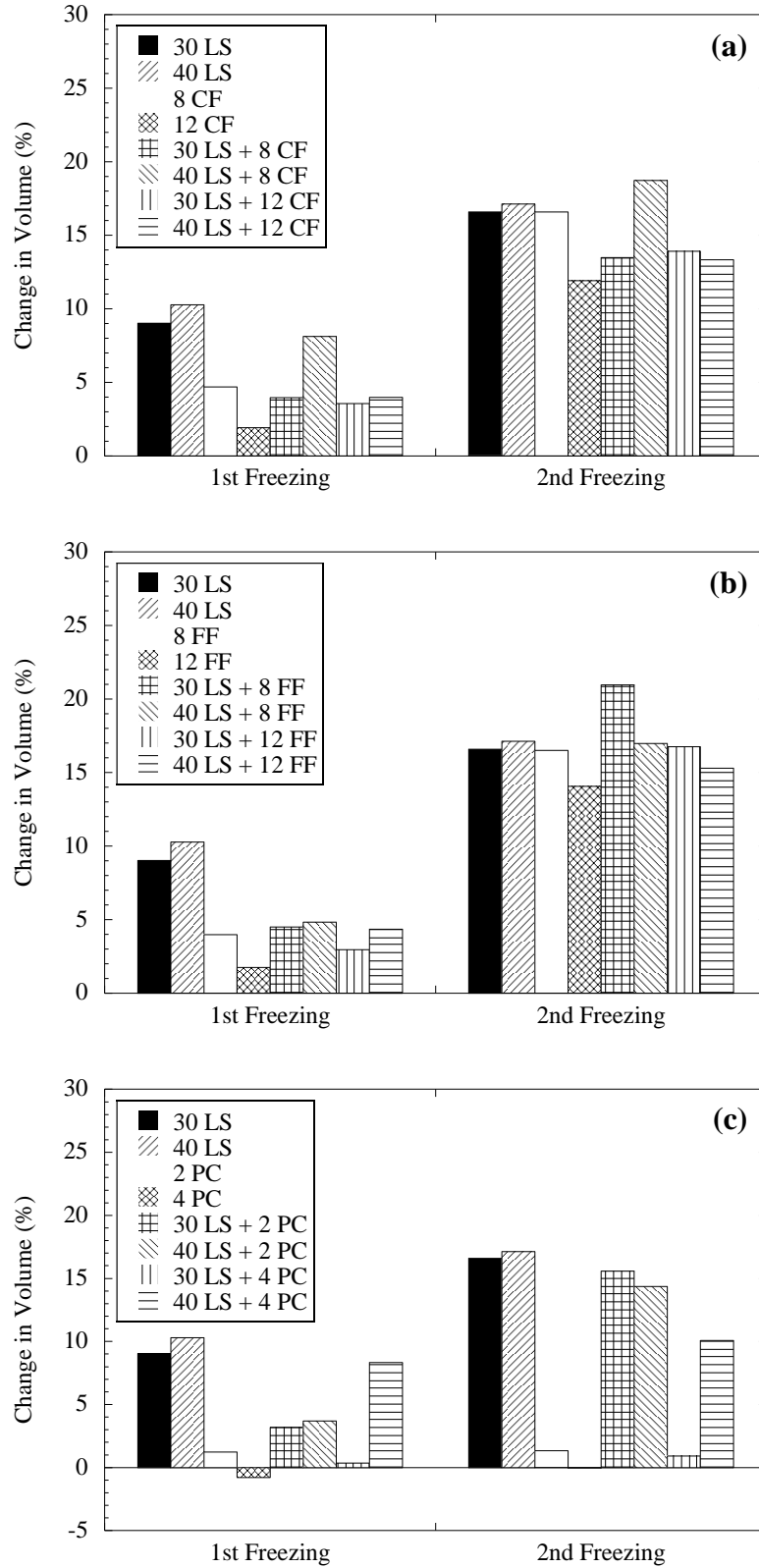
Figure 22. Swelling test results of **(a)** LS + CF **(b)** LS + FF **(c)** LS + PC
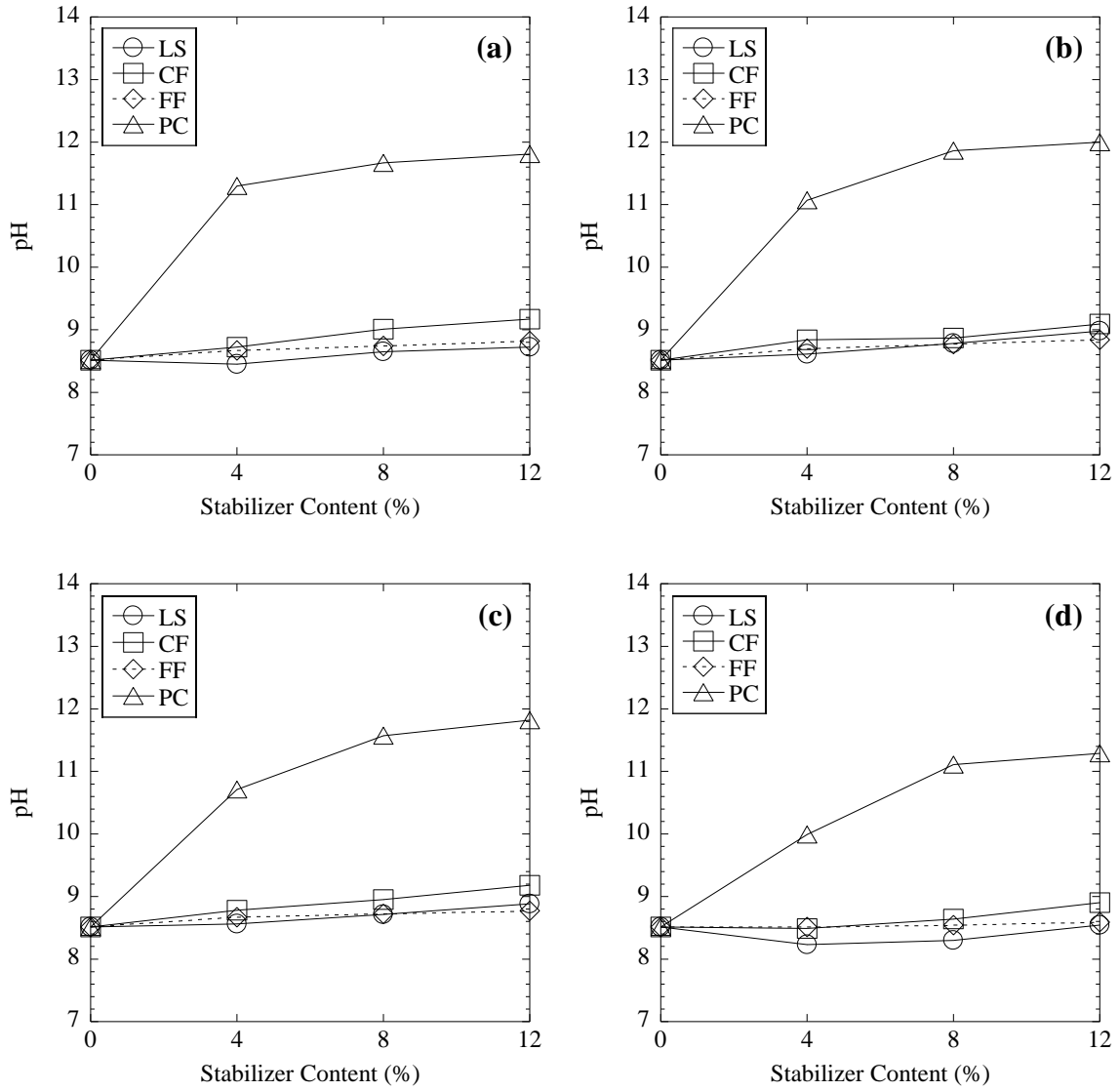
Figure 23. pH test results of **(a)** 1-day **(b)** 7-day **(c)** 28-day **(d)** 90-day cured specimens
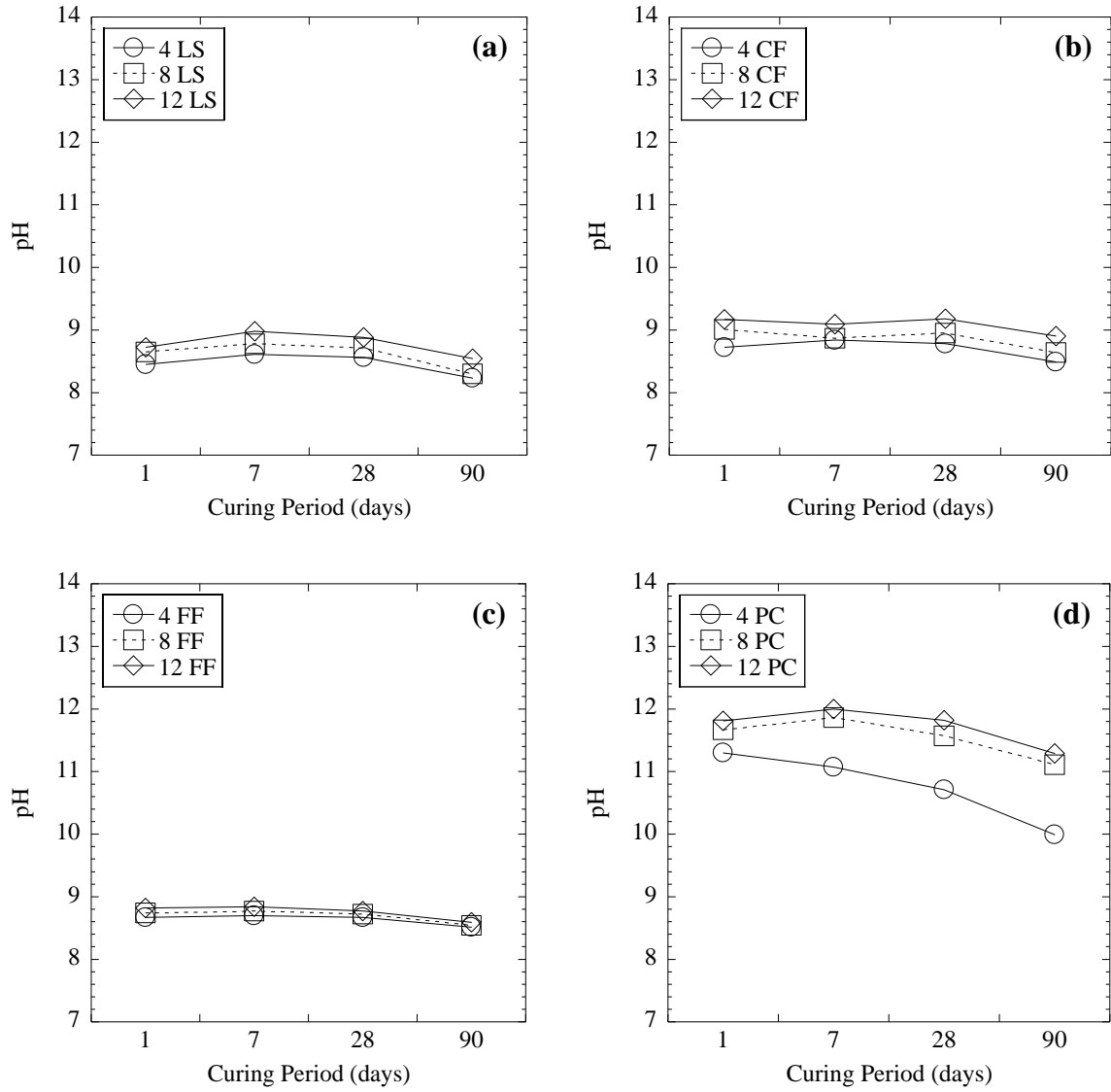
Figure 24. pH test results of **(a)** LS **(b)** CF **(c)** FF **(d)** PC
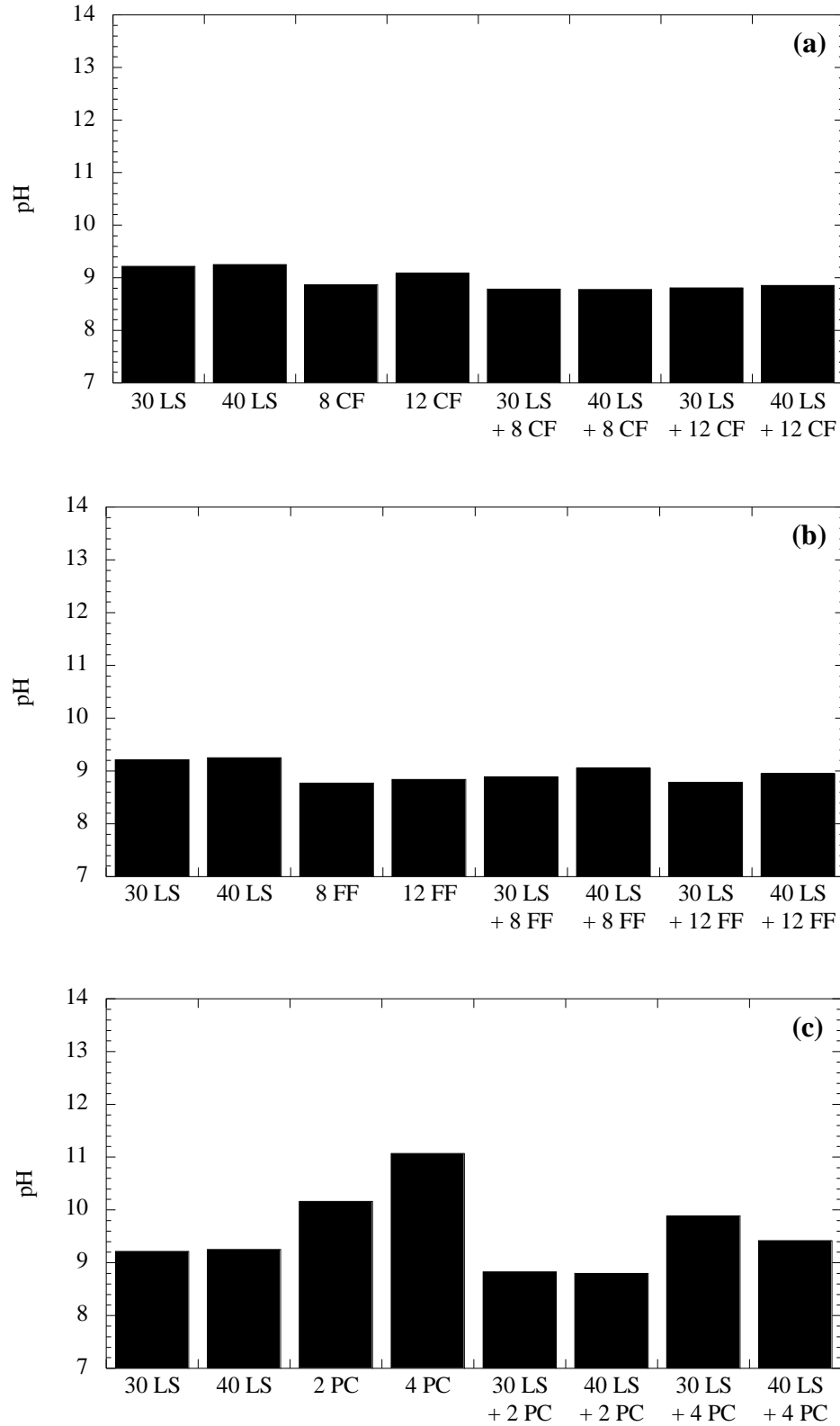
Figure 25. pH test results of **(a)** LS + CF **(b)** LS + FF **(c)** LS + PC
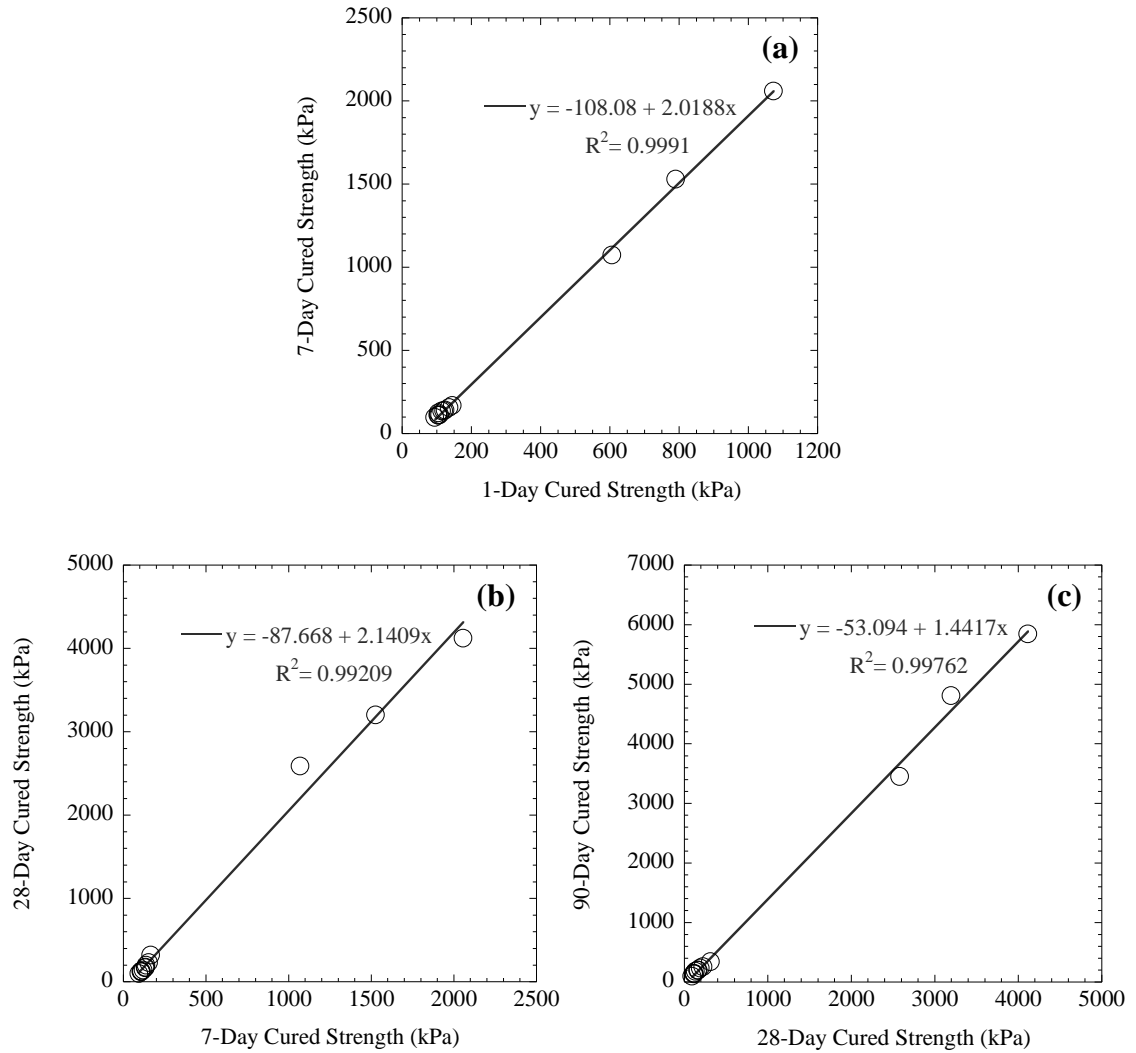
Figure 26. Correlations of UCS test results between **(a)** 1-day/7-day **(b)** 7-day/28-day **(c)** 28-day/90-day cured specimens
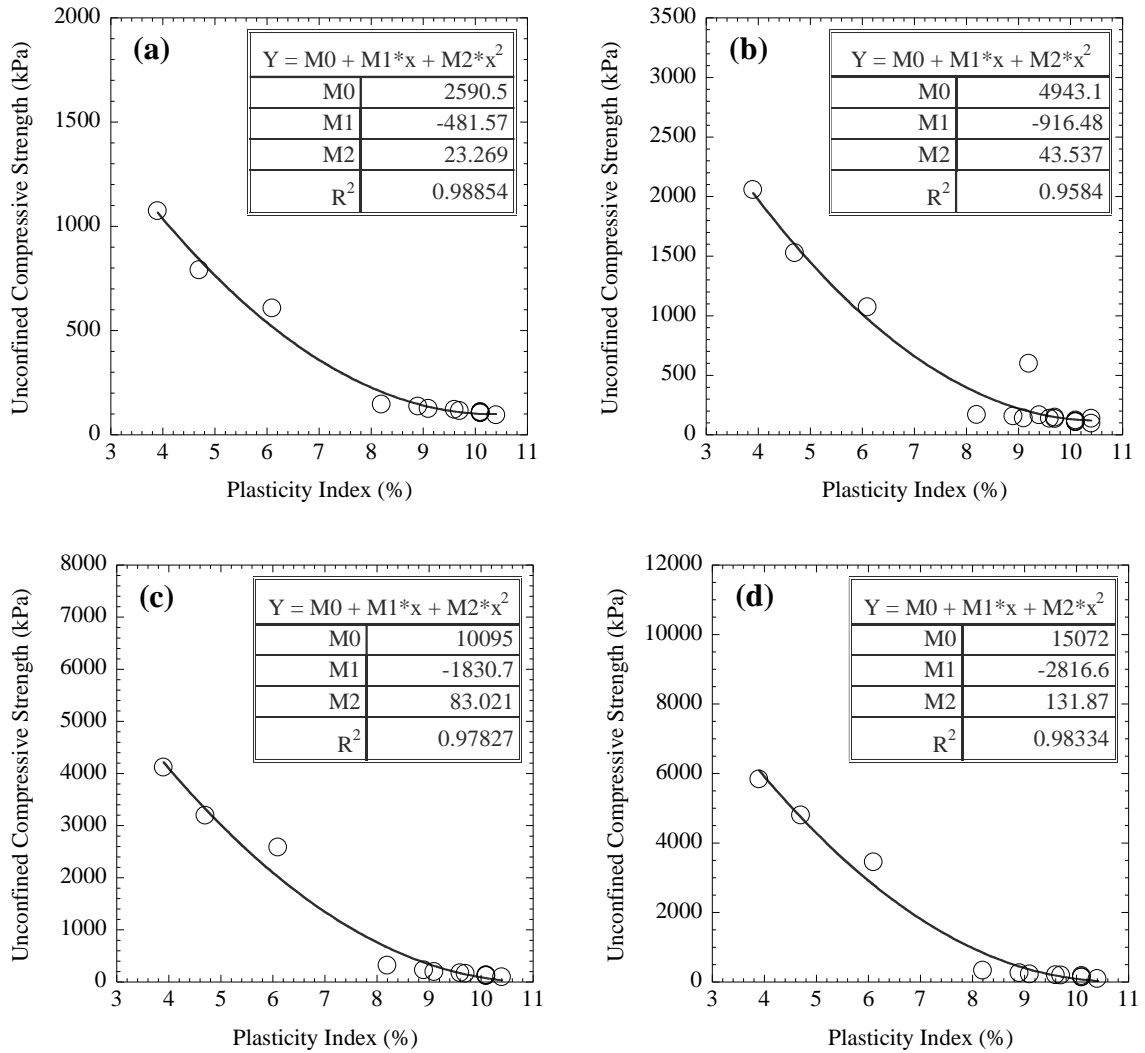
Figure 27. Correlations between UCS and PI of **(a)** 1-day **(b)** 7-day **(c)** 28-day **(d)** 90-day cured specimens
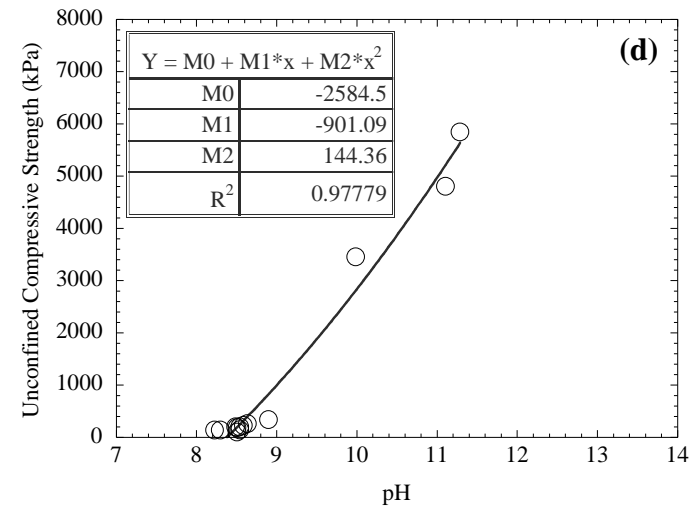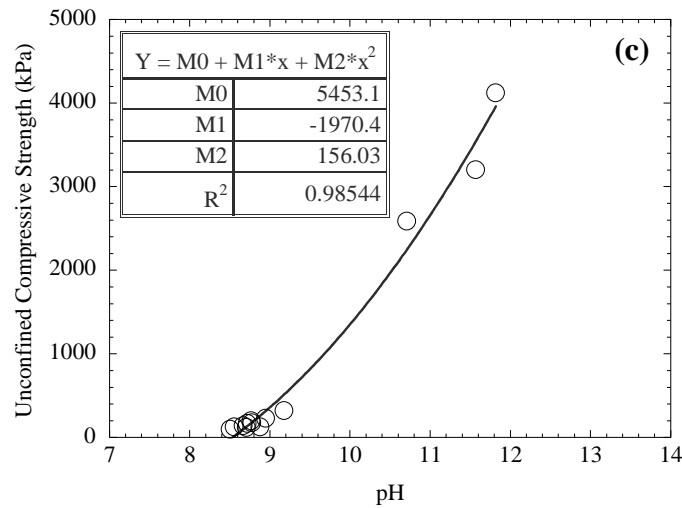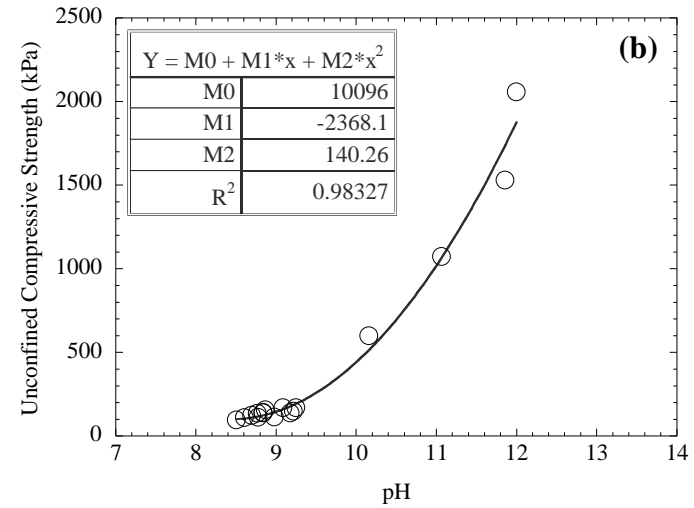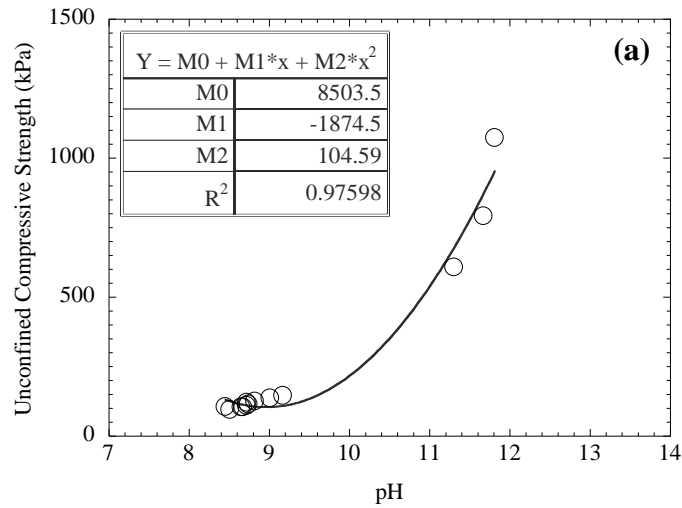
Figure 28. Correlations between UCS and pH of **(a)** 1-day **(b)** 7-day **(c)** 28-day **(d)** 90-day cured specimens
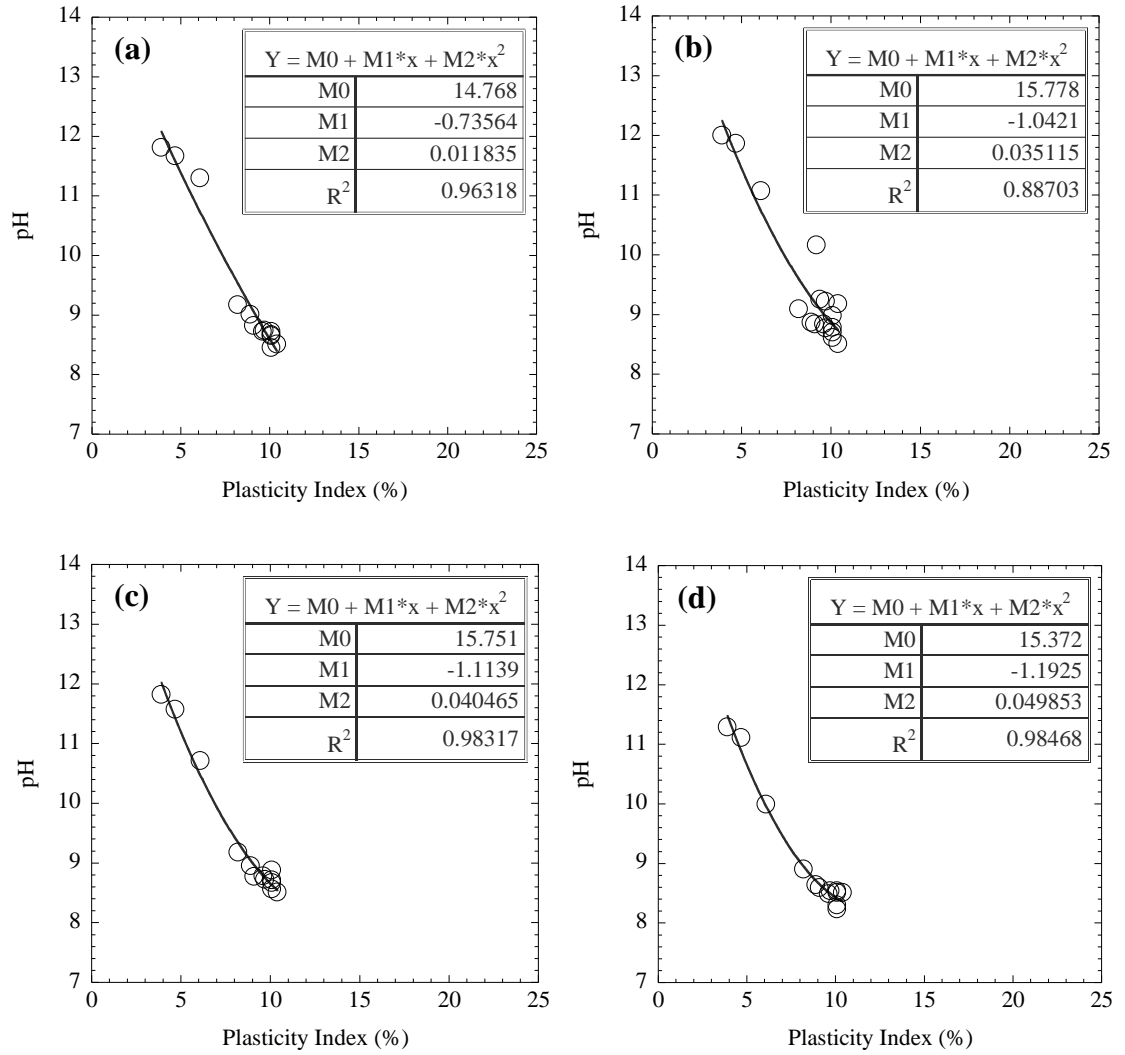
Figure 29. Correlations between PI and pH of **(a)** 1-day **(b)** 7-day **(c)** 28-day **(d)** 90-day cured specimen

APPENDIX A. SELECTION OF THE STABILIZERS
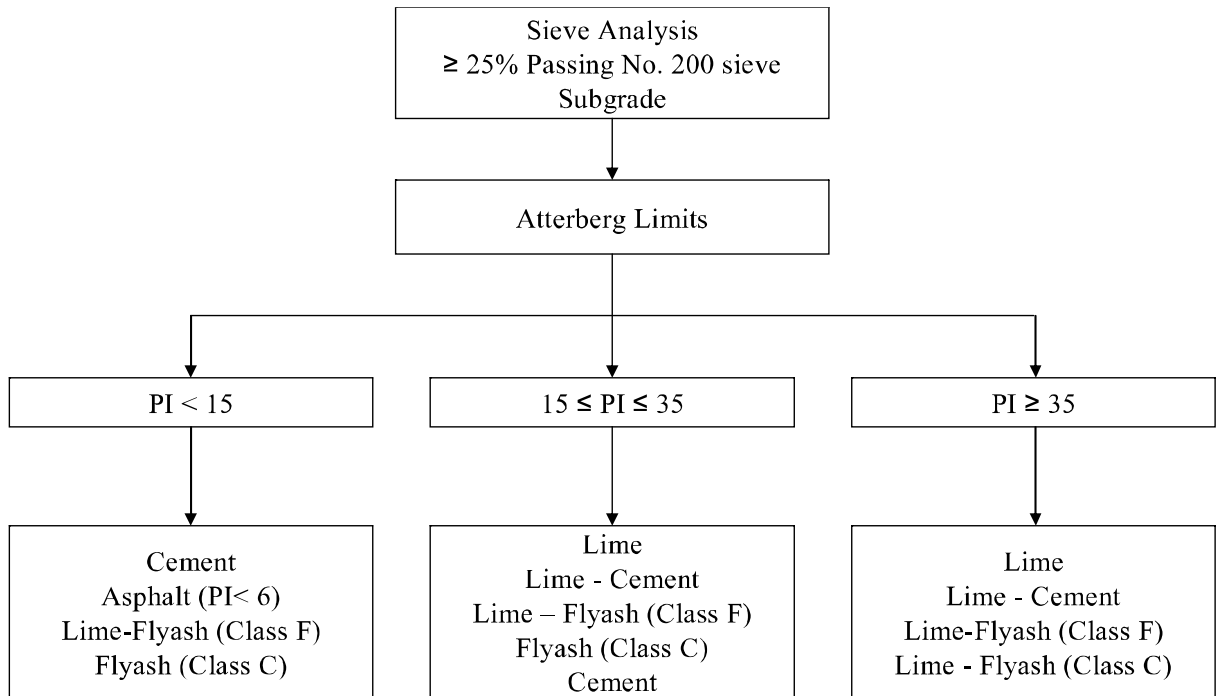
Figure A: Summary of SSIS for the selection of the most suitable stabilizers for subgrade
(Epps et al. 1971; Texas Department of Transportation 2005)

Table A: Recommended amounts of Portland cement for different soil types (Portland
Cement Association 1992)

AASHTO Soil Group	Usual Range in Cement Requirement		Estimated Cement Content, Percent by Weight
	Percent by Volume	Percent by Weight	
A-1-a	5-7	3-5	5
A-1-b	7-9	5-8	6
A-2	7-10	5-9	7
A-3	8-12	7-11	9
A-4	8-12	7-12	10
A-5	8-12	8-13	10
A-6	10-14	9-15	12
A-7	10-14	10-16	13

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APPENDIX B. XRD PATTERN AND SEM IMAGE OF LOESS

A: Quartz - SiO_2
B: Calcite - $CaCO_3$
C: Dolomite - $CaMg(CO_3)_2$
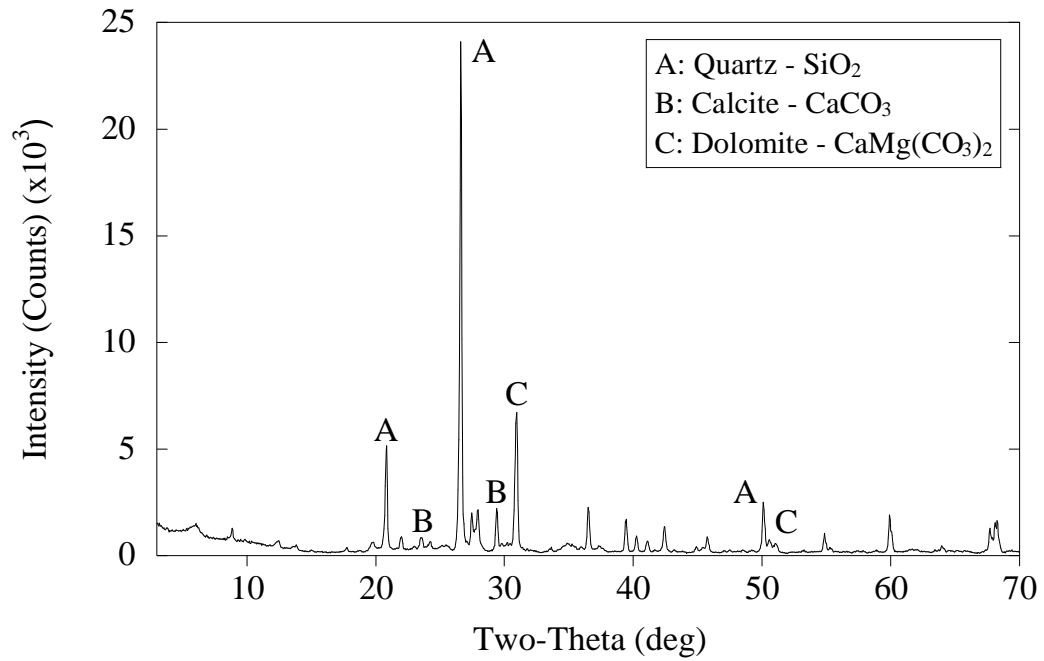
Figure B1. XRD pattern of loess

Figure B2. SEM image of loess

APPENDIX C. TEST EQUIPMENT
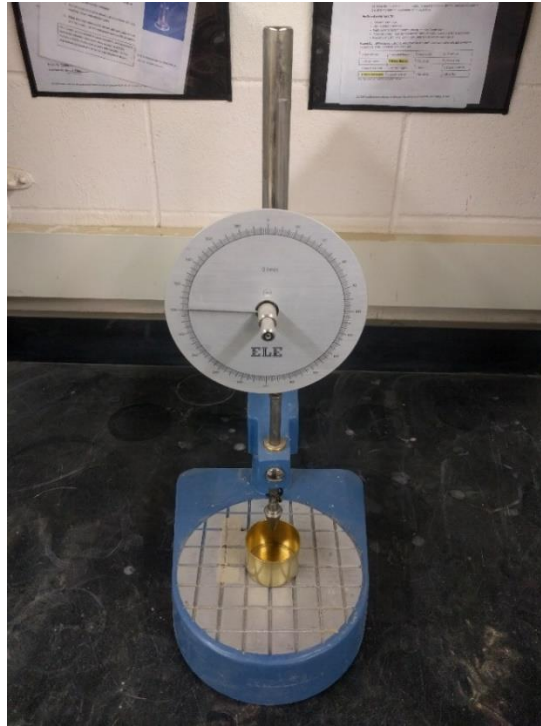
Figure C1. Fall cone penetrometer

Figure C2. Humboldt H-4262 plastic limit device

Figure C3. Automatic Proctor device

Figure C4. GeoTAC Sigma-1 Automated Load Test System

APPENDIX D. CLOSED AND OPEN F-T TESTS

Figure D1. Freezing period of sealed specimens - closed

Figure D2. Unwrapped samples on saturated felt pad - open

Figure D3. Capillary action - open

APPENDIX E. WETTING AND DRYING OF W-D TEST

Figure E1. Wetting period of W-D test

Figure E2. Drying period of W-D test

APPENDIX F. PH ANALYSIS
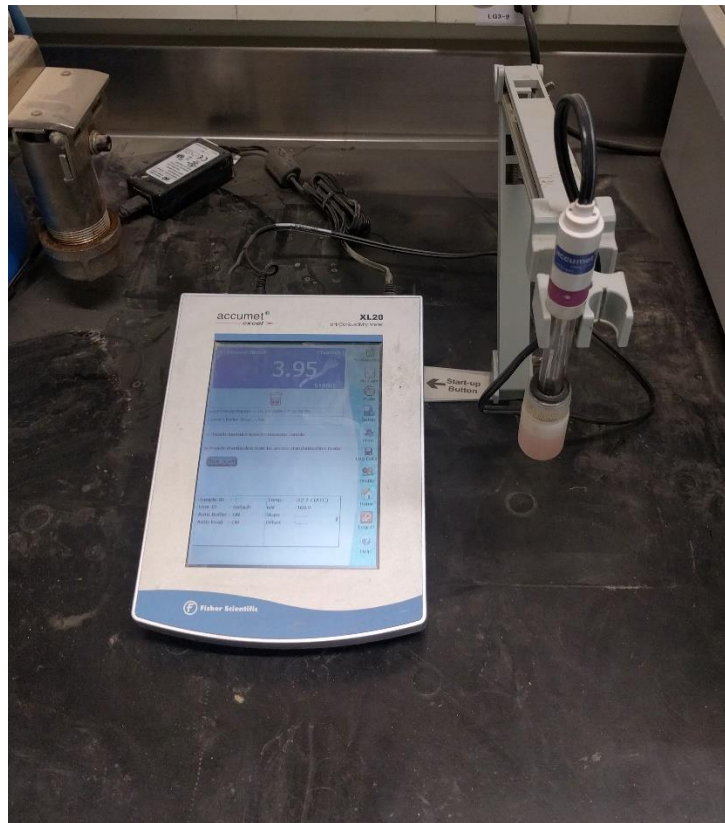
Figure F1. Accumet XL20 pH meter
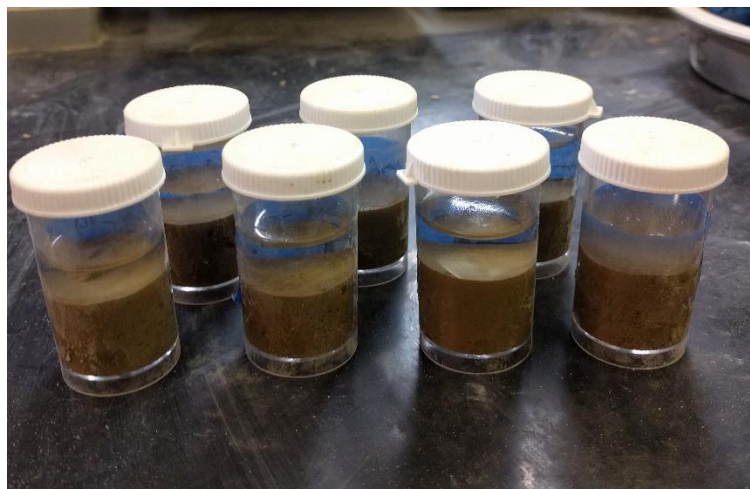
Figure F2. pH test specimens

APPENDIX G. XRD AND SEM EQUIPMENT

Figure G1. Siemens D 500 diffractometer
(Taken from: http://www.marl.iastate.edu/images/samplepreppage/Overview%20of%20 diffractometer%20cabinet.JPG)

Figure G2. Edwards Scancoat Six benchtop sputter coater
(Taken from: http://www.ifr83.idf.inserm.fr/modules/resources/download/ifr83/ upmc/microscopieelectronique /MEB/sputt.jpg)
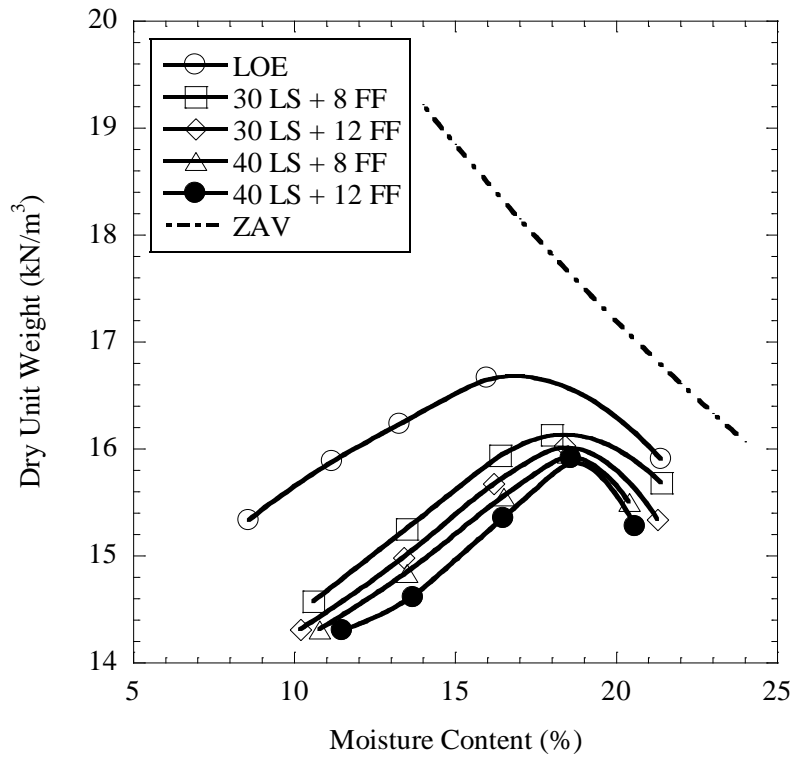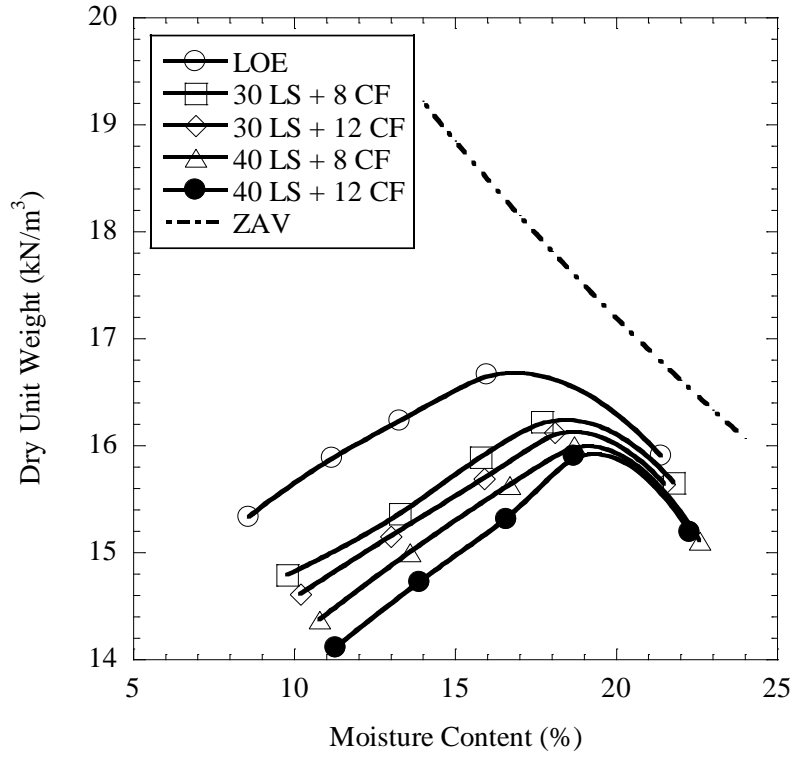
Figure G3. JEOL JSM-6060
(Taken from: http://www.jeolusa.com/Portals/2/prodshots/EO/JSM-IT100x325.jpg)
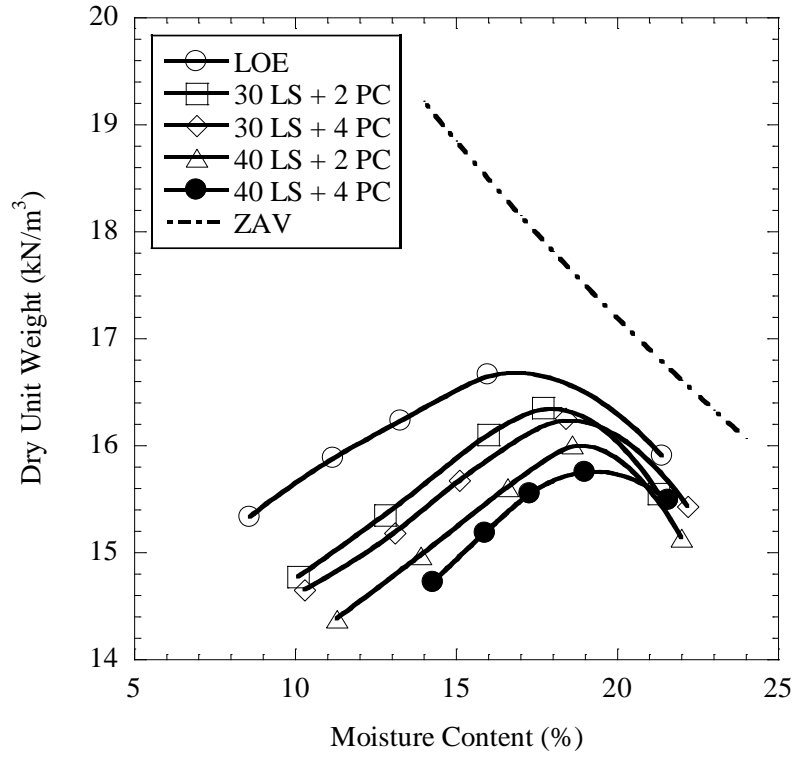
APPENDIX H. STANDARD PROCTOR TEST RESULTS
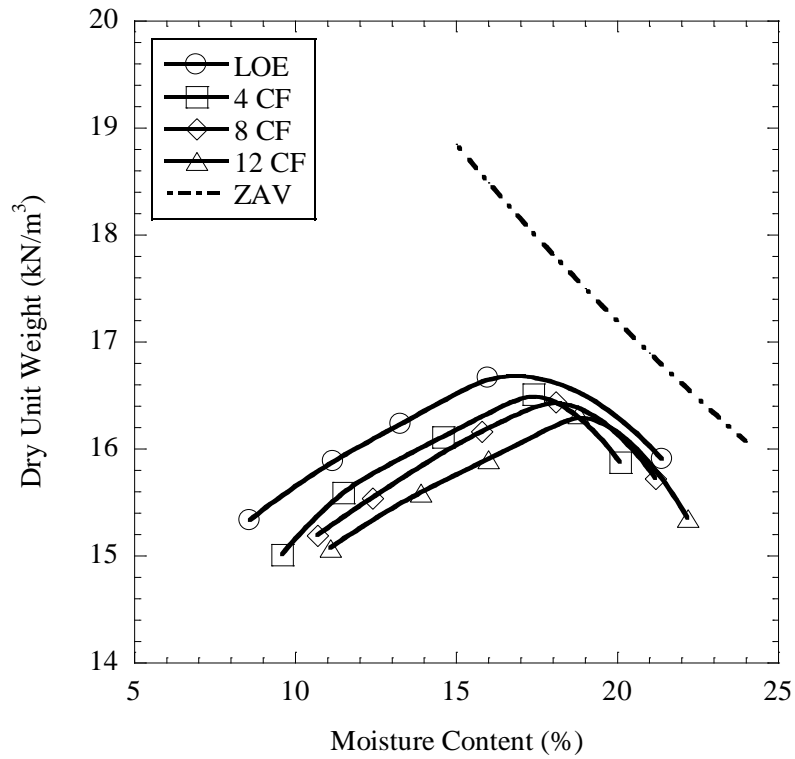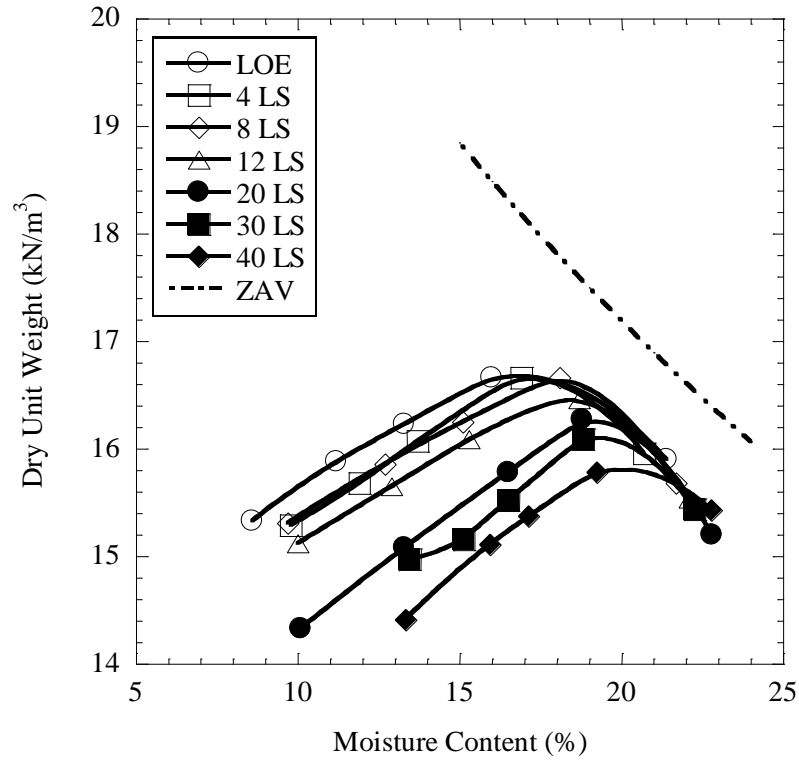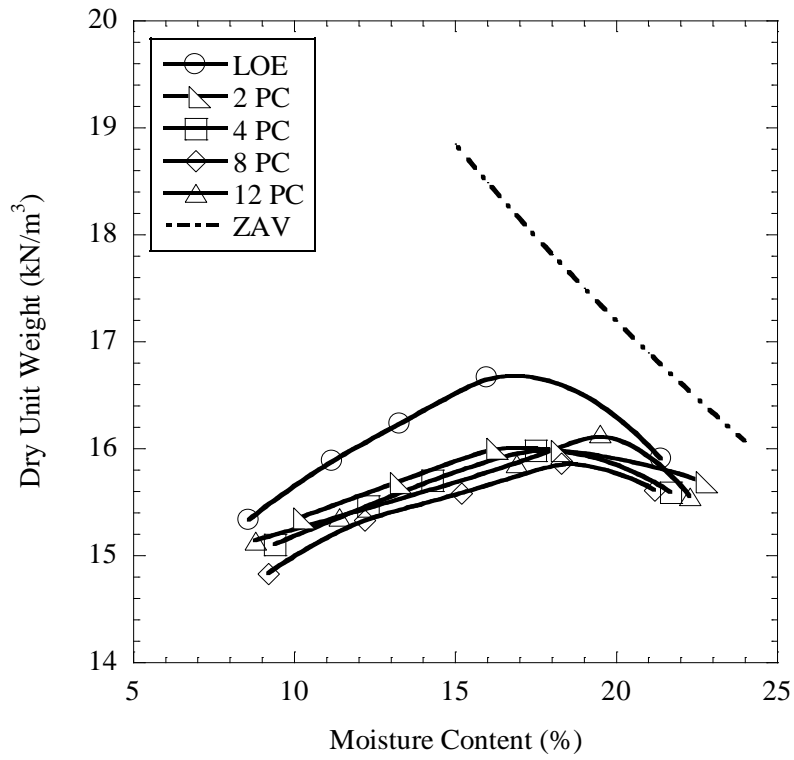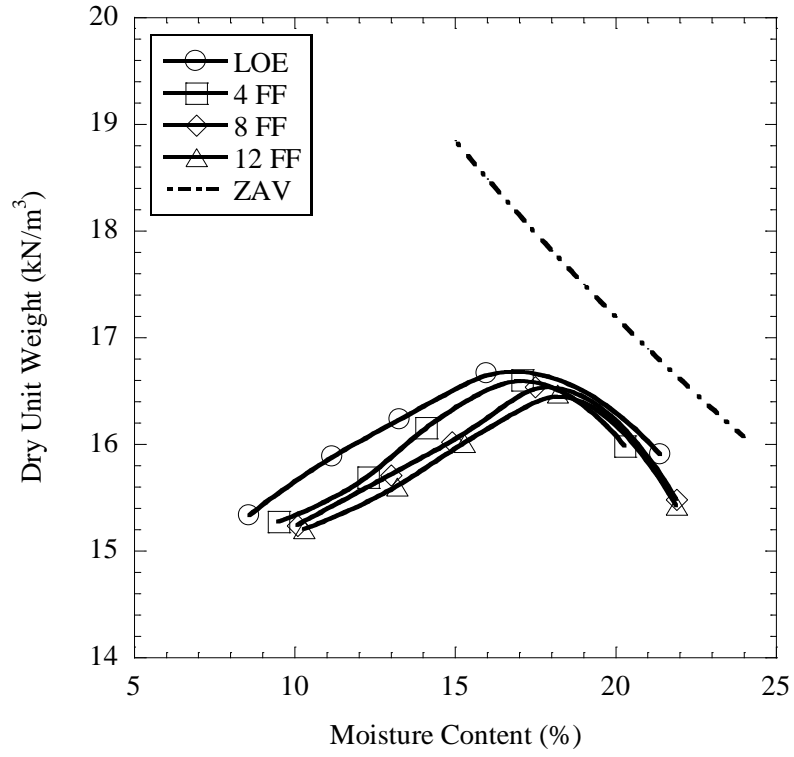
Figure H1. Compaction curves of the specimens