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Effect of Alkali Activated Fly Ash on Shrinkage Characteristics of Expansive Soil

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Abstract. Expansive soils are known as problematic due to their significant volume change during seasonal moisture fluctuation. The present study reports the suitability of alkali-activated fly ash as an alternate binder, to conventional stabilizers like cement, used to mitigate the volumetric shrinkage of expansive soil. Alkali activated fly ash is an alternative binder in which liquid alkali activator (LAA) is added to FA, which consists of 50:50 sodium silicates (Na_2SiO_3) and sodium hydroxide (NaOH) solution by weight. Laboratory investigation includes the determination of volumetric shrinkage strain through image analysis and scanning electron microscopy (SEM) images at 7-, 14- and 28-days curing period. Results indicate a significant reduction in volumetric shrinkage strains from 56 % to 15 %, 11 %, and 5 %, respectively, with a treatment of expansive soil with LAA/FA = 1, 1.25, and 1.5 at a curing period of 28 days. The SEM images captured to observe the microstructural changes at a 28-days curing period reveals that the right amount of dense crystalline products is formed at an LAA/FA = 1.5. From the analysis an LAA/FA ratio of 1.25 may be considered as an optimum dosage to control the volumetric shrinkage strain.

Keywords: Expansive soil, fly ash, alkali activator, image processing, shrinkage strain.

1 Introduction

The expansive soils are well known as problematic soils due to their swell- shrinkage behavior due to seasonal moisture fluctuation. The structures built on these soils will experience severe distress due to differential settlements [1, 2]. Many highways, highway embankments, and airfield pavements were damaged due to shrinkage of such highly expansive soils [3, 4, 5]. To control these adverse effects of expansive soils, conventional binders like cement and lime were used in the past [6, 7]. However, these binders have some disadvantages, including environmental concerns due to the emission of carbon dioxide during the manufacturing process. Alternative binders such as fly ash and slag are promoted as these by-products possess potential pozzolanic compounds. However, activators are generally used along with these binders to accelerate the reactivity. Alkali activated fly ash is the cementitious material in which alumina and silica from fly ash dissolute in the alkali solution to form a geopolymeric gel network of sodium-alumino-silicate-hydrate (N-A-S-H) gel by reorientation [8]. However, the reactivity of alkali-activated fly ash with expansive soils is not fully understood.

The primary purpose of stabilizing the expansive soil is to control swell-shrink behavior. Accurate measurement of the volume of a shrunken soil specimen may be calculated using a mercury displacement method [9,10]. However, it has disadvantages of handling and health issues. Due to these disadvantages, the ASTM standard D427-04 [11] has been withdrawn, and the wax method ASTM D4943-08 [12] was suggested as an alternative for the determination of volumetric shrinkage of soils. However, it was also withdrawn recently. Hence, there is a need to look for a reliable method that excludes the volume of cracks in the volume of a shrunken soil specimen. The image processing methods are new promising techniques in determining the volume of soil specimens [13].

In the present study, alkali-activated fly ash was used as a stabilizer to control the shrinkage characteristics of expansive soil, and the image processing method was used to determine the volume of the shrunken soil specimen accurately by excluding the volume of developed cracks in the expansive soil.

2 Material Properties

The expansive soil was obtained from Amaravati city, Andhra Pradesh, India. The soil consists of 6% sand, 31% silt, and 63% clay. The properties of the expansive soil are listed in Table 1. The liquid limit and plasticity index of the expansive soil were 77% and 44%, respectively. According to the American Society for Testing and Materials, ASTM D2487 [14], the soil can be classified as clay with high plasticity (CH). The maximum dry unit weight (MDU) and optimum moisture content were found to be 14.2 kN/m^3 and 28.5%, respectively. The fly ash was obtained from the Narla Tatarao Thermal Power Station (NTTPS), Vijayawada, India. The chemical oxide composition of the fly ash was determined through x-ray fluorescence (XRF) analysis and is presented in Table 2. The fly ash can be classified as Class F, according to ASTM C618 [15]. Sodium hydroxide (NaOH) at 99% purity and Na_2SiO_3 (consisting of 10% Na_2O, 38% Si_2O, and 52% H_2O) are obtained from a local chemical supplier.

A liquid alkali-activator ratio (LAA), defined as the ratio of Na_2SiO_3 and NaOH, of 50:50, is considered for preparing the liquid component, which consists of LAA and water, of the soil-fly ash mix [16]. Three different liquid components, 20 %, 25 %, and 30 % by dry weight of the soil-fly ash mixture, were considered. A 20% fly ash by dry weight of the expansive soil is considered [17,18]. Hence, the liquid to fly ash ratios are calculated to be 1.0, 1.25, and 1.5, respectively, as shown in Table 3.

Table 1. Properties of expansive soil and fly ash.

Property	Soil	Fly ash
P^H	8.24	7.75
Specific gravity (G_s)	2.74	2.2
Liquid Limit (LL)	77%	--
Plastic Limit (PL)	33%	--
Plasticity Index (PI)	44	--
Shrinkage Limit (SL)	10%	--
Free swell index (FSI)	110%	--
Silt	31%	67%
Clay	63%	30%

Table 2. Chemical oxide composition of expansive soil and fly ash.

Oxide	Expansive soil (ES), %	Fly ash (FA),%
SiO_2	59.02	52.09
Al_2O_3	29.63	17.15
CaO	1.17	3.49
Fe_2O_3	4.98	18.95
K_2O	1.86	1.18
MgO	0.54	3.08
SO_3	0.25	0.49
Na_2O	0.23	0.34
P_2O_5	0.68	0.42
TiO_2	1.84	2.25
MnO_2	0.03	0.17

Table 3. Nomenclature of samples.

FA (%)	LAA (%)	LAA/FA
20	20	1
20	25	1.25
20	30	1.5

3 Experimental Methods

A series of experiments, including volumetric shrinkage tests, scanning electron microscopy (SEM) analyses were conducted at different curing periods. The following sections briefly describe the sample preparation for these experiments.

3.1 Sample preparation procedure

The expansive soil was mixed with 20% fly ash by dry weight. The soil-fly ash mixture was mixed with LAA solution, which consists of 3M NaOH solution and liquid sodium silicate solution of ratio 50:50 by weight at three different LAA/FA ratios shown in Table 3. After mixing with respective LAA, samples were packed in a polythene cover to protect for moisture loss, and it was cured for 7-days,14-days, and 28-days by keeping them in an environmental chamber maintained at 27 ºC temperature and 95% relative humidity. Thereafter, samples were taken out from the environmental chamber on respective curing period, and further, specimens were prepared according to ASTM D4943 [19] to determine the volumetric shrinkage. The volumetric shrinkage strain was determined by using an image processing technique that involves capturing the image, convert the image to grayscale, and convert grayscale to a binary scale. The image capturing was carried out at constant altitude with uniform light intensity and high-resolution digital camera. The setup used in the present study was similar setup reported by Julina et al. [13]. Further, the image processing techniques were applied to the captured images with the free access Image J software. The *image segmentation threshold* image processing method was used to convert the gray image to a binary image, as shown in Figure. 1. The average surface areas of the top and bottom portion of the image processed samples excluding cracked areas were determined by Image J software. The height of the shrunken samples was measured by subtracting the average height from the original sample height, which measured from the top of the mold to the surface of the sample by using Vernier callipers. The volumetric shrinkage was determined by using Equation 1. In the vernier method, the diameter and height of the sample were determined with Vernier callipers and the shrinkage strains was determined by using Equation 2.

$$Volumetric\ shrinkage\ strain, (V_s) = \frac{(V - A_{sr}H)}{V} \times 100 \quad (1)$$

Where V = Initial volume of the soil specimen; A_{sr} = Average surface area of the top and bottom of shrunken soil specimen, and H = Height of shrunken soil specimen.

$$Volumetric\ shrinkage\ strain, (V_s) = \frac{\left(V - \left(\frac{\Pi D_{avg}^2}{4}\ H\right)\right)}{V} \times 100 \quad (2)$$

Where V = Initial volume of the soil specimen; D_{avg} = Average diameter of shrunken soil specimen, and H = Height of shrunken soil specimen.

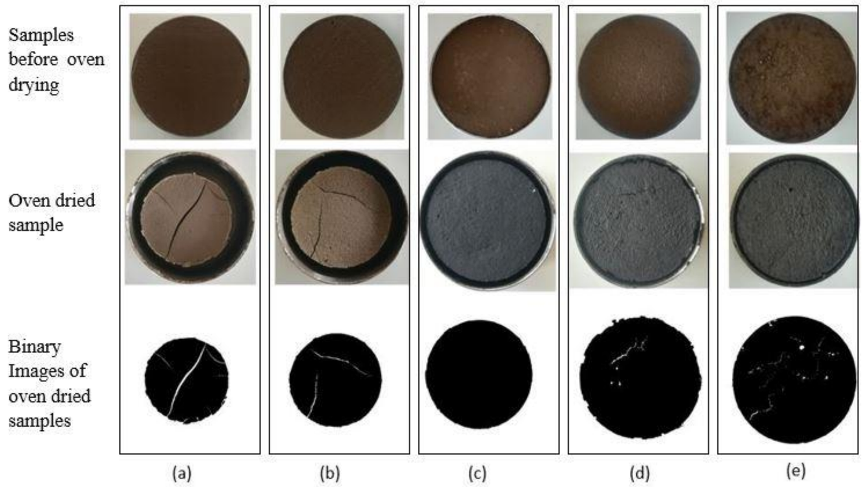

Fig. 1. (a) and (b) are samples of control soil and control soil with 20% fly ash. (c), (d) and (e) are oven-dried samples of treated soil with LAA/FA= 1, 1.25, and 1.5 at 28 days curing period.

Further, scanning electron microscopy (SEM) images of stabilized samples of LAA/FA = 1, LAA/FA=1.25, and LAA/FA=1.5 were captured to investigate the microstructural changes at 28 days curing period. Before capturing the images, samples were coated with gold-palladium to increase the conductivity of the samples. After that, samples were mounted on the aluminum stub with a conductive tap on top. SEM images were captured on selected samples with Zeiss, EVO 60 field emission under backscatter mode at a voltage of 20 kV.

4 Results and Discussion

The volumetric shrinkage strains determined by the Vernier and Mercury methods and image processing method are shown in Figure 2. Mercury method was performed only on treated samples as it was difficult to perform the test on untreated specimen due to severe cracking and splitting of the specimen. The percentage error in volumetric shrinkage between both the methods is relatively high for the untreated sample, which is of about 4.5% compared to the treated samples (2.5%). The error is due to the development of more shrinkage cracks in untreated specimen compared to the treated specimens and also due to the area of shrinkage cracks were included in the Vernier method. The increase in volumetric shrinkage strains in the image processing method indicates the high accuracy over the Vernier/Mercury method. It was reported that the degree of of severity is less when the volumetric shrinkage strain is less than 17% [20]. Hence, this value is considered as a baseline in this analysis.

Figure 3 depicts the volumetric shrinkage of control and stabilized soil specimens at 7-days, 14-days, and 28-days curing period. There is a significant decrease in the volumetric shrinkage of control soil from 56% to 15%,11%, and 5%, respectively, with the treatment of LAA/FA = 1, 1.25, and 1.5 for 28 days cured specimens. The decrease in volumetric shrinkage strains of stabilized soil is due to the activation of pozzolanic compounds in the geopolymerization process. The geopolymerization occurs during the curing period, which includes the dissolution of alumina and silica in alkali solution, reorientation of aluminates, and silicates to form a possible gel network N-A-S-H [21]. The gel network solidifies to form a geopolymer. As the LAA ratio increases, there is an increase in precipitation of the gel network in the soil - fly ash matrix, which was the reason for the significant decrease of volumetric shrinkage from 15% to 5%, respectively, with treatment from LAA/FA= 1 to LAA/FA =1.5. Figure 4 presents the percent reduction in volumetric shrinkage strains of specimens treated with LAA/FA = 1, 1.25, and 1.5 and cured for 7-, 14- and 28-days with reference to the control specimen. The reduction in the volumetric shrinkage of samples treated with LAA/FA = 1.0 from control soil is about 73 %. However, a further increase in the LAA/FA ratio from 1.25 to 1.5 has shown a minimal additional reduction in the vertical shrinkage from 7 % to 17 % for a curing of 28 days shown in Fig. 4. The decrease in the volumetric shrinkage of samples treated with LAA/FA = 1.0, 1.25 and 1.5 is very minimal of 17% to 15%, 12% to 11% and 5.5% to 5% respectively, as the curing period increases from 7 to 28-days. The minimal reduction in V_s may be due to the slow solidification of the gel network during a curing period of 7 to 28-days. At times the complete crystallization of the gel network may take years [22]. However, all the specimens treated with LAA/FA ratios have shown the volumetric shrinkage strains less than the baseline, indicating that the stabilization is effective for all LAA/FA ratios.

To understand this phenomenon, SEM images were captured to investigate the microstructural features of the stabilized soil. SEM images of stabilized soil samples cured at 28 days were chosen for the investigation, which was shown in Fig. 5. It was observed from the sample treated with LAA/FA =1.0 has partial dissolution of fly ash particles, which is due to the insufficient addition of LAA. At the same time, the other samples were found intact, indicating that the LAA/FA ratio is sufficient. Layers of control soil were disappeared in treated samples with LAA/FA.

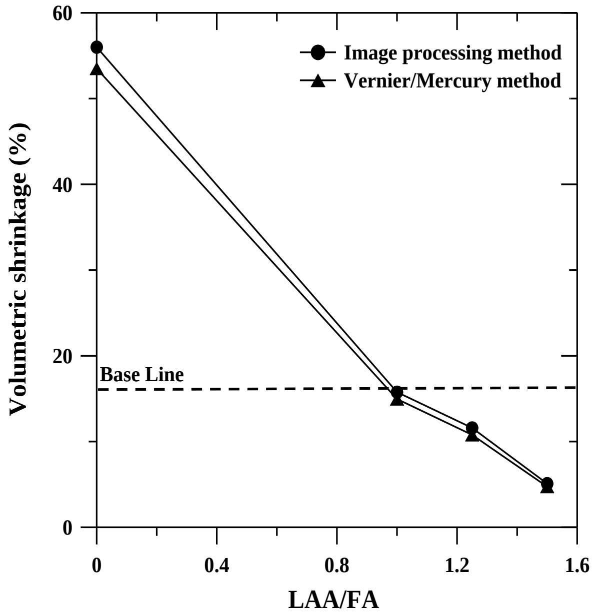

Fig. 2. Comparison of Volumetric shrinkages strains determined by image processing method and Vernier method of an untreated and treated sample at 28 days curing period.

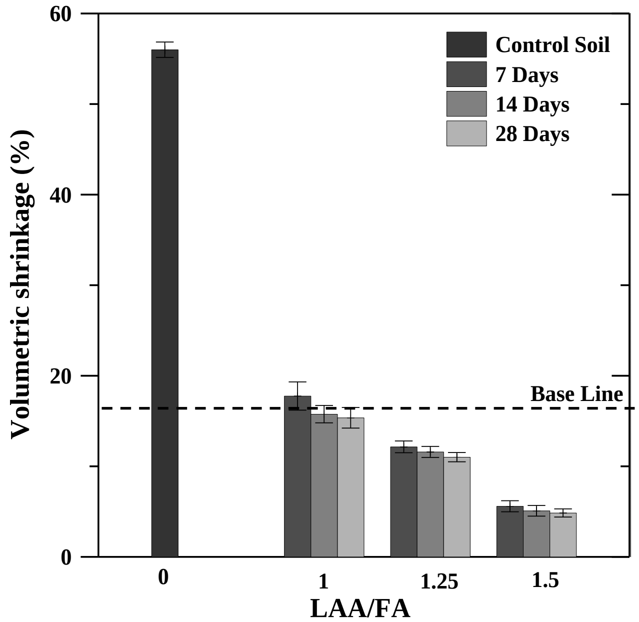

Fig. 3. Volumetric shrinkage strains of control soil and expansive soil treated with different LAA/FA at 7-days, 14-days, and 28-days curing period.

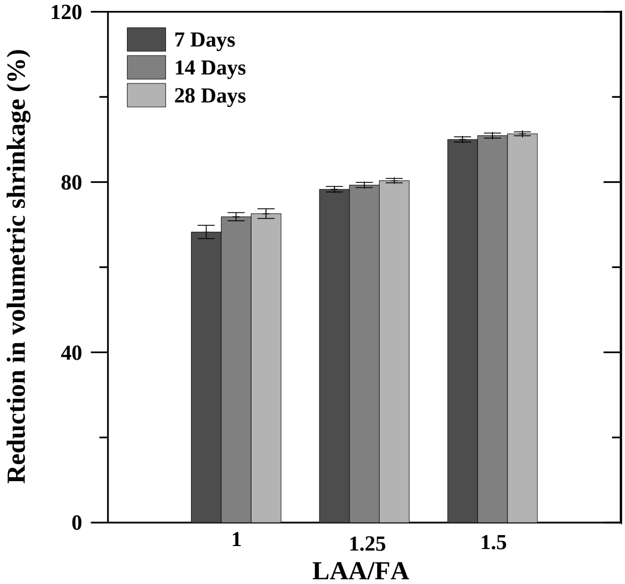

Fig. 4. Percentage reduction in volumetric shrinkage of expansive soil treated with varing LAA/FA from 1 to 1.5 at different curing period.

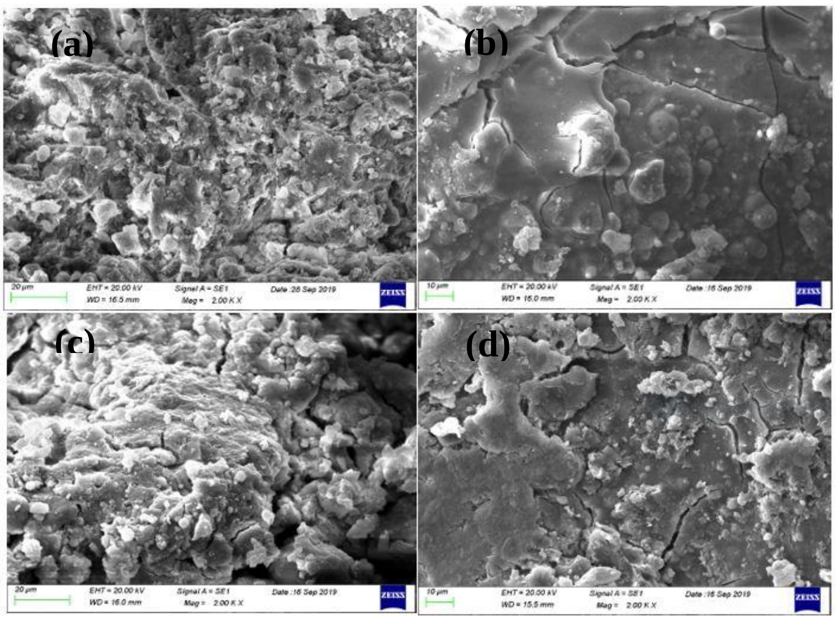

Fig. 5. Scanning electron microscopy images of (a) control soil, (b) soil with LAA/FA= 1.0, (c) soil with LAA/FA= 1.25 and (d) soil with LAA/FA= 1.5 at 28-days curing period.

5 Conclusions

The following conclusion can be drawn from the experimental studies conducted on alkali-activated fly ash treated expansive soils.

1. Alkali-activated fly ash with a liquid alkali activator ratio of 50:50 was effectively controlled the volumetric shrinkage of expansive soil.
2. A three-molar concentration of NaOH is adequate to enable the geopolymer reactions in the fly ash stabilized expansive soil.
3. The image processing method is a promising method to determine the area of the shrinkage, excluding the cracked areas.
4. The volumetric shrinkage strains from image processing method were accurate compared to the veriner method. This method is advantageous especillay when the shrinkage cracks are severe and the specimen is vulnerable to breaking.
5. The volumetric shrinkage was reduced significantly from 56% to 15 %, 11 %, and 5 %, respectively, with a treatment of expansive soil with LAA/FA = 1.0, 1.25, and 1.5 at a curing period of 28 days.
6. The reduction in the volumetric shrinkage of samples treated with LAA/FA = 1.0 from control soil is about 73 %. A further increase in the LAA/FA ratio from 1.25 to 1.5 has shown a minimal additional reduction in the vertical shrinkage from 7 % to 17 % for a 28 days curing period.
7. The LAA/FA=1.25 may be considerd as the optimum dosage to control the volumetric shrinkage of expansive soil at a curig period of 28-days.
8. With a treatment of LAA/FA = 1.5, clay layers were disappeared in the control soil, and a dense crystalline product was seen in the SEM images.
9. SEM images also depict a right amount of dissolution of fly ash that occurred in the control soil treated with LAA/FA =1.5.

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