Article

Influence of Submergence on Stabilization of Loess in Shaanxi Province by Adding Fly Ash

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Abstract: In this study, the influence of fly ash (FA) content (0%, 10%, 20%, and 30%) on the alteration in the physical and mechanical parameters of loess is investigated. The influences of curing time (0, 14, and 28 days) and submergence and non-submergence conditions are analyzed as well. Analysis considers the variation in Atterberg limits (liquid limit, plastic limit, and plasticity index), compaction parameters (optimum moisture content (OMC), and maximum dry density (MDD)), unconfined compressive strength (UCS) stress, UCS strain, California bearing ratio (CBR) value, and swell potential. Results show that the application of FA-stabilized loess (FASL) is effective. Specifically, the MDD decreases and the OMC increases, the UCS stress increases and the UCS strain decreases, the CBR value improves and the swell potential declines, but Atterberg limits are insignificantly changed by the increase in the FA ratio compared with those of untreated loess. The UCS stress and CBR value are improved with the increase in curing time, whereas the UCS strain is negligible. FASL under submergence condition plays an important role in improving the effect of FA on the UCS stress and CBR value compared with that under non-submergence condition. The UCS stress and CBR value are more increased and more decreased than the UCS strain in submerged samples. Therefore, the application of FASL in flood areas is important for obtaining sustainable construction materials and ensuring environmental protection.

Keywords: loess; fly ash; stabilization; California bearing ratio (CBR); unconfined compressive strength (UCS); submergence; non-submergence

1. Introduction

Loess is an eolian precipitate formed by the aggregation of silt, wind-blown clay, and fine sand; it is broken from a larger rock or unit rock, has been deposited by the wind, and is generally found in arid and semi-arid regions [1–4]. Silt is the paramount grain size portion of loess, which constitutes 50%–70% by weight, whereas sand particles larger than 1 mm constitute less than 5%, and clay particles constitute only a few percent [5]. Loess is characterized by an open structure, in which the primary quartz particles are connected with one another by bonding, thereby resulting in high porosity, low density, and low water content [6–9]. The bonds will easily be broken down after loading and wetting [10]. Then, the loess can change in degree of saturation, which results in failure of the soil structure; this condition causes geological and geotechnical hazards, such as abrupt collapse, ground subsidence, landslides, surface cracks, and differential settlement [11,12]. Approximately 10% of loess areas cover the Earth, and they are found in continental dry lands of Asia, Africa, Europe, and South America [13,14]. In China, loess area covers nearly 4.4% of China's land area and approximately 631,000 km^2 of the

total area, and it is mainly distributed in the provinces of Shanxi, Shaanxi, and Gansu located in the central part of the Yellow River basin [4,15,16]. One-third of the geohazards occur in the Loess Plateau of China, whereas around 15,000 geohazards occur in the Loess Plateau of Shaanxi Province with an average density of over 6 per km^2 [17]. Geohazards result in damage of infrastructure and urban construction, such as step-down in farmlands [18,19]. Accordingly, the treatment of the geohazard loess and improvements in its performance by the increase in compaction degree should be the focus of research on the Chinese loess area.

Geohazard loess can be also stabilized or reinforced by chemical stabilization and mixing various additives, such as lime, cement, and fly ash (FA) or any mixture of these additives. Many studies have been conducted by engineers and scientists in science and laboratory tests in China [20], New Zealand [21–24], USA [25], Thailand [26], Bulgaria [27], and the Czech Republic [28]. However, most previous works have focused on loess stabilization, whereas the cost and the environmental pollution have not been paid attention yet. Lime or cement has been widely used in the stabilization of loess [27–30] in spite of consuming a large quantity of energy, emitting the greenhouse gas CO_2, their negative environmental effects during manufacture, and their cost [31,32]. Therefore, the recycling of FA is becoming more important than before with the proposal of strict environmental regulations in North and East China [33]. Lim et al. (2012) studied the decrease in CO_2 discharge from normal and saline soils and obtained improved results by the addition of coal FA [34]. FA has usually been used as a soil additive agent with low cost and long-term exploitable resource to alleviate the problem of solid waste worldwide. Massive amounts of FA of approximately 500 million tons are collected every year from coal-fired power plants in China, which accounts for nearly 60% of the total power supply [35]. The particles of FA are generally in the form of spheres of silicon, aluminum, and iron oxides, and the size ranges from 0.01 μm to 100 μm [36]. FA is usually used in the fields of building materials, road engineering, backfill engineering, agriculture application, and mineral extraction [37]. However, nearly 70% of FA is estimated to be used in China [38]. Thus, more than 150 million tons of FA are dumped every year, thereby resulting in rapid filling in landfills located in coal-concentrated provinces, such as Shaanxi, Inner Mongolia, and Shanxi [39–42]. In the future, power demand will keep increasing in China; specifically, the total amount of FA is expected to accumulate to approximately 3 Gt by 2020 [43]. The vast volumes of solid waste will take up large areas of landfill; this condition will destroy ecological environments, pollute water, soil, and the atmosphere, and even cause geological disasters [44,45]. Thus, the reclamation of FA as sustainable waste is necessary to solve environmental pollution in landfill sites and climate change.

Class C FA of cementitious and pozzolanic properties was used in this study. It typically incorporates more than 10% CaO and mainly conduces to the hydration of FA. Cementitious materials are formed by the reaction of CaO with the pozzolans (SiO_2, Al_2O_3, and Fe_2O_3), and hydrated calcium silicate gel (C–S–H) or calcium aluminate (C–A–H) gel as a cementitious material can bond inert materials together with the presence of water [46,47]. Given its pozzolanic properties, FA has been successfully used as an effective agent for chemical and mechanical stabilization of loess through modifying the particle size distribution, enhancement in bonding strength between particles, and destruction of its open structure [48,49]. Therefore, FA can improve soil density and plasticity and reduce water content and strength performance of loess; thus, FA has been used in treating loess soils by many researchers in recent years [50–54]. For example, Prabakar et al. (2003) studied the influence of FA on strength behavior of three different types of soil by using different percentages of FA from 9% to 46% by weight of the soil [55]. Nalbantoglu (2004) explored the potency of Class C FA as an expansive soil stabilizer, which is effective in improving the plasticity of soils [52]. Luo et al. (2009) examined the engineering properties of class C FA mixed with loess [56]. Trivedi et al. (2013) analyzed the optimum usage of FA for stabilization of subgrade soil by using genetic algorithm [57].

The above-mentioned studies have investigated the effect of FA on the geotechnical properties of loess, but most of them have focused on FA stabilization methods without investigating curing and comparison between submergence and non-submergence of FA stabilized loess (FASL) samples.

Loess has relatively high strength and low compressibility at moisture contents lower than the optimum because of partial cementation by $CaCO_3$, iron oxide, and clay minerals [58]. If the moisture content goes beyond optimum, then the clay and $CaCO_3$ can soften, which results in the collapse of the loess soil structure [59]. Thus, loess stabilized by FA requires further critical examination, and practice in various conditions is necessary for loess ground improvement. The augmentation in curing time has also been adopted to increase the strength of the soil and decrease its compressibility [57]. Thus, this work was carried out to investigate the influence of submergence on the stabilization of loess in Shaanxi Province by the addition of FA via laboratory study. This study aimed to investigate the effect of FA on the strength behavior of loess through exploring the Atterberg limits, standard Proctor compaction (SPC), unconfined compressive strength (UCS), and California bearing ratio (CBR) with curing time under non-submergence and submergence conditions and swell potential of CBR during soaking.

2. Materials and Methods

2.1. Materials

In this study, loess was collected from Yangling, Shaanxi Province. The loess sample was excavated at a depth of 3.5 m. The engineering properties of the studied soil on laboratory determination of liquid limit, plasticity index, and particle size characteristics were in accordance with the Specification of Soil Test SL237-1999, the industry standard of P.R. China [60]. This method of soil classification is similar to the American Society for Testing Materials (ASTM). The natural moisture content of Yangling loess, which was obtained using drying method, is 17.42%. Its natural dry density is 1.26 g/cm^3. Its natural void ratio is 1.151, and its natural degree of saturation is 41.9%. The loess was composed of 32.1% sand, 61.4% silt, and 6.5% clay. Its CBR value after being soaked for 4 days is 4.40%, and UCS value after being soaked for four days is 81.51 kPa, which are lower than the allowable value of subgrade filling in China specification. Table 1 shows the physical properties of loess sample used in this investigation.

Table 1. The physical properties of loess sample.

Specific Gravity G_S	Liquid Limit W_L (%)	Plastic Limit W_P (%)	Plasticity Index (I_P)	Natural Water Content (%)	CBR [1] Value (%)	UCS [2] (kPa)	OMC [3] (%)	MDD [4] (g/cm^3)
2.71	35.69	19.02	16.67	17.42	4.40	81.51	18.02	1.72

[1] California bearing ratio, [2] Unconfined compressive strength, [3] Optimum moisture content, and [4] Maximum dry density.

Class C FA used in this research was collected from the Xianyang Weihe power plant near Xi'an. The physical property indexes of FA was conducted on the basis of grain size distribution terms SL237-001-1999 [60], which is similar to ASTM D2487, as listed in Table 2. The chemical analysis was done by X-ray fluorescence spectroscopy (Hitachi, Japan), which consists of the excitation of the sample using an X-ray source in accordance with ASTM C618 specification [61]. Table 3 shows the chemical composition of FA. As shown in the table, the FA had CaO content of 21.89% (more than 20%) and could, thus, be considered high calcium FA or Class C FA in accordance with American Association of State Highway Transportation Officials (AASHTO) M 295-11 [50,62].

Table 2. The physical property indices of FA.

Specific Gravity Gs	Constrained Diameter/mm			Coefficient of Uniformity C_U	Coefficient of Curvature C_C	Composition of Particles/%		
	D_{60}	D_{30}	D_{10}			2–0.075 mm	0.075–0.005 mm	<0.005 mm
2.07	0.055	0.19	0.005	11.00	1.31	27.0	63.0	10.0

Table 3. The chemical composition of FA.

Component	SiO$_2$	AL$_2$O$_3$	Fe$_2$O$_3$	CaO	K$_2$O	TiO$_2$	MgO	Na$_2$O	Ig
Mass (%)	44.8	20.4	4.1	21.89	0.86	1.05	1.89	1.12	1.65

2.2. Studied Parameters

The key parameters analyzed in this study were (1) the effect of the FA ratio on the strength behavior of FASL, (2) the effect of curing time of FASL on the UCS and CBR, and (3) the effect of non-submergence and submergence of FASL on the UCS and CBR. The investigation reports included the effect of (a) the quantity of FA, and (b) the quantity of loess on (i) Aterberg limits, (ii) SPC, (iii) UCS, (iv) CBR, and (v) swell potential. All these tests were performed at OMC conditions and also extended to the untreated loess specimen as reference tests to compare between the strength behavior of FA-treated loess to untreated loess and non-submergence to submergence on the UCS and CBR tests.

2.3. Sample Preparation and Testing Procedures

In this study, Atterberg limits, SPC, UCS, and CBR were prepared at different FA ratios of 0%, 10%, 20%, and 30% by weight of the dry sample. All of them were done following the Specification of Soil Test SL237-1999 [60]. The procedure used in this test is similar to that presented in the ASTM specifications. The OMC and MDD of SPC tests at varying FA–soil mixtures were used for the compaction of UCS and CBR. Table 4 shows the composition of pastes and the compaction characteristics of loess–FA mixtures.

Table 4. Table containing the composition of pastes.

Sample	Loess (%)	FA (%)	Water (%)	Dry density (g/cm^3)
1	100	0	18.02	1.72
2	90	10	18.92	1.67
3	80	20	19.32	1.63
4	70	30	20.05	1.59

The Atterberg limits were performed in accordance with SL237-007-1999 [60], which is similar to ASTM D4318-10. For the determination of Atterberg limits, oven-dried artificial loess was mixed with a predetermined amount of FA in a dry state by hand with a spatula. Thereafter, water was added and the mixture was again thoroughly mixed to obtain a paste-like consistency. The soil with such consistency was then placed inside the plastic bags and kept in the humidity room for 24 h to reach moisture equilibrium. The liquid limit of loess–FA mixture was determined by cone penetration method, and the plastic limit was obtained by the convention.

SPC was carried out on the loess–FA mixture in accordance with SL237-011-1999 [60], which is similar to ASTM D-698. The specimens had a diameter of 102 mm and a height of 116 mm. Before conducting the SPC test, loess–FA mixtures were prepared by mixing varying percentages of FA mass of dry loess. The mixtures were again thoroughly mixed after a certain amount of water was added, and they were kept in plastic bags in the humidity room for 24 h to obtain moisture equilibrium. Compaction tests were then conducted to determine the OMC and MDD.

UCS was performed on the loess–FA mixture in accordance with SL237-020-1999 [60], which is similar to ASTM D-2166. The specimens had a diameter of 39.1 mm and a length of 80 mm. First, an oven-dried soil sample was thoroughly mixed with different percentages of FA in dry state, and then the required amount of OMC was added and placed in plastic bags for 24 h before being compacted into the cylindrical mold. The required bulk densities for compacting UCS samples were calculated using MDD from SPC. The specimens were prepared by static compaction. After extruding the sample, each specimen was wrapped in plastic cover and kept in the humidity room for curing. The UCS test was conducted at different curing times of 0, 14, and 28 days under submergence and

non-submergence conditions. The curing temperature and relative humidity in the humidity room were approximately 20 °C and 99%, respectively. After curing, all soaking samples were soaked in water for four days. This test was performed on specimens at the penetration load of 2.120 N/0.01 mm until specimens failed.

CBR was conducted on the loess–FA mixture in accordance with SL237-012-1999 [60], which is similar to ASTM D-1883. The specimens had a diameter of 152 mm and a height of 116 mm. First, an oven-dried soil sample was thoroughly mixed with different percentages of FA in dry state, and then the required amount of water was added and placed in plastic bags for 24 h before being compacted into the cylindrical mold. The specimens were prepared by SPC and compacted at their OMC into the mold. After being compacted into the mold, each specimen was kept in the humidity room for curing. The CBR test was conducted at different curing times of 0, 14, and 28 days under submergence and non-submergence conditions. The curing temperature and relative humidity in the humidity room were approximately 20 °C and 99%, respectively. After curing, all soaking samples were soaked in water for four days. This test was performed on specimens at the penetration rate of 1.27 mm/min with the loading ring of 226.586 N/0.01 mm. Swell potential was observed when the specimens were kept submerged for four days.

3. Results and Discussion

3.1. Effect of Variation in Fly Ash-Stabilized loess on Atterberg Limits

Atterberg limits, namely, liquid limit, plastic limit, and plasticity index, are used to study the activity and the frost susceptibility of fine grained soil. The plastic limit is the limit between the semi-solid and plastic state, and the liquid limit separates the plastic state from liquid state [63]. The plasticity index is the difference between the liquid and plastic limits [64]. Table 5 shows the effects of the addition of various FA ratios on the liquid limit, plastic limit, and plasticity index of the loess.

Table 5. The effects of the addition of various FA ratios.

FA (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index
0	35.69	19.02	16.67
10	38.55	18.23	20.32
20	39.62	17.15	22.47
30	37.54	20.23	17.31

In comparison with the untreated loess, the plasticity index of loess increased significantly by 21.90%–34.79%, whereas the liquid limit of loess only increased slightly by 8.01%–11.01% at the FA ratios from 10% to 20%. The plasticity index of FA-treated soils increased mainly due to the decrease in plastic limit [65]. The plastic limit of loess first slightly decreased by 4.15%–9.83% in soil exposed to FA from 10% to 20% compared with those of the untreated loess (Table 5). This initial increment might be due to the addition of FA of fine particles, thereby resulting in the soil becoming similar to a fine material and increased water holding capacity of loess.

However, the liquid limit showed a decreasing trend with the increase in FA ratio. A decrease in liquid limit (5.24%) was observed as FA ratio increased to 30% compared with FA ratio increased at 20% (Table 5). The reduction in liquid limit was attributed to that FA created an excellent bonding between the loess and FA particles because the very fine particles of the FA were slightly smaller than the particle size of loess [66]. This condition resulted in variations in grain and pore size distributions [67]. Specifically, the soil particles of natural loess were affected by the reduction in the specific surface area of the FA particles, thereby decreasing the fine particle surface adsorption of water [68]. The increment in plastic limit was also observed, which increased by 17.96% in soil exposed to 30% FA compared with soil exposed to 20% FA (Table 5). The above-mentioned results indicated that the reduction in liquid limit with the increment in plastic limit reduced the plasticity index of the loess with FA piles.

A decrease in plasticity index (22.96%) was observed as FA ratio increased to 30% compared with FA ratio increased at 20% (Table 5). This result agreed with the previous conclusions that the increase in percentage of FA decreased the plasticity index and liquid limit of the treated soils [46,66,69–72]. The decrease in plasticity index of specimens might be due to cementitious reactions from the FA fraction, which dissociated CaO and formed cementitious and pozzolanic gels [73] and, thus, produced a cement-stabilizing effect that reduced loess plasticity [74]. Thus, the addition of high percentages of FA would result in improved workability of soils. Interestingly, an opposite trend was observed in the previous studies that showed a constant increase or no difference with any ratio of FA [52,72].

On the contrary, the liquid limit, plastic limit, and plasticity index were insignificantly changed for all stabilized samples compared with those of the untreated loess (Table 5). This result was consistent with that of a recent study [52]. Thus, the effect of FA treatment on the plasticity index of Shaanxi soil was very small. The reason was that the low plasticity of Shaanxi soil (16.67; Table 1) led to that FA slightly influenced on its plasticity index [52].

3.2. Effect of the Variation in Fly Ash-Stabilized Loess on Compaction

Compaction characteristics have an important impact on the engineering properties of soil, such as strength, compressibility, hydraulic conductivity, and dispersibility [75]. In this study, SPC test was conducted for loess with different FA ratios to determine the impact of FA on the stabilization of loess. Table 6 shows the effect of FA stabilization of loess on compaction test with varying FA ratios.

Table 6. The effect of FA stabilization of loess on compaction test with varying FA ratios.

FA (%)	OMC (%)	MDD (g/cm^3)
0	18.02	1.72
10	18.92	1.67
20	19.32	1.63
30	20.05	1.59

Loess treated with 10%, 20%, and 30% FA significantly increased the OMC than the untreated loess. The OMC increased from 4.99% to 11.27%, and the significantly high value was observed at the addition of 30% FA (Table 6). A similar trend was observed in previous studies, which applied FA to loess [55,76] and clay [72,75]; however, neither no consistent variation nor gradual decreases in OMC were observed with the increase in the FA ratio in a few studies [57,77] and soft soil [46]. On the contrary, as OMC increased, a significant decrease from 2.90 to 7.56% in the MDD was observed in loess treated with 10%, 20%, and 30% FA compared with that of the untreated loess (Table 6). This result was consistent with that of recent studies [46,55,72,75,76,78]. The increase in OMC might be attributed to progressive hydration of loess–FA mixtures that required additional amount of water to complete the cation exchange reaction [72]. Moreover, the formation of cemented products with the increase in the number of fine particles in the loess–FA mixtures by the particle size of FA was relatively small; this condition resulted in compaction effort, which increased the number of voids, decreased dry densities, and weakened water absorption [55,72,76,79]. In addition, the specific gravity of FA was lower than that of loess. Thus, the specific gravity of loess mixed with FA was decreased with the increase in the amount of FA; this condition decreased the maximum dry density [55,71]. The aforementioned results showed that FA was a suitable additive agent for improving the engineering characteristics of loess soils.

3.3. Unconfined Compressive Strength

The UCS is the main index to measure the effect of FASL on stress and strain. Experiments were conducted under submergence and non-submergence conditions after three curing times: 0, 14, and 28 days.

3.3.1. Effect of Variation in Fly Ash-Stabilized Loess on Stress

Figure 1 provides information on the UCS stress under submergence and non-submergence conditions at different FA ratios and curing times.
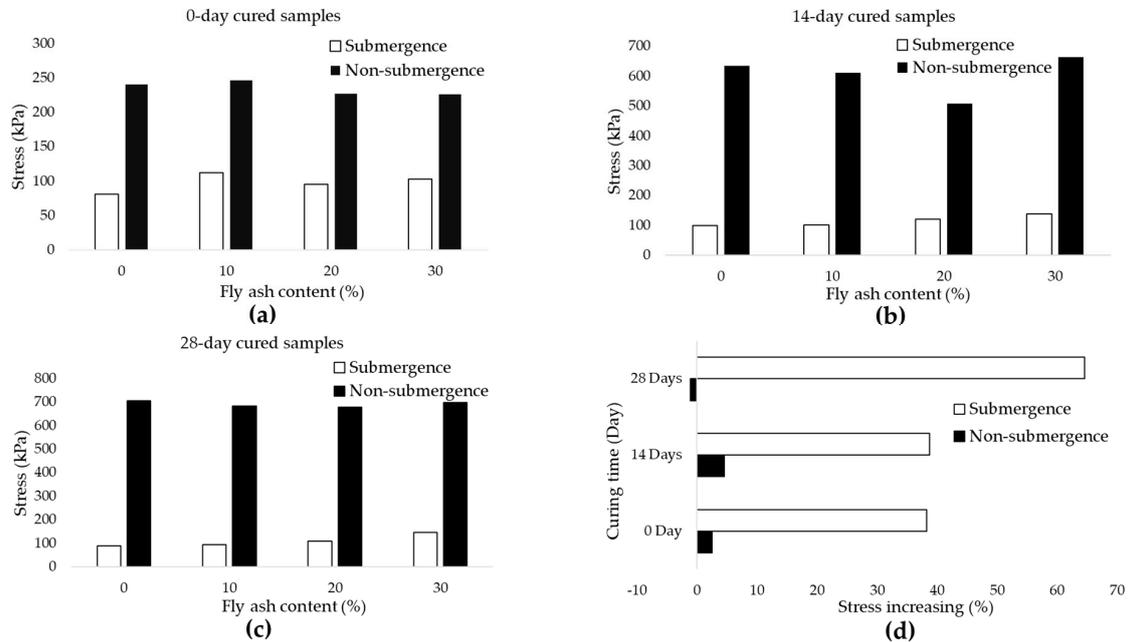

Figure 1. The influence of the variation in FA-stabilized loess (FASL) specimen on stress at different curing times under non-submergence and submergence conditions: (**a**) zero days; (**b**) 14 days; (**c**) 28 days; and (**d**) stress increasing.

With the addition of FA from 0% to 30%, the effect of FA on the UCS stress was significantly great, especially for the FA ratio higher than 20% under the submergence condition. The UCS stress increased by 17.32%–38.27% and 2.07%–38.80% at 0 and 14 days of curing time compared with that of the untreated loess (Figure 1). The impact of the FA ratio on the results was much greater during the curing time of 28 days, and this condition increased UCS by 5.19%–64.56% compared with that of the untreated loess (Figure 1). The aforementioned results indicated that the FA ratio altered the intrinsic soil property. The hydration process and pozzolanic reactions significantly increased the soil strength by producing C–S–H and C–A–H gels through the increase in the amount of CaO in the mixture as the FA ratio increased [52,76,80]. The remarkable increment in the UCS stress under submergence conditions might be due to that the UCS stress depended on the chemical compatibilities of FA with plasticity soil with the addition of water [51]. The reduction in the plasticity index with the increase in the FA ratio (Section 3.1) implied an increase in the soil strength because of the inversely proportional relationship between soil strength and plasticity index [69]. This result was consistent with that of other researchers [46,51,69,81]. On the contrary, UCS stress did not change under non-submergence condition. The UCS stress first increased by 2.51% with 10% FA and then slightly decreased with 20% and 30% FA (maximum of 5.84%) compared with that of the untreated loess at zero days of curing time with non-submergence samples (Figure 1). This initial increasing trend indicated that FA-treated loess exhibited a more brittle behavior than the untreated loess. However, the decrease in UCS stress at high FA ratio (20% and 30%) might be due to the excessive amount of FA added, which was probably related to high compaction, water content, and low compaction characteristics; as a result, the specimens failed to stand the amount of stress applied [46,66]. This change trend was opposite at 14 days of curing time, during which UCS stress first decreased by 3.85%–20.03% with 10% and 20% FA and then slightly increased by 4.55% with 30% FA compared with that of the untreated loess (Figure 1). Specifically, the UCS stress only decreased (3.74%–1.04%) at 28 days of curing time

compared with that of the untreated loess (Figure 1). These results suggested that the addition of FA under non-submergence condition slightly affected the UCS stress for the loess. This phenomenon might be due to the uneven distribution of FA without water in the loess–FA mixtures [82]. Therefore, the submergence condition had a greater contribution to the UCS stress due to the addition of FA than the non-submergence condition.

Surprisingly, a variation in UCS stress was observed at different FA ratios with the change in curing time (Figure 1). For example, under non-submergence condition, the highest UCS stresses of specimens at 0, 14, and 28 days of curing time were observed with 10%, 30%, and 0% FA, respectively. By contrast, the lowest UCS stresses of specimens at 0, 14 and 28 days of curing time were obtained with 30%, 20%, and 30% FA, respectively. A similar trend was also observed for submergence condition. In particular, the highest UCS stresses of specimens at 0, 14, and 28 days of curing time were observed with 10%, 30%, and 30% FA, respectively. On the contrary, the lowest UCS stresses of specimens at 0, 14, and 28 days of curing time were obtained with 20%, 0%, and 0% FA, respectively.

The UCS stresses of FA-treated loess specimens were in the range of 227.17–241.25 kPa for the curing time of zero days under non-submergence condition. Then, the value increased as curing time increased. Specifically, the UCS stresses were in the range of 635.43–664.35 kPa at 14 days of curing time and reached the range of 678.93–705.33 kPa at 28 days of curing time. However, the UCS stress of FA-treated loess specimens decreased under submergence condition. The UCS stresses of FA-treated loess specimens were only in the range of 81.51–112.70 kPa for the curing time of zero days, 99.34–137.88 kPa at 14 days of curing time, and 89.09–146.61 kPa at 28 days of curing time. Compressive strength reached its highest value when the FA ratio was 30% at 28 days of curing time. Therefore, curing time had an important effect on the strength results, especially for samples under long curing time. These results were consistent with those of recent studies [83,84]. A high FA ratio could lead to increased pozzolanic reactions; as a result, a large amount of cementitious materials combined with the soil particles as time progressed [85,86]. With a high amount of stabilizer, a large amount of CaO could contact with silica and alumina from the soil and thus form the main short-term product, which was mainly influenced by dilution effects [87,88]. As time progressed, a large amount of CaO could react with a large amount of silica and alumina released from the stabilizer; accordingly, the formation of C–S–H accelerated, which played a major role in strength degradation as time progressed [80,83,87,88]. However, this result was completely opposite to that of Zia (2000), who suggested that the strength of specimens increased up to seven days of curing time and then UCS decreased for all the mixtures after 7–14 days [76]. Strength degradation probably occurred because of fast hydration and consequent shrinkage cracking or possible formation of ettringite [76]. The UCS stress under non-submergence condition was higher than that under submergence condition. This behavior was probably due to that the submerged soil and FA mixtures had the same FA ratio as the non-submerged mixtures. However, the increase in water content might decrease the sodium concentrations, which resulted in low UCS stress [81,83]. Therefore, the strength of FASL enhanced with the increase in curing time.

Overall, non-submergence showed a downward trend, whereas submergence showed an upward trend for all FA ratios and curing times. The UCS stress of both conditions had some fluctuations. Although submergence had lower stress, it outperformed non-submergence in improving the effect of FA on loess.

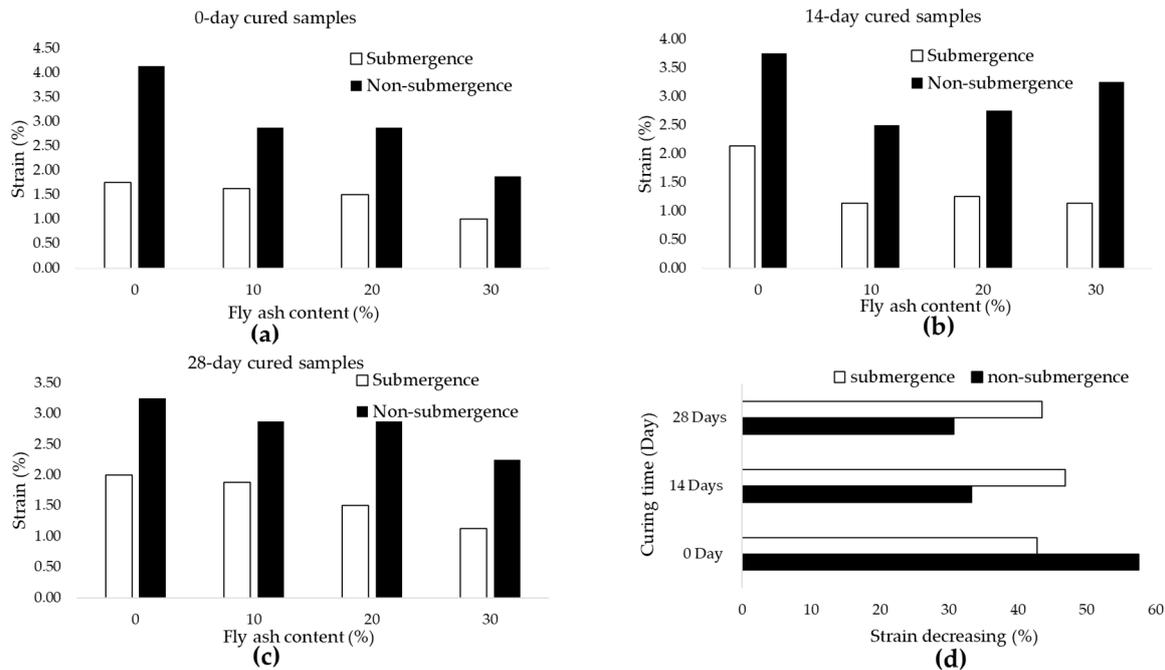### 3.3.2. Effect of Variation in Fly Ash-Stabilized Loess on Strain

Figure 2 shows the influence of the variation in FASL specimen on strain at different curing times under non-submergence and submergence conditions. The addition of FA to loess influenced the UCS strain. For non-submergence samples, the UCS strain decreased by 30.27%–54.48%, 13.33%–33.33%, and 11.69%–30.77% at 0, 14, and 28 days of curing time (Figure 2), respectively, compared with that of untreated loess especially for the high FA ratio (30%). A similar trend was also observed for submergence samples; in particular, the UCS strains of specimens at 0, 14, and 28 days of curing time

decreased by 6.86%–42.86%, 41.31%–46.95%, and 6.01%–43.51%, respectively, compared with that of untreated loess (Figure 2). These results suggested that the addition of FA significantly reduced the UCS strain of loess; therefore, FA-treated soils exhibited a more brittle behavior than untreated soils. This finding agreed with the previous conclusion [66,83,89]. However, this result was in contrast to that of Brooks (2009), who concluded that failure strains increased by 50% when the FA ratio was increased from 0% to 25% [51]. This difference might be explained by the difference in properties of clay used in the investigation [51]. However, the UCS strain under submergence condition was more decreased than that under non-submergence condition. Thus, the submergence condition played an important role in decreasing the UCS strain on FASL.

Figure 2. The influence of the variation in FASL specimen on strain at different curing times under non-submergence and submergence conditions: (**a**) zero days; (**b**) 14 days; (**c**) 28 days; and (**d**) strain increasing.

The decreasing trend of UCS strain differed with the change in curing time under dissimilar FA ratios. The UCS strain gradually increased with the increase in FA ratio under non-submergence and submergence conditions at zero and 28 days of curing time. The highest UCS strain was obtained with 0% FA, and the lowest UCS strain was observed with 30% FA. Surprisingly, a completely opposite finding was obtained at 14 days of curing time. Under non-submergence condition, the highest UCS strain was observed with 0% FA, whereas the lowest UCS strain was obtained with 10% FA. Under submergence condition, the highest UCS stress was found with 0% FA, whereas the lowest UCS strain was derived with 10% and 30% FA.

3.4. Effect of Variation in Fly Ash-Stabilized Loess on CBR

The CBR value is an indicator of soil strength and bearing capacity. Figure 3 shows the CBR value of non-submergence and submergence conditions at different FA ratios and curing times of specimens. As shown in the figure, the CBR value increased as the curing time and FA ratio increased.
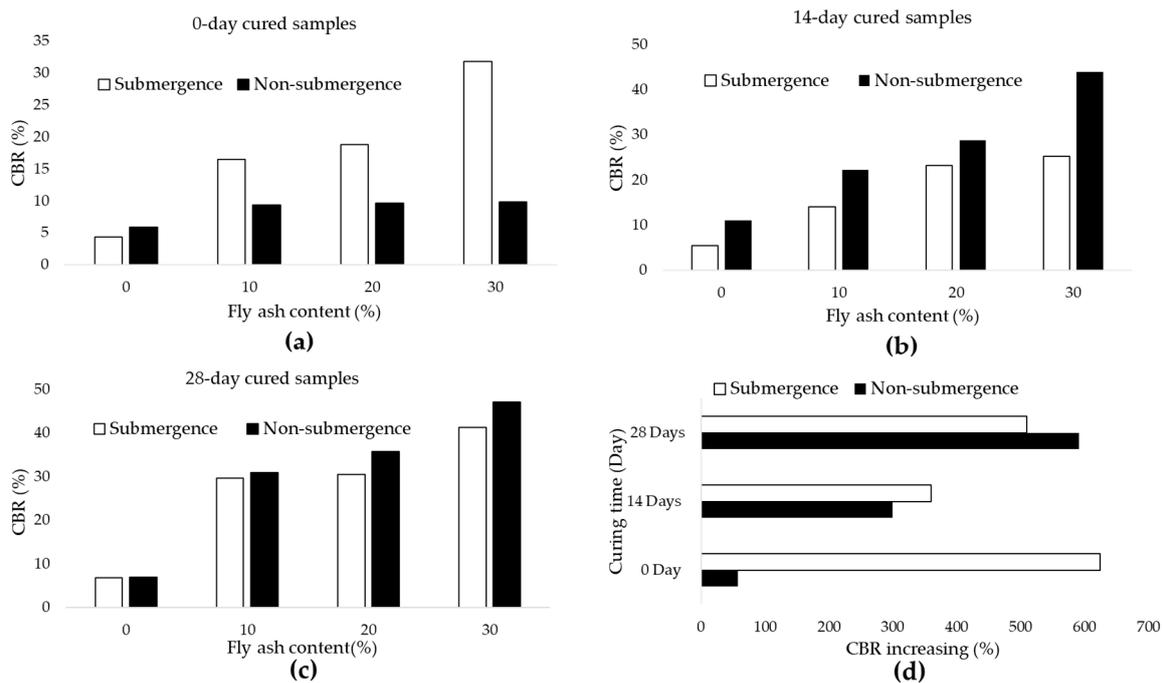
Figure 3. The CBR value of non-submergence and submergence conditions at different FA ratios and curing times of specimens: (**a**) zero days; (**b**) 14 days; (**c**) 28 days; and (**d**) CBR increasing.

With the addition of FA, the CBR value increased. Such increase is suitable for the strength and bearing capacity of loess. At zero days of curing time, the CBR value significantly first increased by 57.41% with 10% FA and then significantly decreased by 48.15%–50.0% with 20% and 30% FA, respectively, compared with that of untreated loess of non-submergence samples (Figure 3). Nevertheless, this CBR value was significantly increased as curing time increased with the addition of FA from 10% to 30%, which increased by approximately 2–4 and 4–7 times in the non-amended FA at 14 and 28 days of curing time, respectively. A sharp improvement in the CBR value was found at high FA ratio (30%) treatment compared with the CBR value of pure loess (Figure 3). Similarly, the non-submerged loess and FA mixtures also caused a notable improvement in the load-bearing properties; however, the CBR value under submergence condition significantly increased for all FA treatments. The CBR value increased by approximately 3–7, 3–5, and 4–6 times at 0, 14, and 28 days of curing time, respectively, compared with that of untreated loess (Figure 3). The increase in the CBR value was consistent with the data obtained on soft soil and loess by previous authors [51,55,57,71,72,90], who characterized FA to improve soil bearing capacity. However, previous studies have also demonstrated that the increase in CBR with the addition of FA to loess was insignificant, which implied that an alternative method must be sought [77]. However, this discrepancy might be due to the addition of FA and lime to loess by the previous authors besides the addition FA to loess as in the present study. A decrease in CBR value was observed after the addition of 25% FA in the study of Dixit et al. (2016). This decrease was due to the pore water filled in the flocks [72]. These results indicated that the CBR value of FASL would significantly increase when the FA ratio was increased. The improvement in loess strength in CBR due to the addition of FA was the function of loess–FA interlocking phenomena [55]. Hydraulic binder initiated the pozzolanic properties of FA, which caused the ion exchange reaction between soil particles and FA and the increase in strength properties of treated soils [78]. The submergence condition also displayed more considerable behavior than the non-submergence condition in increasing the effect of FA on CBR value.

The CBR value significantly increased with the increase in curing time under non-submergence condition by approximately 2–5 and 1–5 times at 14 and 28 days of curing time, respectively, compared with the CBR value at zero days of curing time. By contrast, no significant difference in the CBR

value under submergence condition was found at 14 and 28 days of curing time compared with the CBR value at zero days of curing time; specifically, the CBR values only increased by approximately 0.8–1.2 and 1.3–1.8 times, respectively (Figure 3). This result might be due to that the CBR value under submergence condition was 0.7–3.5 times higher than that under non-submergence condition at zero days of curing time (Figure 3). This result agreed with those of Cabrera et al. (2018), who suggested that un-soaked CBR was lower than soaked CBR [90]. Furthermore, the increased CBR value as curing time increased also agreed with the result of a previous study [69]. Therefore, the CBR value of FASL samples would significantly increase when they were cured.

3.5. Effect of Variation in Fly Ash-Stabilized Loess on Swell Potential

Swelling occurs when unsaturated soils absorb water by interaction and thus increase in volume [75]. Figure 4 shows the influence of the variation in FASL on swell potential at different curing times.
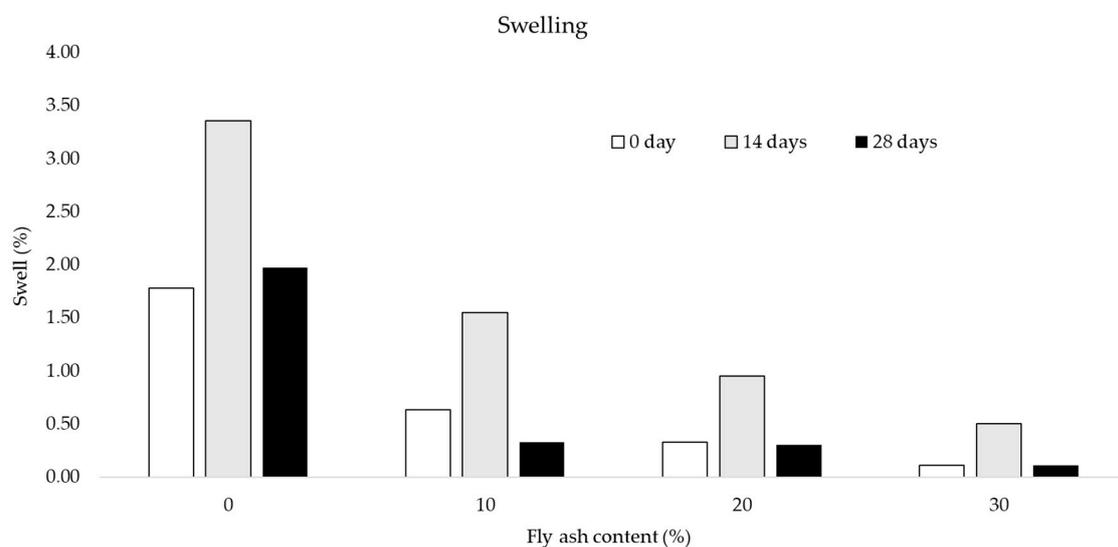

Figure 4. Swell potential at different FA ratios and curing times.

The swell potential significantly increased by 88.20% at 14 days of curing time compared with that at zero days of curing time in the pure loess treatments. However, this value was higher than that at the next days, which decreased by 10.67% at 28 days (Figure 4). Thus, the effect of the increase in curing time on swell potential was insignificant. The test results indicated that the untreated loess provided a swell potential with the addition of FA, whereas FA-treated loess provided significantly decreased swell potential with the increase in FA ratio. Specifically, the swell potential in loess and FA mixtures (with 10%, 20%, and 30% FA) decreased by 64.61%–93.82%, 53.73%–85.07%, and 83.25%–94.42% at 0, 14, and 28 days of curing time, respectively, compared with that of untreated loess (Figure 4). The increment in swell potential might be due to various factors, such as specific gravity mixture, particle size and shape of mixture, and chemical reaction between FA and soil. The rapid hydration process and simultaneous cation exchange reduced the swell potential when FA was added into the soil; in these phenomena, the sodium ions in the soil were replaced by the calcium ions in the FA, the soil flocculated into larger lumps, and new pozzolanic reaction products, such as C–S–H and C–A–H, were produced [51,52,70]. The change in the physical properties of loess–FA mixtures might also be a reason, which was dependent on the non-expansive characteristics and particle size and shape of FA [55]. Meanwhile, the plasticity index of the soil is an important indicator of the swell potential; thus, the reduction in plasticity index in the current study (Section 3.1) decreased the swell potential [2]. Therefore, the addition of FA was very effective in reducing the swell potential of loess, especially with high FA ratio. This result was consistent with that of previous studies with the addition of FA on

loess [51,52,55,75] or the addition of FA on clays [70]. However, Ozdemir (2016) suggested that the addition of FA did not change the swell potential at zero days of curing time, and but it significantly decreased the swell potential at seven and 28 days of curing time [46]. This result might be explained by the lower FA ratio than that in the present study or the time-consuming pozzolanic reaction.

4. Conclusions

In this study, FASL was experimentally explored after the addition of various FA ratios (0%, 10%, 20%, and 30%) by investigating Atterberg limits, SPC, UCS, and CBR under non-submergence and submergence conditions with different curing times. From the results, the following conclusions were obtained:

- The liquid limit and plasticity index first increased with the addition of FA from 10% to 20% and then decreased as FA ratio increased to 30%. However, the values were insignificantly changed for all stabilized samples compared with those of the untreated loess.
- Loess treated with 10%, 20%, and 30% FA showed a significant increase in the OMC but a significant decrease in the MDD. With the addition of 30% FA, the OMC increased by 11.3% and the MDD decreased by 7.6% compared with those of the untreated loess.
- The submergence condition had a greater contribution to UCS value for the addition of FA than the non-submergence condition. The UCS stress was significantly increased, especially when the FA ratio was greater than 20% under the submergence condition. On the contrary, the UCS stress did not change under non-submergence condition.
- The strength of FASL was improved with the increase in curing time, especially for samples at 28 days of curing time. The UCS stress under non-submergence condition was higher than that under submergence condition.
- The addition of FA to loess decreased the UCS strain. However, the UCS strain under submergence condition had a larger decrease than that under non-submergence condition. The decreasing trend of UCS strain was unremarkable as curing time was extended.
- The mixture of loess and FA caused a notable improvement in the load-bearing properties. However, the CBR value under submergence condition significantly increased compared with that under non-submergence condition. The CBR value also significantly increased with the extension in curing time.
- Submergence condition played an important role in improving the effect of FASL on UCS and CBR compared with non-submergence condition.
- The swell potential of FASL would significantly decrease to smaller than 0.5% when the FA ratio was increased to 30%. However, the effect on the swell potential was insignificant when curing time was extended.

The above-mentioned conclusions indicate that the bearing capacity of loess in Shaanxi Province can be improved by adding 10% or more FA. The addition of FA with the extension in curing time is effective for ensuring UCS, CBR, and swell potential. Submergence condition improves the effect of FA as stabilizing agent on loess. Thus, FASL is expected to be significantly used in flood areas. However, the results of the CBR tests demonstrate that both conditions have excellent load-bearing characteristics with the addition of FA due to low specific gravity and decreased UCS strain. Therefore, the application of FA in areas prone to erosion should be considered cautiously.

Conflicts of Interest: The authors declare no conflict of interest.

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