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Compaction and consolidation characteristics of chemically treated expansive soil of Jamshoro

Nizakat Ali, Aneel Kumar * and Manoj Kumar

Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro Pakistan

* Corresponding author: Dr. Aneel Kumar, Email: aneel.kumar@faculty.muet.edu.pk

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K E Y W O R D S

Jamshoro Soil

Lime

Fly Ash

Silica Fume

Consolidation Parameters

A B S T R A C T

The Jamshoro soil is a weak and expansive soil. The construction of infrastructure on such soils has resulted severe damages and huge maintenance costs. Thus, it needs treatment to enhance its geotechnical properties. This research work investigates the effects of chemical stabilizers such as lime, fly ash, and silica fume on the compaction and consolidation characteristics of expansive soil of Jamshoro. The stabilizers were added individually in different proportions (5%, 10%, 15%, and 20%) in the soil. The results show that maximum dry density decreased, while optimum moisture content increased with the increase of the stabilizers' content in the soil. The compression index and swelling index of lime treated soil significantly decreased than that of soils treated with silica fume and fly ash. On the other side, the coefficient of consolidation and permeability of fly ash treated soil considerably increased than that of soils treated with silica fume and lime.

1. Introduction

The civil engineering structures supported on expansive soils are prone to danger due to their tendency to undergo unusual settlement [1]. This behaviour of expansive soil of being hard in a dry state and weak or unstable in a wet state is due to its high shrinkage and swelling potential, low shear strength when wet, high plasticity, low permeability and volumetric instability [2–3]. These properties of clayey soil are due to presence of clayey minerals such as montmorillonite, which swells by absorbing the moisture in the rainy season and shrinks in the dry season by leaving cracks on the top [4]. Moreover, the unusual movement of this soil due to objectionable swell-shrink behaviour causes serious damages to the structures or pavements overlaying it [5]. The damages or cracks caused to such structures requires high repairing and rehabilitation cost. The cost of rehabilitation due to damages induced by expansive soils has been figured in billions of dollars [3] and sometimes it exceeds the cost incorporated due to natural disasters (earthquake, floods, hurricanes, etc.) [6].

Due to the unpredictable behaviour of expansive soil in terms of the settlement, such soil is less likely to be used in any type of construction. However, due to the rapid increase in urban areas, it is inevitable to use lands covered with such soil [7]. Therefore, to make this soil less-problematic, various methods are employed including common techniques such as soil replacement, treating with chemicals or mechanical stabilization, etc. Replacing the whole of the problematic soil with quality soil and mechanical stabilization of weak soil are found to be costly methods [2]. Hence, treating the weak soil with chemicals is the most commonly adopted technique. In practical applications, various chemicals are used as a stabilizer with expansive soil to make it bearable soil. The expansive soil can undergo volumetric changes; therefore, the compressibility characteristics are analysed.

Commonly, the chemical stabilizers added to heighten the compressibility characteristics of the weak soil are lime, cement, fly ash, precipitated silica, sawdust ash, coffee ash, peat ash, rice husk ash, plastic waste, tire buffings, coal combustion product, fibre, etc. [2, 8-20]

In the literature, the work has been carried out to analyse the consequence of lime (in the dose of 2%, 4%, 6% and 8% of the dry mass of soil) on permeability and compressibility characteristics of two different soils (saprolitic soil and lateritic soil) [8]. From the findings of this research, it has been deduced that both the soils reacted differently on the addition of lime. The prompt effect on soil was found as aggregation and cation exchange, which is due to the increase of pH value. In saprolitic soil, the permeability first increases on the addition of 2% and thereby decreases on further addition. However, in lateritic soil, permeability decreases as the content of the lime have increased. For compressibility characteristics, the lime was found to be an efficacious stabilizer for both the soils. The soils stabilized with lime depicted high resistance to the compressibility as compared to untreated soil.

A comparative study [13] has been performed to know the effect of fly ash and lime on the swell, shear strength and consolidation characteristics of expansive soil. The additive lime was added in the proportion from 2% to 6% and that of fly ash at 10% and 20%. From the research outcome, it has been observed that the compression index and coefficient of consolidation increased on the initial content of stabilizers and decreased on later addition of both the stabilizers. Furthermore, the secondary consolidation of expansive soil has a minimum value when it is blended with 4% lime and 20% fly ash.

The work has also been carried out to analyse the effect of blending silica in a problematic soil [2]. The plasticity, strength, compressibility, and permeability were the properties under question, while the silica added was up to 70%, with an increment of 10% in each sample. From this work, it has been concluded that the properties of weak soil have been enhanced as the stabilizer has been added. Moreover, the plasticity of the soil decreased, soaked strength, permeability and rate of consolidation increased.

In the previous work, the comparative study of different stabilizer's effect on enhancing the consolidation characteristics was rarely found. Furthermore, no work has been performed to know the effects of stabilizer on consolidation parameters of Jamshoro soil which is an expansive soil [21-23]. Therefore, this research work has been carried out extensively to compare the effect of lime (L), fly ash (FA), and silica fume (SF) on the consolidation characteristics of Jamshoro soil.

2. Material and Methods

2.1 Soil and Stabilizers

The expansive soil was obtained from Jamshoro, Pakistan along with river Indus, (25º20'11" N, 68º14'13.39" E). The soil was excavated after removing 6 inches topsoil cover to avoid organic impurities. The soil was then brought to the laboratory for the necessary experiments under the scope of this research.

The lime employed in this study was of non-hydraulic hydrated type lime, which constitutes more than 90% of calcium carbonate. The fly ash, a secondary product in coal combustion is collected from Lakhra Coal Power Plant, Jamshoro. The chemical formation of the fly ash obtained from the plant is presented in Table 1 [24]. In addition to lime and fly ash, the commercially available silica fume is utilized in this research.

Table 1

Chemical composition of fly ash obtained from Lakhra Coal Power Plant

Oxides	Composition (%)
Al_2O_3	22
SiO_2	63
CaO	3.80
Fe_2O_3	7.22
MgO	0.7
K_2O	1.3
Na_2O	0.2
TiO_2	1.3

2.2 Sample Preparation

The collected soil was first air-dried and then pulverized so that the particles should not be clumped together. Afterwards, the soil was properly blended with various percentages (by dry weight) of lime, fly ash, and silica fume to obtain the homogenous mix. Thereafter such soils are called treated soils in this research.

2.3 Testing Methodologies

2.3.1 Index properties

The soil finer than 425 μm was taken to evaluate the index properties of soil. The specific gravity of the soil particles was calculated by using Pycnometer method following ASTM D854 [25] and the sieve analysis was performed following ASTM D7928 – 17 [26]. The consistency indices (plastic limit and liquid limit), were also determined by the standard procedure given in ASTM D4318 [27].

2.3.2 Compaction characteristics

Each of the sample, with or without the respective amount of stabilizer was compacted at modified Proctor energy with an increasing amount of water content. Accordingly, a relationship was drawn between dry density and moisture content, to determine the maximum dry density (MDD) and optimum moisture content (OMC). The laboratory test procedure for the moisture-density relationship complied with ASTM D1557 – 12 [28].

2.3.3 Consolidation

The consolidation test was performed by following the procedure given by ASTM D1883 [29]. The samples for consolidation test were prepared by mixing the soil with respective optimum moisture content and then compacted with modified Proctor energy using standard compaction moulds and rammers. The soil cakes were then extruded by using soil extruders. The oedometer specimen ring of 5 cm dia. and 2 cm height was then carefully inserted in the compacted cake of the soil.

The soil in consolidation cell was loaded with the stress of 0.25, 0.5, 1, 2, 4, 16 and 32 kg/cm^2 and unloaded from 32 kg/ cm^2 to 8 kg/cm^2, 8 kg/cm^2 to 2 kg/cm^2 and 2 kg/cm^2 to 0.5 kg/cm^2. The successive stress was kept for 24 hours. On application of every loading, the consequent settlement at 0, 0.1, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480 and 1440 min was recorded. From the collected data, the consolidation parameters like compression index, swelling index, coefficient of volume change, coefficient of consolidation, and hydraulic coefficient were calculated.

3. Results and Discussion

3.1 Geotechnical Properties of Untreated Soil

The basic geotechnical properties of Jamshoro soil are shown in Table 2. The soil was categorized as A-7-6 from AASHTO soil classification [30], and the group index calculated from the Eq. 1 [31].

$$GI = (F_{200} - 35)\left[0.2 + 0.005(LL - 40)\right] + 0.01(F_{200} - 15)(PI - 10) \quad (1)$$

where PI is plasticity index, F_{200} is percentage passing through 75 μm sieve and LL is the liquid limit, which was found to be 20.

Table 2

Basic geotechnical properties of Jamshoro soil

	Property	Value
Classification / Gradation	Gravel (> 4.75 mm)	2.67 %
	Sand (0.075 to 4.75 mm)	22.96 %
	Silt and clay (< 0.075 mm)	74.366 %
	AASHTO soil classification	A-7-6
	Group Index	20
Physical	Natural moisture content	4.32 %
	Plastic limit	28 %
	Liquid limit	54 %
	Plasticity index	26 %
	Optimum moisture content	14.2 %
	Maximum dry density	1.72 gm/cm^3
	Co-efficient of consolidation	0.356 mm/min^2
	Co-efficient of permeability	1.09 × 10^{-8} cm/sec

The Jamshoro soil was identified as shale, with high swelling potential and low CBR value [21]. The colour of the soil was found to be yellowish-brown, along with that some white traces of lime were also observed. The specific gravity of the soil, lime, fly ash and silica fume and soil stabilizer mixtures are shown in Table 3. These values are utilized to calculate the settlement characteristics of the soils.

3.2 Effect of Lime, FA, and SF on Specific Gravity

Specific gravity tells us about the heaviness of any material in comparison with that of the water. Fig. 1 shows the specific gravity of all the samples. It can be seen that the more the amount of stabilizer lesser would be the specific gravity. This behaviour is due to the replacement of soil solids with the tiny particles of stabilizers, which are lighter in weight than that of soil particles. Furthermore, as SF is lighter than FA and Lime, hence the mixture of soil and SF showed higher steepness that that of FA and Lime.

Table 3

Specific gravity of soil, lime, fly ash and silica fume and soil stabilizer mixtures

Material/Sample	Specific gravity			
		Lime	Fly ash	Silica fume
Soil	2.73	-	-	-
Lime	2.35	-	-	-
Fly ash	2.20	-	-	-
Silica fume	1.94	-	-	-
95 % Soil + 5 % stabilizer	-	2.72	2.7	2.685
90 % Soil + 10 % stabilizer	-	2.7	2.68	2.66
85 % Soil + 15 % stabilizer	-	2.65	2.64	2.6
80 % Soil + 20 % stabilizer	-	2.63	2.62	2.59

3.3 Effect of Lime, FA, and SF on Compaction Characteristics

The compaction behaviour of all the samples compacted at modified Proctor energy is shown in Fig. 2. From the figure, it shows that with the increase of stabilizer content, the optimum moisture content (OMC) increased while the maximum dry density (MDD) decreased.

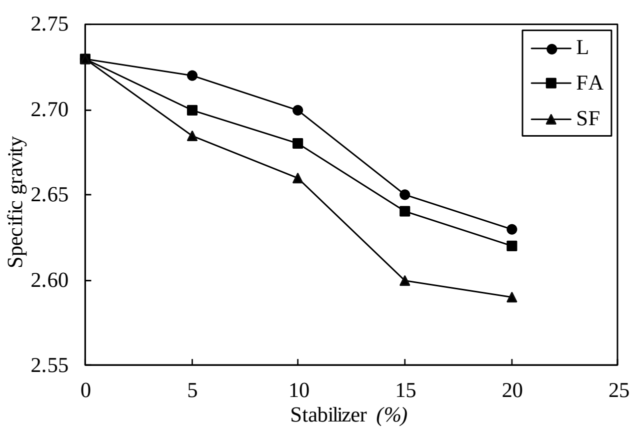

Fig. 1. Change in specific gravity of soil on mixing of stabilizers

The decrease in MDD of treated soil with the increase of stabilizers-content can be due to the creation of cementitious compounds and which may have reduced the further compaction to higher density [32–33]. This effect remains more dominant in the case of SF followed by Lime and FA. On the other hand, the enhancement of OMC of treated soil on the increment of Lime, FA, and SF content is attributed to the prevention in the formation of agglomeration of soil particles, which is due to the coating of stabilizer on soil particles [2]. Hence, the more quantity of water is needed to reach the amount of maximum dry density.

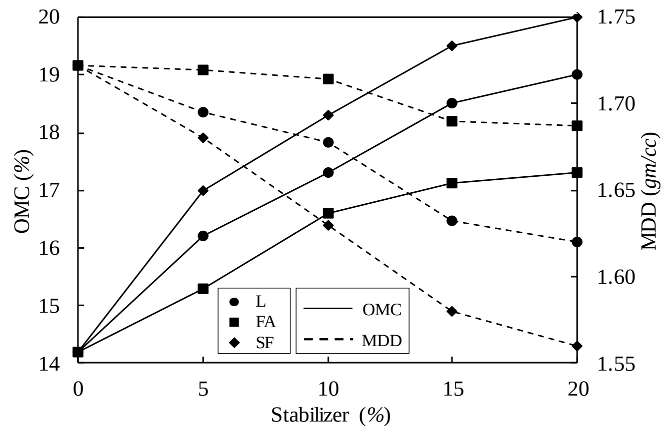

Fig. 2. Effect of stabilizers on maximum dry density and optimum moisture content

3.4 Effect of Lime, FA, and SF on Consolidation Characteristics

3.4.1 Compression index (C_c) and swelling index (C_s)

The graph of void ratio (*e*) versus the log of effective stress (log *p*) in the region of compression of normally consolidated clay (NCC) can be approximated to a straight line, and the gradient of this straight line is designed by a parameter named as compression index (C_c) as shown in Fig. 3. The mathematical formulation of compression index is given by Eq. 2 [34].

$$C_c = \frac{e_0 - e}{\log p - \log p_0} \quad (2)$$

where e_o is the void ratio at pressure p_o and *e* is the void ratio at pressure *p* as shown in Fig. 3.

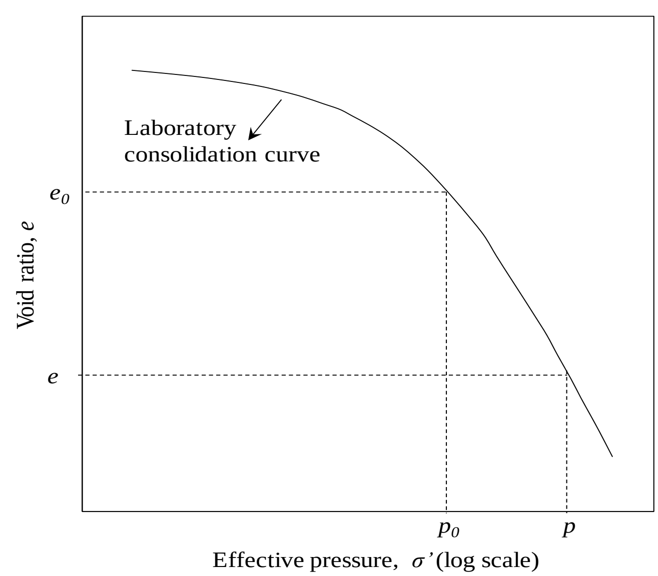

Fig. 3. Typical consolidation characteristics of normally consolidation clay

Compression index (C_c) is a key parameter to predict the settlement of an engineering foundation. Higher the value of compression index, high will be the settlement.

The graph of void ratio (e) versus the log of effective stress (log p) in the region of unloading can be approximated to a straight line, and the gradient of this straight line is defined by a parameter named as a swelling index (C_s) as shown in Fig. 4. The mathematical formulation of the re-compression index is given by Eq. 3 [34].

$$C_s = \frac{e - e_0}{\log p_0 - \log p} \tag{3}$$

Figs. 5, 6 and 7 show the change in void ratio due to the change in stress exerted to the specimens in the one-dimensional consolidation test for soils treated with Lime, FA, and SF respectively. The effect of FA, Lime and SF on the C_c of soil, is shown in Fig. 8. Whereas, Fig. 9 shows the effect of FA, Lime and SF on swelling index (C_s).

From Figs. 8 and 9, the swelling and compression index of all the samples treated with lime reduces as lime content increases. The percentage decrease or percentage increase in C_c and C_s is calculated by Eq. 4, where A is the swelling or compression index of untreated soil and B is the compression or swelling index of the treated soil.

$$\%\,decrease\ in\ compression/swelling\ index = \frac{A-B}{A} \times 100 \tag{4}$$

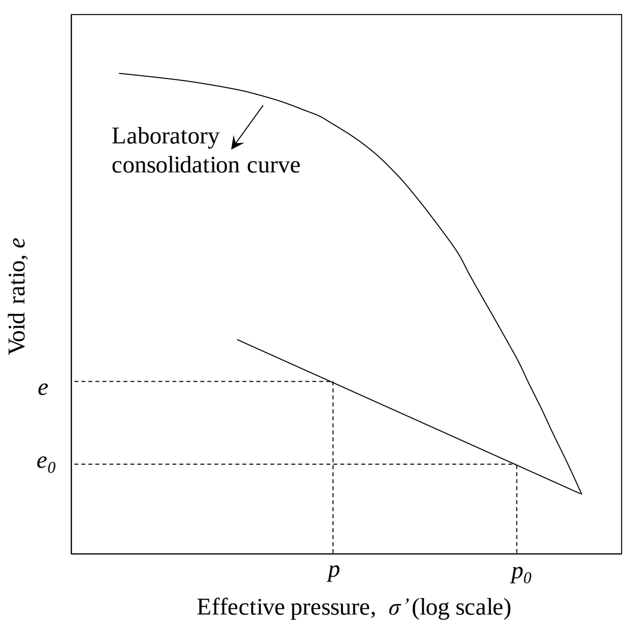

Fig. 4. Typical consolidation characteristics while loading and unloading of normally consolidation clay

It is seen that the compression index was reduced up to 57% when 20% of lime was blended with soil, the decrease in compression index is an indication that the lime treated soil will undergo with less settlement. This change in treated soil is ascribed as the filling-up of voids with finer particles of stabilizers, which decreases the further reduction in voids and development of strength due to reaction products on adding lime and makes the blend strong, which then can sustain the load with reduced settlement [35].

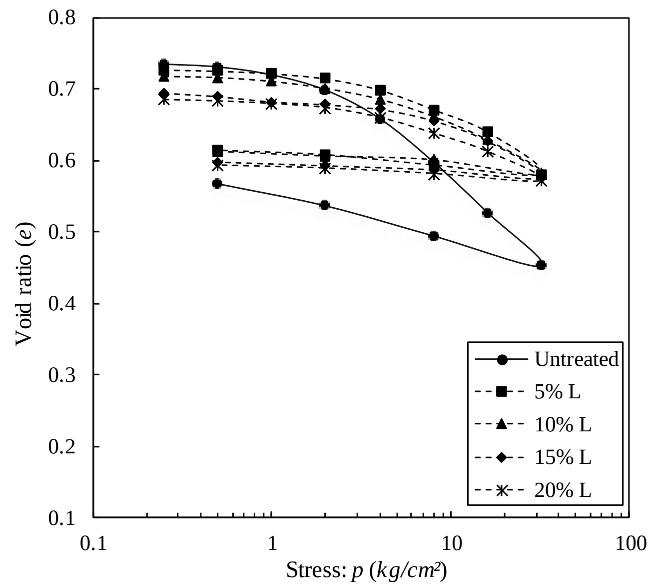

Fig. 5. e - log p curve at various contents of lime

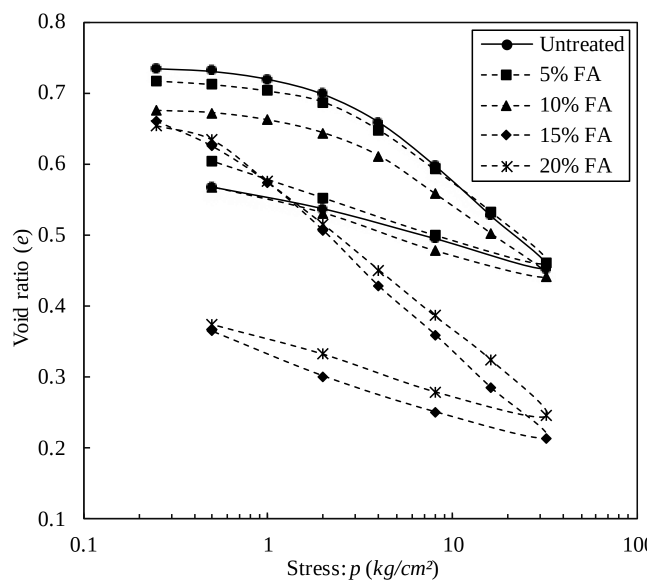

Fig. 6. e - log p curve at various contents of fly ash

When the soil was mixed with FA and SF, the compression index initially reduced and then climbed back as their content is raised. The maximum decrease in compression index value was up to 17.5% at 10% of FA and then it starts increasing, while the maximum decrease in compression index value was up to 17% at 5% of SF and then increased. The initial decrease in the compression index could be due to the filling-up of voids with a stabilizer, which results in a decrease of void ratio with the same applied load. Later, the increment in the compression index with an increase of the FA or SF may be attributed to the less-denser blend, hence more vulnerable to compressibility.

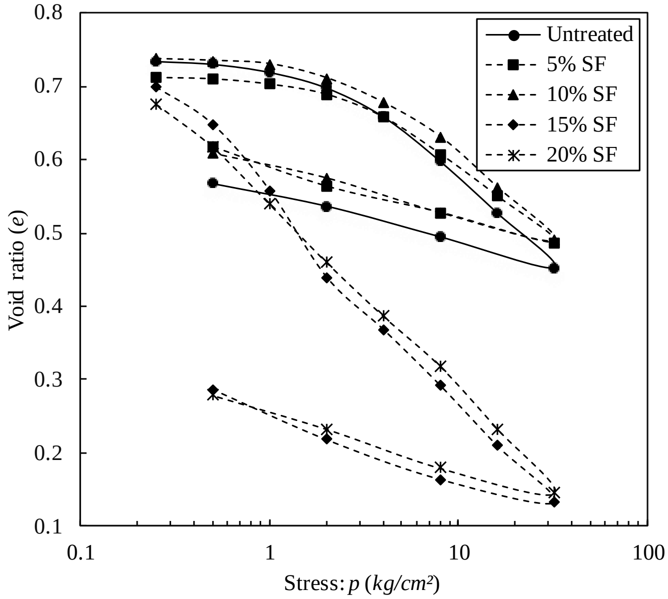

Fig. 7. *e* - log *p* curve at various contents of silica fume

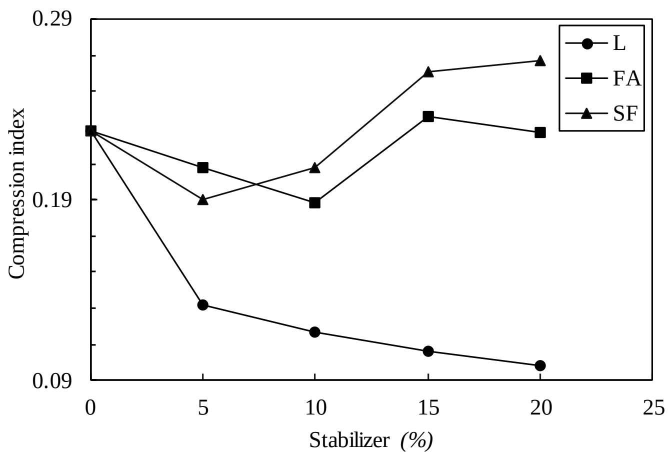

Fig. 8. Change in compression index on the addition of stabilizers

The swelling index of lime treated samples decreased up to 81% when 20% of lime was blended with the soil. The decrease in swelling index of lime treated samples indicates the less potential of soil to get swell. Such a change of swelling index may be attributed to the formation of cementitious products which on the release of the load, hold the soil particles together and prevent them from getting swelled.

The swelling index of treated samples with FA and SF showed no consistent trend. Besides, in all the samples, unlike lime-treated samples, the swelling index slightly increased, which indicates that the cementitious compounds are rarely formed in the presence of FA and SF.

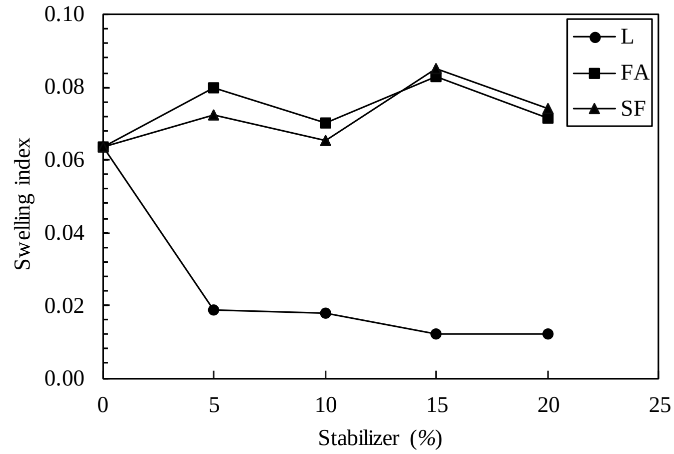

Fig. 9. Change in swelling index on the addition of stabilizers

3.4.2 Coefficient of consolidation (C_v)

The coefficient of consolidation is the measure of the rate at which the consolidation takes place for a certain increase in stress. The C_v versus stabilizer content is given in Fig. 10. The C_v values, presented in this study are calculated for the test conditions when applied stress was increased from 16 kg/cm^2 to 32 kg/cm^2, as this is the maximum stress applied in the test conditions of this study.

Fig. 10 shows that, on the addition of lime up to 10%, the C_v increased and then decreased with the further increase of lime content. While, when the soil was mixed with FA and SF, the C_v has gradually enhanced with an increment of the percentage of FA and SF. The maximum value of C_v for both the stabilizers was found at the blend of 20% stabilizer. The increase in the value of the coefficient of consolidation indicated that with the increase of stabilizers, the consolidation process will speed up, therefore, the treated soil will take less time to get consolidated. Such a trend agrees with the work carried out by Gobinath et al. [2] and Phanikumar [13].

The increase in the rate of consolidation is attributed to the aggregation of clay particles on the addition of a stabilizer [36]. Such a change in blend open-up space for water to dissipate. Hence, increasing the rate of getting consolidated.

3.4.3 Coefficient of volume change (m_v)

The coefficient of volume change can be defined as the change in volume caused by a change in stress per unit volume [37]. Fig. 11 shows the effect of different stabilizers on the change of m_v when the applied stress changed from 16 kg/cm^2 to 32 kg/cm^2. The representation of data of mv follows a similar trend as that of the C_c shown in Fig. 8. When the soil was treated with lime, the m_v decreased as the content of lime increased. Contrary, the m_v initially decreased up to 10% of FA and then increased with the further addition of FA. While in the case of SF, m_v initially decreased up to 5% of SF and then increased with the further addition of SF.

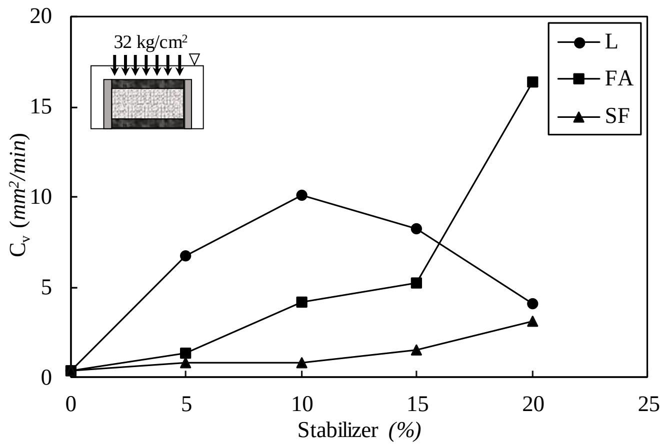

Fig. 10. Change in the coefficient of consolidation on the addition of stabilizers

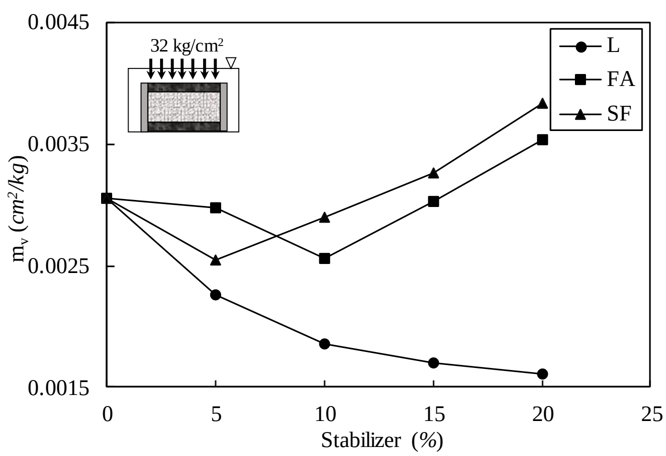

Fig. 11. Change in the coefficient of compressibility on the addition of stabilizers

The m_v decreased by nearly 47%, 16% and 17% when 20% of lime, 10% of FA and 5% of SF were added, respectively. The decrease in coefficient of volume change is the evidence that the additives added have lessened the capability of the soil to undergo any volume change. The lime-treated samples showed a sharp decrease in the value of m_v than the other stabilizers, hence lime could be the more effective stabilizing agent when large volume change caused by consolidation is in question. This behaviour of treated soil of experiencing lesser volume change is attributed to the pozzolanic reaction between soil particles and stabilizers. Such a change in m_v is also observed by S. Mousavi and Wong [16], Atahu et al. [19], Eberemu [20]. Furthermore, the later increase in m_v, in the case of FA and SF treated soil samples may be attributed to the less dense blend of the samples hence more voids, which is also evident from the data of compaction and C_v.

3.4.4 Coefficient of permeability (k)

The coefficient of permeability is the unique property of soil which tells us about the rate of flow of water through interconnected voids of the soil. The coefficient of permeability was determined by using Eq. 5 [34].

$$k = C_v \times m_v \times \gamma_w \tag{5}$$

From equation 5, we can infer that the coefficient of permeability depends upon the coefficient of volume change and coefficient of consolidation. Fig. 12 presents the permeability with the change of stabilizers-content. The permeability is calculated by utilizing C_v and m_v values obtained from Figs. 10 and 11, respectively. The variation of *k* value of all the samples with different stabilizers-content resembles with that of the coefficient of consolidation as shown in Fig. 10. The similarity in both the parameters clarifies the fact that the rate of consolidation depends upon the rate at which the water leaves the soil mass. Besides C_v, the change in the permeability also depends upon the coefficient of volume change (m_v). The porous soil shall have the high capability of undergoing volume change, also when the soil mass has pores, the water can easily move through the interconnected pores. Hence, more the volume change more would be the permeability.

Fig. 12 presents the effect of stabilizers on the permeability. The percentage increase or decrease in the permeability of soil with the addition of the stabilizer is calculated by Eq. 6, where A is the *k* value of the treated sample and B is the *k* value of the untreated sample.

The permeability of samples treated with lime increased by 17 times with the 10% of lime content than that of the untreated soil. Contrary, on further addition of lime, the permeability decreased. The increase of *k* may be attributed to the possible increase of pores due to the flocculation of clay particles with the blending of pozzolanic material [8]. The later decrease of permeability could be due to the obstruction created by the cementitious compounds [38].

On the other hand, the permeability of FA and SF treated samples increased as their percentage content increased. The tremendous increase was found in the sample with 20% of FA, whose permeability was 53 times more than that of untreated soil and at 20% of SF, the permeability was nearly 11 times more. The increase in the value of permeability in the treated samples indicates that with the mixing of such stabilizers can increase the rate of consolidation. This increase of permeability may be attributed to the porous nature of the samples caused by their lower MDD [39]. The similar trend of permeability is found in the work of Galvão de Brito et al. [8], Rahman et al. [39] and Locat et al. [40].

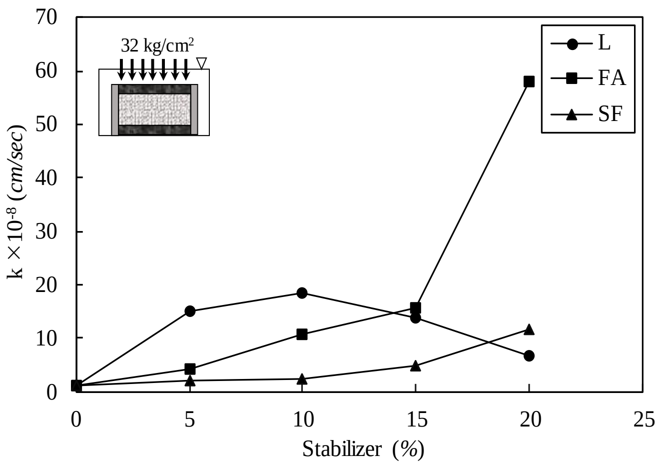

Fig. 12. Change in the coefficient of permeability on the addition of stabilizers

$$Ratio\left(times\,increase\right)=\frac{A}{B} \tag{6}$$

Table 4

Effectiveness of stabilizers with respect to consolidation parameters studied stabilizer mixtures

Consolidation parameter	Effective stabilizer
Compression index	Lime
Swelling index	Lime
Coefficient of volume change	Lime
Coefficient of consolidation	Fly ash
Permeability	Fly ash

The effective stabilizer is the one which decreases the chance of settlement/swelling and increases the rate of consolidation of treated soil. The effectiveness of stabilizers for the consolidation parameters studied in this research can be found in Table 4. Also, the comparison of this work was made with the available literature and is shown in Table 5. In comparison with previous work, this study shows the resemblance in most of the parameters.

4. Conclusion

This study was aimed to investigate the effect of chemical stabilizers (lime, fly ash and silica fume) on consolidation and compaction characteristics of expansive soil. The following conclusions are made from this work.

1. The addition of lime, fly ash and silica fume results in the decrease of maximum dry density of the expansive soil and increase of optimum moisture content. Higher the content of stabilizer contents in the soil lower would be the maximum dry density and higher would be the optimum moisture content. This effect would be dominant in the soil blended with lime than that of soils treated with silica fume or fly ash.

2. The addition of lime in the expansive soil results in the decrease of compression index. Higher the lime content in the soil lower would be the compression index of soil. While the lower amount of the compression index of the expansive soil blended with fly ash or silica fume could be only obtained up to certain percentages of the fly ash or silica fume in the soil.

3. On the addition of lime in the expansive soil results in the decrease of swelling index. Higher the lime content in the soil lower would be the swelling index of soil. However, the addition of fly ash or silica fume in the soil has no clear influence on the swelling index of soil.

4. The coefficient of permeability and consolidation of the soil would increase with the increase of the fly ash or silica fume content in the soil. While the higher amount of the coefficient of consolidation and permeability of the expansive soil treated with lime could be only obtained up to certain percentages of the lime.

5. Based upon the results of this study it is concluded that the lime is more effective chemical stabilizer than fly ash and silica fume for improving the consolidation properties of expansive soil of Jamshoro.

Table 5

Comparison of this study with the available literature

Stabilizer	Previous work	Results of properties studied					
		Soil	C_c	C_s	C_v	m_v	k
Lime	Wang *et al.* [15]	Sediments	Increased	Decreased	Increased	-	-
	Galvão de Brito *et al.* [8]	Residual soil	Decreased	Decreased	-	-	Decreased
	Phanikumar [13]	Expansive clay	Increased up to 2% lime and then decreased	-	Increased up to 2% lime and then decreased	-	-
	Nalbantoglu [38]	Expansive clay	Decreased	Decreased	-	-	Increased
	This study	Expansive clay	Decreased	Decreased	Increased up to 10% lime and then decreased	Decreased	Increased up to 10% lime and then decreased
Fly ash	Phanikumar [13]	Expansive clay	Increased up to 10% fly ash and then decreased	-	Increased	-	-
	Nalbantoglu [38]	Expansive clay	Decreased	Decreased	-	-	Increased
	Atahu *et al.* [19]	Expansive clay	Decreased	Decreased	-	Decreased	-
	This study	Expansive clay	Decreased up to 10% FA and then increased	Slightly increased	Increased	Decreased up to 10% FA and then increased	Increased
Silica fume	Gobinath *et al.* [2]	Black cotton soil	-	-	Increased up to 60% of silica and decreased later	-	Increased
	This study	Expansive clay	Decreased up to 5% silica and then increased	Slightly increased	Increased	Decreased up to 5% silica and then increased	Increased

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