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Development of Design Guideline for Deep Soil Mixing (DSM) to Stabilize Expansive Soils using Fly Ash as the Stabilizer

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Abstract: Deep soil mixing (DSM) is a ground improvement technique used to improve the ground by in-situ stabilization of soft soil using stabilizers such as cement, lime and fly ash for depths greater than 1.5 m. To date, there are no studies focusing on developing a design guideline for DSM method to treat expansive soil using fly ash. Therefore, aim of this study was to develop a design guideline for DSM to stabilize expansive soil using fly ash as the stabilizer. Four different expansive soil samples obtained from Digana, Sri Lanka were treated with 10 - 25% fly ash by weight. A series of swell pressure tests were conducted on the untreated and treated samples to calculate the surface heave of the expansive soil – fly ash composite ground for different area ratio values (10 - 60%). Altogether sixteen heave versus area ratio design charts were developed for various fly ash contents and DSM column lengths (2 - 8 m). Further, spacing versus area ratio charts were developed for different diameters of the DSM columns for square and triangular arrangements. Based on the findings, it was noticed that incorporation of fly ash into expansive soil reduces the swell pressure significantly (53 – 86% reduction compared to the untreated expansive soil). The developed heave versus area ratio design charts can be used for the design and construction of DSM columns in expansive soils using fly ash as the stabilizer to maintain the total heave within the project specified limit. On the whole, DSM technique can be successfully used to treat expansive soils using fly ash as the stabilizer.

Keywords: Deep soil mixing, Design guideline, Expansive soil, Fly ash, Stabilizer design

1. Introduction

Expansive soils experience large changes in volume when subjected to moisture content variations. These soils can be found in arid and semiarid regions, where the expansive clay minerals such as montmorillonite or illite contents are present [1]. Due to the swell-shrink behaviour of expansive soils, civil infrastructure such as residential buildings, pavements and canal linings are severely distressed and several billions of dollars are spent annually on the rehabilitation of these structures [2]. Deep Soil Mixing (DSM) technique is one of the most effective ground improvement techniques used to stabilize expansive soils at depths greater than 1.5 m [2-4]. This method helps to improve the mechanical and physical properties of expansive soils after mixing with stabilizers, such as cement, lime and fly ash. The DSM technique can be classified into two methods based on the method of mixing: (i) wet method; and (ii) dry method. In the wet method, the soil is mixed with the slurry that includes the binder, while the soil is mixed with the dry binder in the dry method [4]. Wet method is more appropriate for soft clays, silts and fine-grained sand with lower moisture content, while the dry method is more appropriate for soft soils with very high moisture content greater than 60% [5]. In this study, wet method of DSM was used as the moisture content of the expansive soil used was not very high.

The DSM treatment method comprises the following two major steps [2]: (1) Stabilizer design - stabilizer design consists of (a) selection of the binder type and optimum binder content and (b) determination of optimum water-binder ratio for maximum performance of DSM column; and (2)

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Geometric design - determination of geometric parameters such as length, diameter and spacing between DSM columns. In the early stages of the DSM application, it was assumed that the binder content is the only factor controlling the strength development of the DSM treated samples [6, 7]. In recent studies [8-11], it has been proved that, in addition to the binder content, amount of water added (water-binder ratio) in the mix also plays a vital role in the engineering behaviour of treated DSM samples as the water is important for the hydration of the binder and for efficient mixing.

Most commonly used binder types in the DSM treatment are cement and lime. However, manufacturing of ordinary Portland cement (OPC) is energy intensive and emits approximately 0.7 – 1 ton of CO_2 per 1 ton of cement produced [12, 13]. This makes OPC and OPC based products highly untenable and it is necessary to look for sustainable alternatives for OPC based binders for construction applications, including soil stabilization. It has been found that fly ash can be used as a sustainable alternative to OPC based binders in soil stabilization work and it is well documented that fly ash is an effective stabilizer for expansive soils [4, 14-17]. Based on previous findings, the optimum fly ash content for soil stabilization work is between 10% to 20% by weight [14, 17, 18]. To date, there are no studies focusing on the development of a DSM guideline for expansive soil using fly ash as the stabilizer. Therefore, aim of this study was to develop a design guideline (stabilizer design and geometry design) to stabilize expansive soil using fly ash as the stabilizer.

2. Materials and Methodology

2.1 Materials

2.1.1 Expansive Soil

The expansive soil samples used in this study were collected from four different locations [Location 1 (L1) - 7.299103, 80.710539, L2 - 7.298720, 80.710369, L3 - 7.298401, 80.710369 and L4 - 7.298639, 80.709775] in Digana area, Sri Lanka. The basic index properties of the soils were determined using bulk unit weight, initial moisture content, Atterberg limits, hydrometer analysis and sieve analysis in accordance with BS1377: Part 2: 1990. Constant volume swell pressure tests (BS 1377: Part 5: 1990) were conducted on the disturbed soil samples to determine the final swell pressure of the untreated expansive soils. Prakash and Sridharan [19] proposed free swell tests to classify the swell potential of the expansive soil samples. A free swell test is conducted by taking the equilibrium volume of 10 g oven dry soil passing 425 µm in distilled water (V_d) and kerosene (V_k). Free swell ratio (FSR) is determined by the ratio V_d/V_k. The soil classification is done using Unified Soil Classification System (USCS). Grain size distribution curves are given in Figure 1 and the index properties and the free swell test results of all the four expansive soils (L1 – L4) are given in Table 1. Of the four expansive soil samples obtained, three samples were classified as moderately expansive while the other possessed low swell potential. Prior to the use of these expansive soils for the stabilizer design experiments, they were oven dried, sieved through 2 mm sieve and then were homogenized as suggested by Bhadriraju et al. [3] and Liu et al. [20].

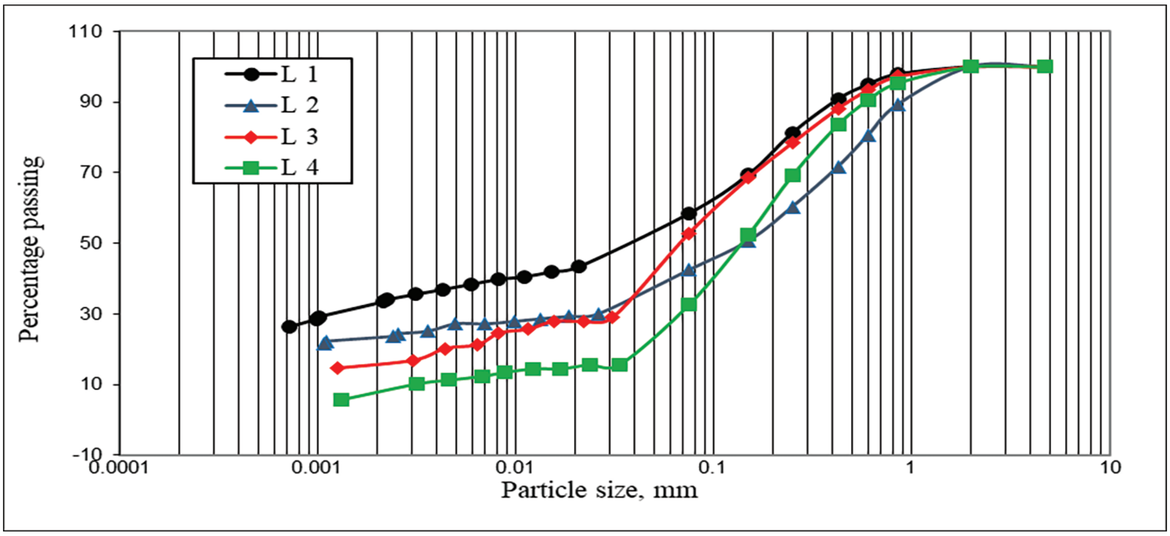


Figure 1 - Grain Size Distribution Curves for Untreated Samples

Table 1 - Basic Properties of Expansive Soils used in the Study

Property	Sample Location			
	L1	L2	L3	L4
Bulk density (kg/m^3)	1597	1681	1963	1733
Natural moisture content (%)	26	16	18	27
Liquid limit (LL) (%)	45	37	36	34
Plastic limit (PL) (%)	36	30	26	26
Plasticity index (PI) (%)	9	7	10	8
Free swell ratio (FSR)	1.60	1.55	1.55	1.40
Potential swell classification according to the FSR as per Prakash and Sridharan [19]	Moderate	Moderate	Moderate	Low
Sand % (4.75 -0.075 mm)	45	60	47	67
Silt % (0.075 – 0.002 mm)	22	18	38	25
Clay % (< 0.002 mm)	33	22	15	8
Unified Soil Classification	CL	SC	ML	SM
	Low-plasticity clay	Clayey Sand	Low-Plasticity silt	Silty sand

2.1.2 Fly Ash

Fly ash used in this study was collected from Lakwijaya coal power plant, Norochcholai, Puttalam, Sri Lanka and the type of fly ash used is ASTM Class F (low calcium fly ash). There are two major types of fly ash. ASTM Class F fly ash possesses more than 70% weight percentage of $SiO_2 + Al_2O_3 + Fe_2O_3$ and contains low amounts of lime, whereas ASTM Class C fly ash contains 50 – 70% weight percentage of $SiO_2 + Al_2O_3 + Fe_2O_3$ and is high in lime content [21]. The chemical composition of the fly ash determined by X-ray fluorescence (XRF) analysis is given in Table 2.

Table 2 - Chemical Composition of FA

Constituent	Percentage (%)
SiO_2	45.55
Al_2O_3	33.48
Fe_2O_3	3.07
CaO	8.40
P_2O_5	2.83
TiO_2	1.93
MgO	1.59
K_2O	0.71
SO_3	0.81
MnO	0.06
Na_2O	0.62

2.2 Methodology

2.2.1 Stabilizer Design Process

The method of laboratory mixing followed in this research for the stabilizer design was adopted from Bhadriraju et al. [3]. In the stabilizer design, water/binder ratio of 0.6 was used. It should be noted that this water/binder ratio excludes the natural water content of the soil and the water quantity corresponding to the natural water content was added separately as proposed by Bhadiraju et al. [3]. The following steps were followed in the stabilizer design:

1. Prior to the mixing, bulk weight of untreated expansive soil passing US Sieve No 10 (2 mm) was oven dried at 105 ˚C for a period of 24 hours.
2. As recommended by Bhadiraju et al. [3], mix design given in Table 3 was adopted to prepare the fly ash stabilized sample. In this study, stabilized samples were prepared with the fly ash contents (hereafter referred as "binder content", a_W) of 10%, 15%, 20% and 25% and these values were chosen as this range has been used in many studies in the literature [2, 14, 16, 17, 22]. Table 3 also shows trial values of the mix design parameters for the expansive soil at Location 1 (L1) with 10% binder content (fly ash content). For each binder content, appropriate amount of binder was weighed based on the parameters including binder factor (α), required amount of dry soil (W_S), and total water content (w_T) which includes the initial water content (w_n) and

amount of water from the water/binder ratio ($W_{w,slurry}$), to prepare the soil-binder mixture, as explained in Table 3.

3. The quantities of binder and dry soil estimated as per Table 3 were mixed uniformly in dry state. Total amount of water was then added to the dry soil-binder mixture and it was thoroughly mixed manually for a period of 5 to 7 minutes until a homogenous mixture was obtained.

Table 3 - Mix Design used for Stabilizer Design and a Sample Set of Calculation for Expansive Soil at Location 1 (L1) with 10% Binder Content

Description and Notation	Equation	Trial Values for a_w = 10%
Bulk unit weight, γ_b (kg/m^3)	W/V	1597.4
Initial water content, w_n (%)	Calculated as per BS 1377: Part 2: 1990	26.1
Dry unit weight, γ_d (kg/m^3)	$\gamma_b/(1+ w_n)$	1267.1
Total volume per one sample mix, V (m^3)	User specific	9.89×10^{-4}
Dry weight of soil per sample, W_s (kg)	$\gamma_d \times V$	1.253
Binder content, a_w (%)	W_b / W_s	10
Binder factor, α (kg/m^3)	$(a_w \times \gamma_b)/100(1+ w_n)$	126.8
Weight of binder per sample, W_b (kg)	$\alpha \times V$	0.125
Water binder ratio, w: b	$W_{w,slurry}$ / W_b	0.6
Weight of water for slurry, $W_{w,slurry}$ (kg)	W_b × (w: b)	0.075
Total water content of the mix, w_T (kg)	$w_n + W_{w,slurry}$	0.402

4. Final stabilized mixture was transferred to the compaction mould (100 mm inner diameter and 127 mm height) in three layers. The samples were compacted with the compactive energy imparted in the standard Proctor compaction test (BS 1377: Part 4: 1990). Each layer was compacted by 27 blows using 2.5 kg light weight hammer free falling from 300 mm. This delivers a nominal compaction energy of 593 kJ/m^3 which corresponds to the compaction energy imparted by a light roller in the field.
5. The samples were extruded and wrapped with airtight polythene bags to prevent any moisture loss and these were cured at room temperature (28 ± 2 ˚C) for a period of 28 days.
6. After 28 days of curing, constant volume swell pressure test (BS 1377: Part 5: 1990) was conducted to determine the swell pressure of the stabilized samples. Initially, stabilized sample passing through 0.425 mm sieve was kept in an oven for a period of 24 hours. Pre-determined quantity of soil was placed into the consolidation ring (with 75 mm inner diameter and 20 mm height) and the sample was compacted to the field density. Two porous stones were placed at the top and bottom of the sample and filter papers were placed between the soil specimen and the porous stone on both sides. The specimen was then placed on the base of the test apparatus and base plate was adjusted until the load measuring proving ring attached to the loading frame touches the sample. At this point, the displacement dial gauge reading was set to zero. Distilled water was added to the specimen to initiate the swelling. To prevent any volume change of the specimen in the constant volume test, the base plate was adjusted (by rotating the arm) to ensure dial gauge reading is constant (at zero). When the specimen was in equilibrium (no change in the dial gauge reading) under a given load for a period of 20 minutes, the corresponding load proving ring reading was recorded and the final swell pressure of the treated soil was calculated.

Heave of expansive soil was calculated based on the swell pressure test results of the untreated and treated soil. A schematic view of the DSM treated expansive soil layout used for the heave calculation is given in Figure 2. The swell of the composite ground (S_w) was estimated using Eq. (1) while Eq. (2) was used to estimate the total heave of the expansive soil-DSM composite ground [2, 23]. Area ratio (which is defined as the total area of the DSM columns divided by the total treated area) values were changed from 10 – 60% as per literature [2, 4].

$$S_w\,\% = S_{w,col}\,\% \times a_r + S_{w,soil}\,\% \times (1 - a_r) \qquad ...(1)$$

where $S_w\ \%$ is swell percentage of expansive soil-DSM column composite region, $S_{w,col}\ \%$ is swell percentage of treated DSM column, $S_{w,soil}\ \%$ is swell percentage of untreated expansive soil and a_r is the area ratio [2].

$$\Delta H = \Sigma\, [S_{w,i}\,(\%)\,]\,(H_i)(0.01) \qquad ...(2)$$

where ΔH is surface heave, $S_{w,i}\ (\%)$ is swell percentage of composite soil and H_i is thickness of layer i [23].

These equations Equs. (1) and (2) were used to develop heave versus area ratio design charts for a given binder content and DSM column length. The length of the DSM column should be equal to the depth of active zone. Generally, active zone depth varies between 1.5 m to 9 m depending on the region [2, 3]. Hence, DSM column lengths of 2 m, 4 m, 6 m and 8 m were used in the present study.

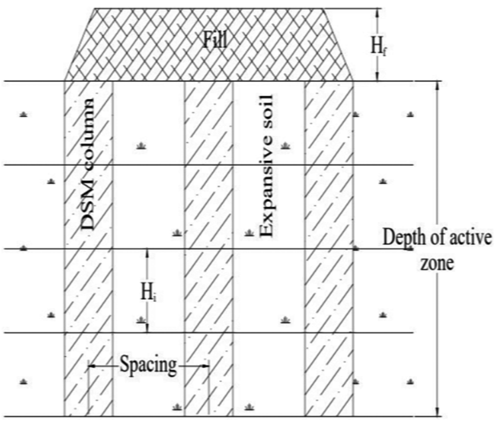


Figure 2 - Schematic View of the Expansive Soil Layers for Heave Calculation

2.2.1 Geometrical Design Process

The purpose of geometrical design is to determine the final installation pattern and dimensions of the improved ground on the basis of appropriate stability and settlement analyses to satisfy functional requirements of the supported structure. Length and diameter of the column and centre to centre spacing between two columns are the geometric parameters to be included in the design guideline [2]. DSM column diameters from 0.3 m to 0.9 m have been used in previous studies [2]. Therefore, DSM column lengths of 2 m, 4 m, 6 m, and 8 m and DSM column diameters of 0.2 m, 0.4 m, 0.6 m, 0.8 m and 1.0 m were selected in the present study to develop the design guideline. Spacing between the DSM columns depends on the configuration of the column arrangement (square, triangular, etc.) A correct spacing between the columns needs to be maintained to obtain the required treated area ratio to limit the heave within the acceptable range [2]. The spacing between columns for square and triangular arrangements of the DSM columns (Figure 3) can be estimated from Equations (3) and (4), respectively [2].

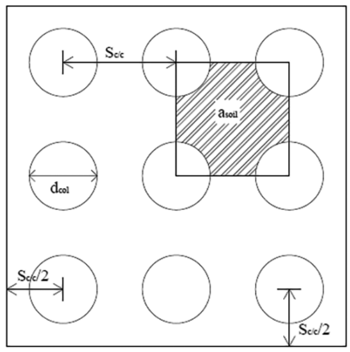
$$S_{c/c} = (\Pi/4 \times a_r)^{0.5} \times d_{col} \qquad ...(3)$$

$$S_{c/c} = (\Pi/3.464 \times a_r)^{0.5} \times d_{col} \qquad ...(4)$$

where $S_{c/c}$ is spacing between the columns, a_r is treated area ratio and d_{col} is diameter of the column.

Generally, area ratio used for the DSM treatment varies from 10% to 60% [2, 4]. According to Equs. (3) and (4), the recommended spacing for square and triangular arrangements are 2.8 - 6.9 times the diameter of the DSM column and 3.0 - 7.4 times the diameter of the DSM column, respectively.

Equs. (3) and (4) were used to develop spacing versus area ratio design charts for square and triangular arrangements of the columns, respectively.



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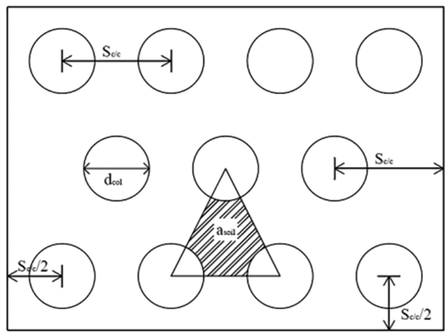


(b)

Figure 3 - Treated Ground Arrangement; (a) Square Arrangement; (b) Triangular Arrangement

3. Results and Discussion

3.1 Effect of Fly Ash Stabilization on the Swell Behaviour of Expansive Soils

Figure 4 shows the variation of swell pressure with the binder content (fly ash content) for all the four expansive soils obtained from L1 – L4. The swell pressure values of the untreated expansive soils obtained from L1 to L4 were 104 kPa, 73 kPa, 48 kPa and 35 kPa, respectively. According to Figure 4, swell pressure values of all the stabilized samples reduce with the increase in binder content in the mixture. The percentage reduction in the swell pressure varies from 53 – 83% depending on the location of expansive soil sample. The fly ash particles have the potential to provide multivalent cations (Ca^{2+}, Al^{3+}, Fe^{3+}, etc) that promote flocculation of clay particles by cation exchange [14]. As a result, the surface area and water affinity of the samples decrease leading to reduced swell potential values [14, 22].

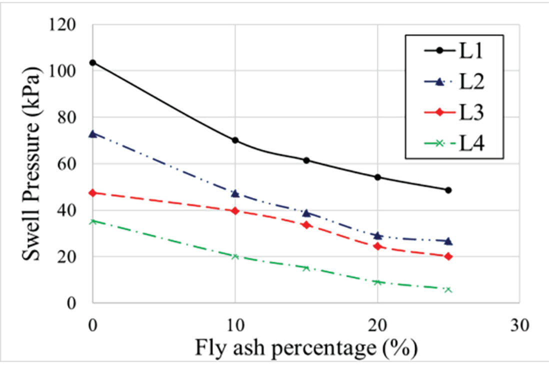
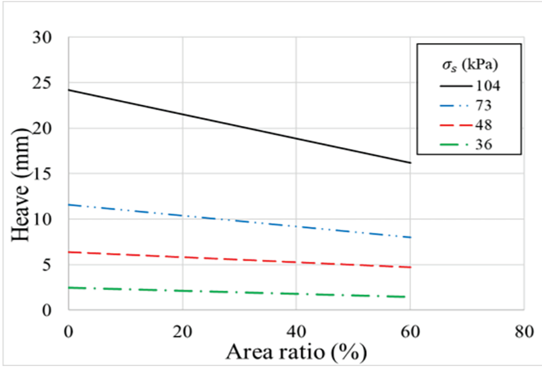


Figure 4 - Variation of Swell Pressure with Binder Content for Expansive Soil Samples from Different Locations

3.2 DSM Design Charts for Expansive Soil Treated with Fly Ash

For a given swell pressure (σ_s), heave versus area ratio charts depend on the binder content and length of the DSM columns. In this study, four different binder contents (10%, 15%, 20%, and 25%) and four different DSM column lengths (2 m, 4 m, 6 m, and 8 m) were used. Therefore, a total of sixteen heave versus area ratio design charts were developed in this study and they are presented in Figures 5 to 8. According to Figures 5 to 8, it can be seen that total heave reduces with the increase in the area ratio. When the area ratio increases, more and more area of the site is covered with the fly ash stabilized soil. Provision of multivalent cation increases with the increase in amount of fly ash particles and this reduces the water affinity of the samples leading to reduced heave values.



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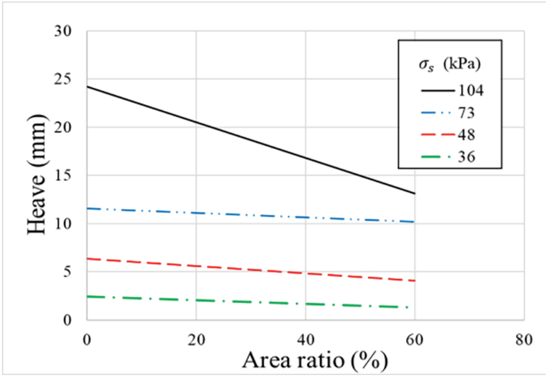

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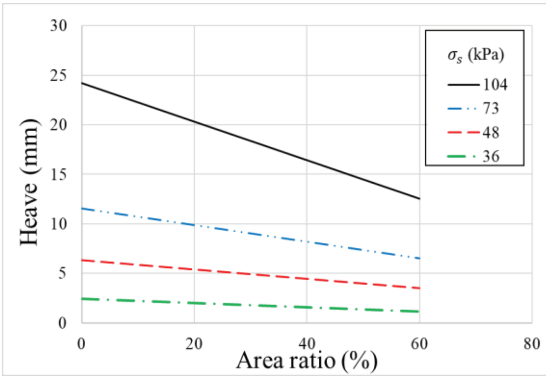

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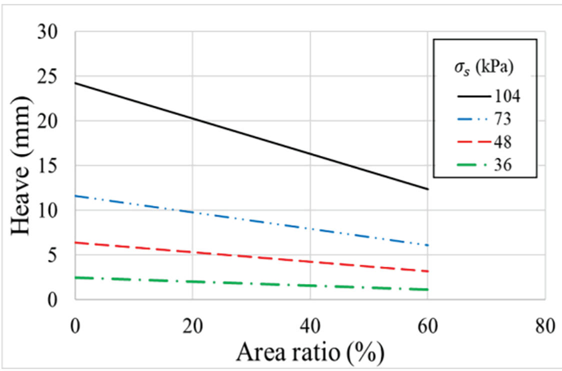
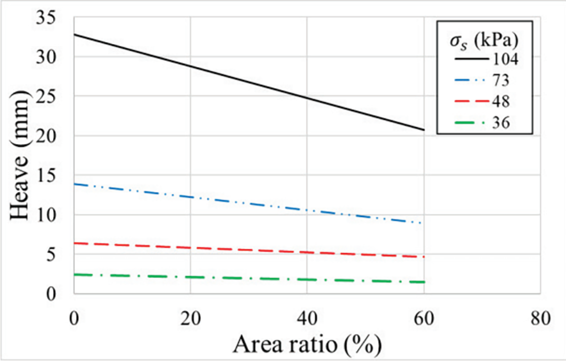


(d)

Figure 5 - Heave Versus Area Ratio Design Charts for Column Length 2 m; (a) 10% Fly Ash (b) 15% Fly Ash; (c) 20% Fly Ash; (d) 25% Fly Ash



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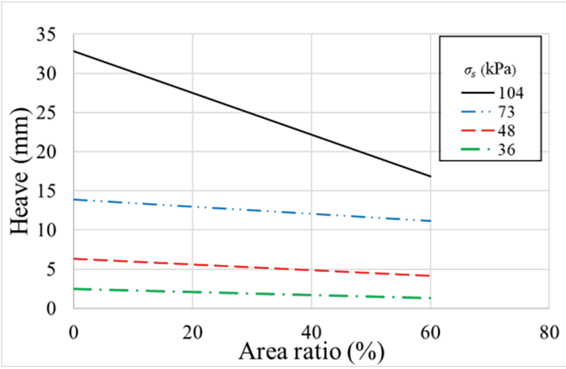

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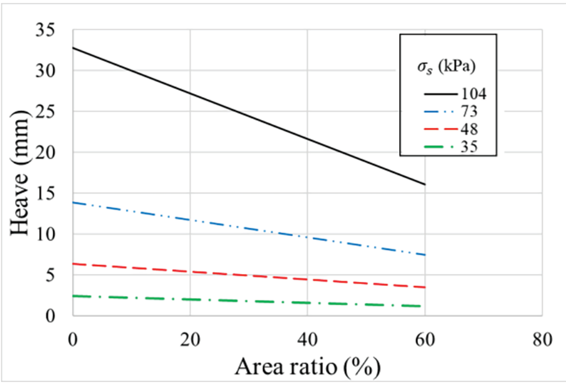

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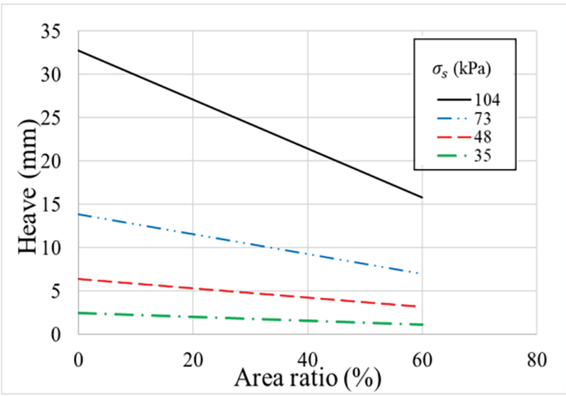
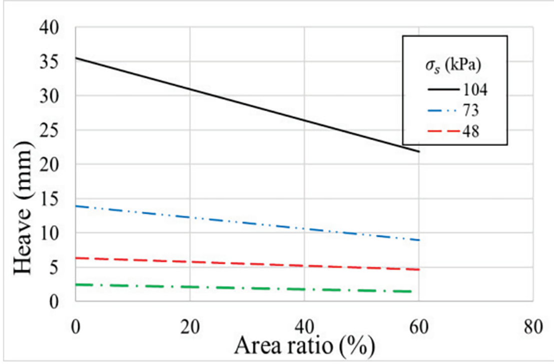


(d)

Figure 6 - Heave Versus Area Ratio Design Charts for Column Length 4 m; (a) 10% Fly Ash; (b) 15% Fly Ash; (c) 20% Fly Ash (d) 25% Fly Ash



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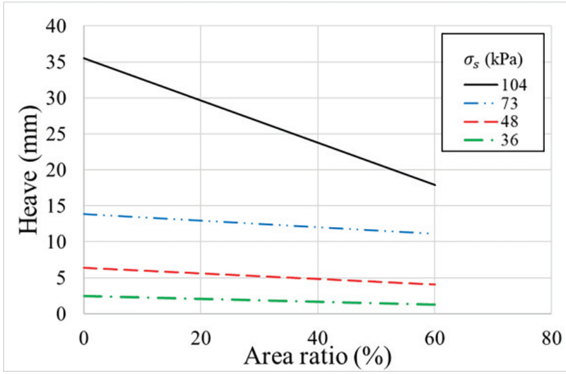

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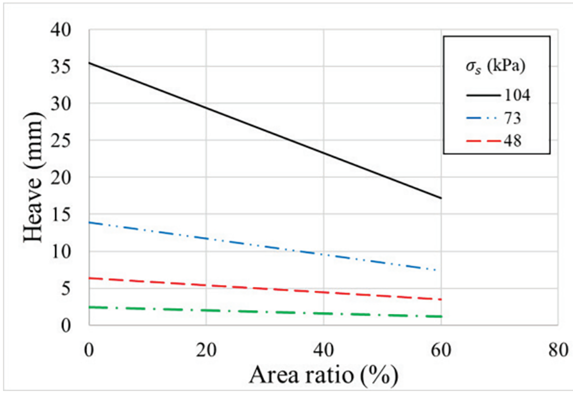

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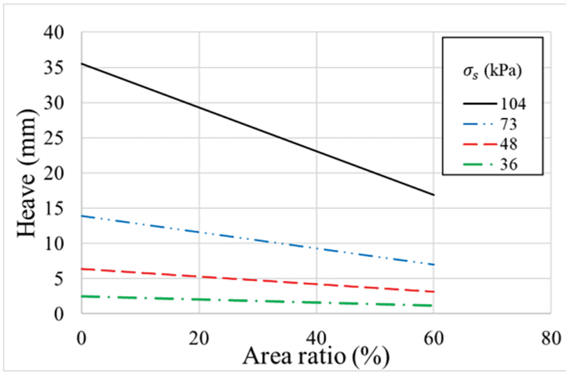
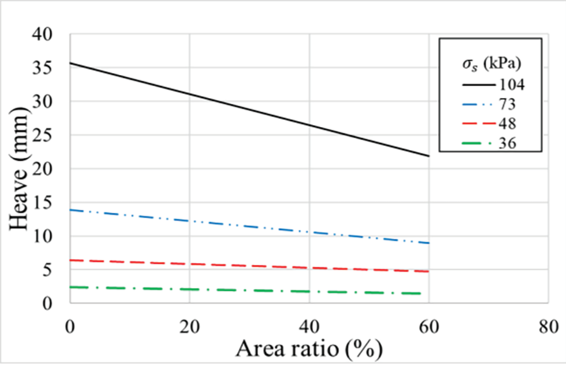


(d)

Figure 7 - Heave Versus Area Ratio Design Charts for Column Length 6 m; (a) 10% Fly Ash; (b) 15% Fly Ash; (c) 20% Fly Ash; (d) 25% Fly Ash



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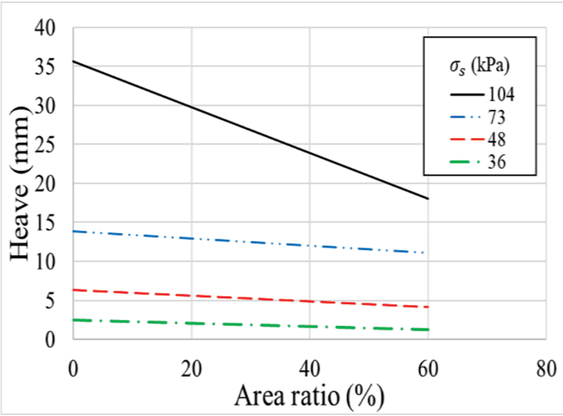

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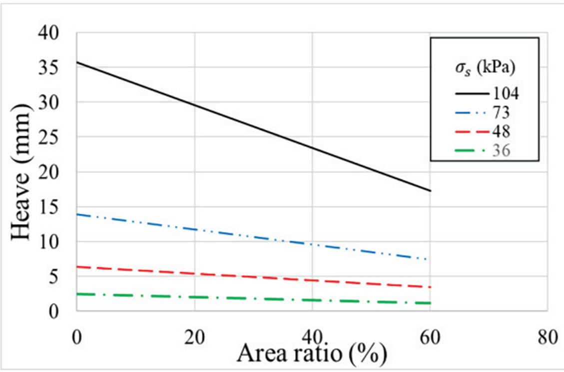

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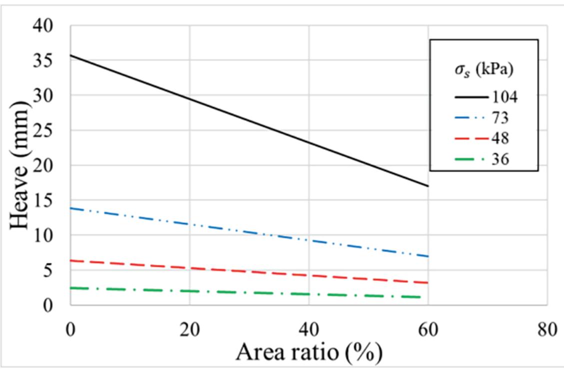
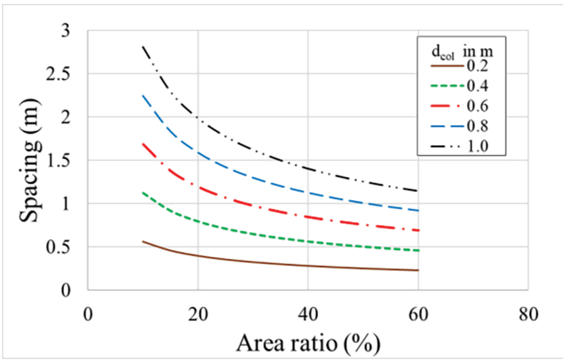


(d)

Figure 8 - Heave Versus Area Ratio Design Charts for Column Length 8 m; (a) 10% Fly Ash; (b) 15% Fly Ash; (c) 20% Fly Ash; (d) 25% Fly Ash

It should be noted that the cost of the DSM work is inversely proportional to the established value of the total heave. The total limiting heave for a given project needs to be defined and, for instance, the total allowable heave values for flexible pavements, rigid pavements, tunnels and building projects are 12 mm, 18 mm, 10 mm and 40 mm, respectively [2, 4]. These developed charts (Figure 5 - 8) can be used to determine the required area ratio for a given binder content and the DSM column length based on the established total heave value in the project. As can be seen from these charts (Figures 5 - 8), total heave predicted for L1 is significantly higher than the other three locations and it is due to the high swell pressure value recorded at L1 (104 kPa) compared to other three locations (36 – 73 kPa). The swell pressure values (σ_s) obtained for these four locations vary from 36 to 104 kPa and therefore these charts can be used to design the DSM columns for expansive soil sites having swell pressure values within this range.

For a given arrangement (square or triangular), spacing versus area ratio design charts depend on the diameter of the column. The spacing versus area ratio design charts for the two arrangements used are given in Figure 9.



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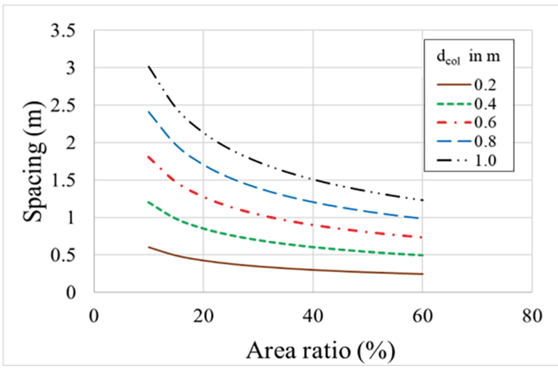

(b)

Figure 9 - Spacing Versus Area Ratio Design Charts for; (a) Square Arrangement; (b) Triangular Arrangement

3.3 Design Guideline for DSM to Stabilize Expansive Soil with Fly Ash

Planning of the DSM treatment involves assessment and selection of engineering properties of stabilized soil in specific ground conditions (soil-fly ash mixture) and selection of the installation pattern (square or triangular) and dimensions of improved ground (geotechnical design). The following design steps can be adopted to design and construct DSM columns to treat expansive soil using fly ash the stabilizer:

1. Estimate the swell pressure (σ_s) and unit weight (γ_s) of the untreated expansive soil. The swell pressure can be determined using either conventional consolidation tests or constant volume swell pressure tests.
2. Estimate the active zone depth at the construction site. Based on the active zone depth, estimate total heave of the untreated soil by using Eq. (2) reported in section 2.2. Check whether the estimated total heave is within the recommended value for the project. If the magnitude of the total heave is more than the project specified value and the length of the active zone is more than 1.5 m [4], DSM technique can be employed to reduce the heave to allowable values.
3. If the DSM technique is the feasible option, decide the percentage of the fly ash to be used (binder content = 10 – 25%). Estimate the swell characteristics of stabilized soil using a constant volume swell pressure test. The total heave of the composite ground can be obtained using Equation (2) reported in section 2.2. Develop a set of heave versus area ratio charts for a given binder content and length of the DSM column (active zone depth). Figures 5 to 8 show the heave versus area ratio design charts using fly ash as the stabilizer for various DSM column length values (2 – 8 m) and fly ash contents (10% - 25%).
4. Estimate the required treated area ratio from the heave versus area ratio design charts (Figures 5 - 8) to reduce the total heave to the allowable value established for the project. It should be noted here that these design charts can be used for expansive soils having swell pressures in the range of 36-104 kPa, fly ash content of 10-25% and DSM column lengths of 2-8 m.
5. Decide the diameter of the DSM column based on the dimensions of the available DSM rigs [2, 4].
6. Determine the configuration of the DSM column in the site. Based on the treatment area ratio and the DSM column diameter established, spacing between the DSM columns can be established from Figure 9 for square or triangular arrangements of the DSM column.

4. Conclusions

A research study was carried out to develop a design guideline for deep soil mixing (DSM) to stabilize expansive soil using fly ash as the stabilizer. Based on the findings of this research, following conclusions can be drawn:

1. When the expansive soil is stabilized with ASTM class F fly ash, swell pressure reduces significantly. In this study, for moderately expansive soil, swell pressure reduction of 53 - 83% was obtained when the binder content (fly ash content) was increased from 10 to 25%. When the binder content in the stabilized mixture increases, amount of exchangeable cations increases and hence flocculation increases. This causes reduction in the surface area and water affinity of the samples thereby reducing the swell potential values.
2. A total of sixteen heave versus area ratio design charts were developed for various DSM column lengths (2 – 8 m), treated area ratios (10 - 60%), binder contents (10 - 25%), and swell pressure values of expansive soils (36 – 104 kPa). These charts can be used to predict the total heave of the DSM treated ground when fly ash is used to treat expansive subgrade.
3. Further, spacing versus area ratio charts were developed for various DSM column diameters (0.2 – 1.0 m) for square and triangular arrangements. Depending on the decided DSM column arrangement, the spacing between the columns can be determined from these charts.
4. On the whole, fly ash can be successfully used to stabilize expansive soil and the developed design charts in this study can be used for the DSM treatment of expansive soil using fly ash as the stabilizer.

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