

Engineering properties of cement/lime-stabilized Egyptian soft clay

M A Mansour¹, A M Samieh² and H E Matter

Civil Engineering Dept, Faculty of Engineering, Helwan University, Cairo, Egypt

monamansor83@gmail.com

Abstract. Soft clay formations are extensively located in many coastal areas around the world. The significant high compressibility and low shear strength of these formations impose challenging engineering problems. The deep cement/lime-mix-in-place method is one of the ground improvement techniques exhibiting successful use in stabilizing soft clay. Analysis and design of the deep mixing systems necessitate the identification of the additive content, the proportions of the lime to cement and the characteristics of the stabilized clay. This paper investigates experimentally the influence of adding lime and cement or cement alone, as stabilizing additives, on the engineering behavior of an Egyptian soft clay extracted from the north delta region. A series of laboratory tests were carried out considering, different additive contents of 8, 10, 12, and 14% of the dry weight, with different proportions of lime to cement of 50:50, 25:75 and 0:100. A series of unconfined compression strength tests were performed after different periods; one week, four weeks and 8 weeks, to assess the effect of curing period on the stabilized clay response. In addition, one dimensional consolidation tests were carried out to evaluate the compressibility properties of the stabilized clay. This study declared that the use of an additive content in the range of 12% and more is recommended to improve the characteristics of the considered Egyptian clay. It was pointed out that addition of lime and cement to soft clay significantly increases the strength characteristics and significantly reduces the compressibility characteristics of such clay.

1. Introduction

Inevitable coastal urbanization in many countries has compelled engineers to construct infrastructure, including major highways, over soft marine and alluvial deposits. Construction on soft clay formations encounters the problems of excessive total and differential settlements, large lateral displacement and inadequate bearing capacity. It is therefore crucial to treat soft clay deposits prior to construction activities in order to avoid the undesirable behaviour and the subsequent potential damages to structures. Nowadays, different techniques of soft clay stabilization are successfully employed. The injection method using chemical grouting in the ground has been widely applied to improve soft soil formations. Lime and cement admixture has been extensively used in both shallow and deep stabilization to improve inherent properties of soil such as strength and deformation behaviour. This process was developed simultaneously in Sweden and Japan in the 1970's [1], [2] and [3]. The cement/lime columns developed using dry jet mixing (DJM) that pneumatically delivers cement or

¹ Associate Professor of Geotechnical Engineering

² Professor of Geotechnical Engineering



lime powder into ground and mixes it with soil to form soil-cement/soil-lime column, were preliminary reported to be successfully executed in practice in 1980 and 1982 [4], [5], [6], [7] and [8]. This technique is recommended when time is of major concern [9].

Analysis of structures resting on deep mixed soil columns requires identification of such columns characteristics. This need triggered the research and laboratory studies all-over the world to identify the engineering characteristics of local clays when mixed with lime and/or cement. Laboratory test results indicated that, cement is more effective than lime in stabilization of organic soils [6]. It was found that, increasing plasticity index of the clay decreases its improvement readiness, [10] and [8]. Generally, as the amount of the added stabilizer increases, the strength of the treated soil increases with time [11] and [12].

The current research investigates, experimentally, the impact of lime and cement or cement alone, as stabilizing additives, on the shear strength and compression of an Egyptian soft clay extracted from the north delta region. It is aimed to identify engineering characteristics of soft clay when mixed with different contents of lime and cement, considering different proportions of the lime and cement or cement alone. A series of unconfined compression strength tests were performed after different periods to assess the effect of curing period on the stabilized clay response. In addition, one dimensional consolidation tests were carried out to evaluate the compressibility characteristics of the stabilized clay.

2. Experimental work description

2.1. Natural soil characteristics

The soil considered in the current research is an Egyptian soft clay extracted from the north delta region, Damanhur city, at a depth of around 2m below ground surface. It was classified as silty clay with some sand. The liquid limit of the soil ranged from 65 % to 67 % and the plastic limit value ranged from 27% to 34% which indicates clay with high plasticity. Grain size distribution of the natural soil sample is shown in figure 1.

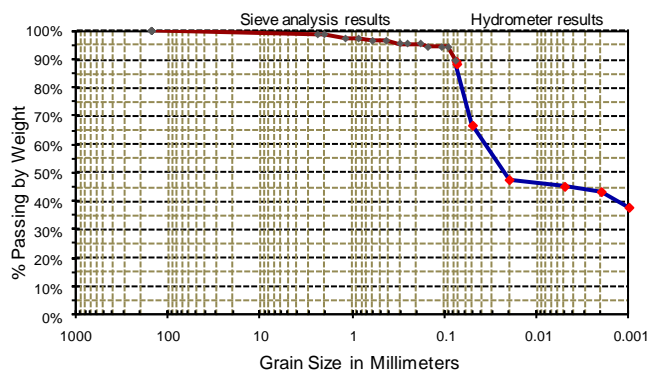


Figure 1. Sieve analysis and hydrometer analysis results

2.2. Method of preparing the lime–cement–soil specimens

A bulk of the soil was dried and then crushed to a powder form. The dry soil that passes from the 4.75mm sieve was mixed with the required percentage of additives (lime and/or cement). The water was then added to the mix with an amount corresponding to 75% of the dry weight of soil. The used water content is within the range recommended by [13] for laboratory testing of chemically stabilized clay, to be between the liquid limit and twice the liquid limit of the clay. This water content value was found to give a high workability mix for the clay considered in the current study. However, such high water content makes preparing samples with no additives for testing, not visible.

2.3. Experimental program

The additives content values examined in the current study were 8%, 10%, 12% and 14%, expressed as a percent of the dry weight of soil. Three proportions of lime to cement were considered; 50:50, 25:75 and 0:100. Table 1 illustrates the considered combinations of the additive contents and lime/cement proportions.

Table 1. Combinations of additive contents and the proportions of lime and cement considered in the study.

Additive contents (%)	Lime content (%)	Cement content (%)
8	0	100
	25	75
	50	50
10	0	100
	25	75
	50	50
12	0	100
	25	75
	50	50
14	0	100
	25	75
	50	50

3. Analysis of experimental results

The unconfined compressive strength tests were performed at curing periods of 7, 28, and 56 days. Three samples for each curing time were prepared. Whereas, oedometer tests were carried out after curing time of 28 days only.

3.1. Results of unconfined compression strength tests

The unconfined compression tests were carried out on 12 different mixtures at three curing periods of 1, 4 and 8 weeks. A summary of the peak strength results obtained for each specimen is presented in Table 2.

Table 2. Summary of the unconfined test results.

Lime content (%)	Cement content (%)	Additives content, (%) dry weight	Curing time (weeks)		
			1	4	8
			Peak strength (kPa)	Peak strength (kPa)	Peak strength (kPa)
50	50	8	17.36	39.05	59.3
		10	30.37	45.56	85.33
		12	98.35	147.52	182.23
		14	138.12	251.66	323.97
25	75	8	195.25	274.8	390.50
		10	254.55	334.1	435.34
		12	371.70	512	585.75
		14	543.81	604.56	759.31
0	100	8	325.42	448.36	513.44
		10	361.58	529.35	571.3
		12	533.69	943	992.17
		14	549.6	989.27	1157.05

Figure 2 shows the soil strength gain with time due to adding various additives contents having different lime to cement ratios. The summarizing table 2 and figure 2 reveal that, with the increase of the additives content, the strength of the stabilized clay increases, firstly with a low rate till 10% content. Then, more increase in additives content, results in increasing the clay strength with a higher rate.

The figure shows also that, for the same additives content, the increase of the cement proportion significantly increases the improved clay strength. The soil strengths corresponding to lime/cement ratio of 25:75 are about 2.3 to 6.6 times those corresponding to lime/cement ratio of 50:50. Moreover, soil samples treated with cement only (L:C = 0:100) has gained strengths equal 3.6 to 8.7 times the strengths obtained using 50:50 lime/cement ratio.

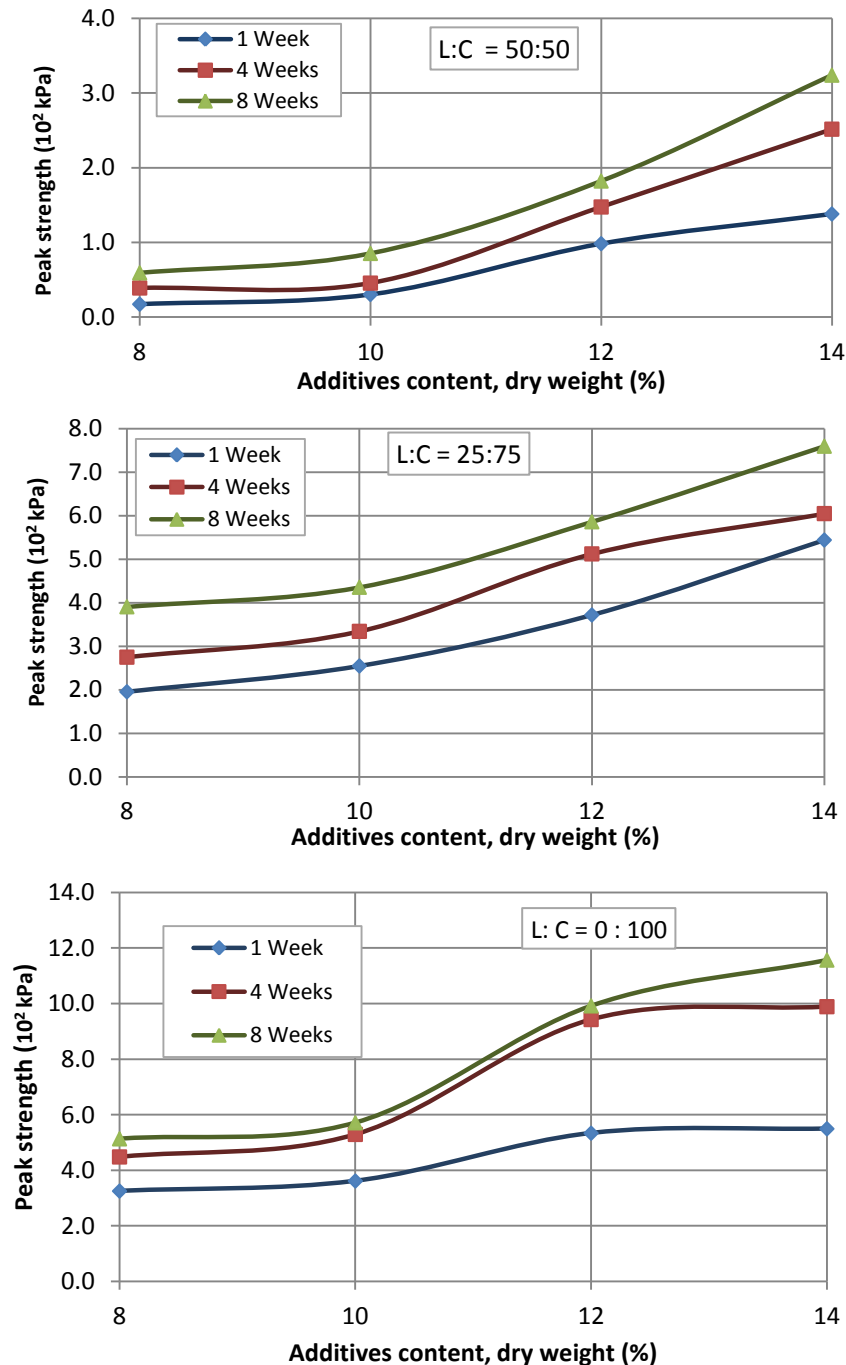


Figure 2. Relationship between additives content and peak strength of the stabilized soil at different curing periods for different lime to cement ratios

For the examined clay, the obtained results exhibits that the use of additives content in the range of 12% or more with higher cement proportion, is recommended to obtain a significant increase in the soil strength. In addition, cement proportion is more effectual in increasing the improved soil strength.

3.2. Deformation / secant modulus

The secant modulus of elasticity (E_{50}) calculated at stress equal to half the unconfined strength, was determined for all the tested specimens. For the specimens tested at 28 days, the variation of the deformation modulus with the additives contents and considering different ratios of the lime to cement, is presented in figure 3. The figure exhibits that, the deformation modulus values were found to increase with increasing the additives content and with increasing the cement proportion, which has a considerable impact.

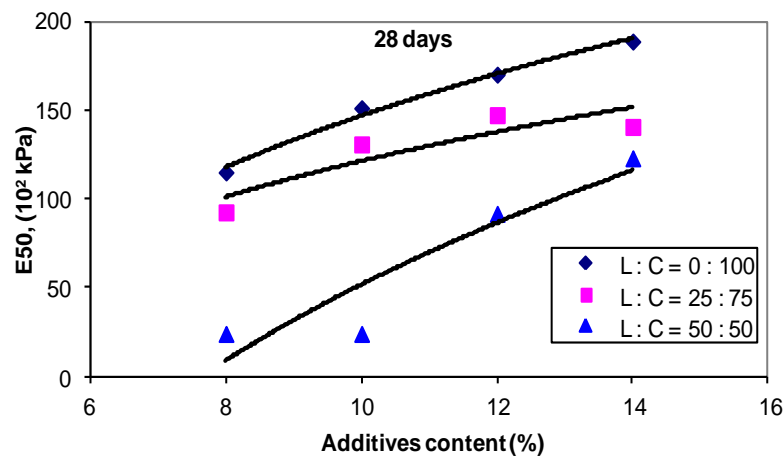


Figure 3. Variation of deformation modulus with the additive content, considering different ratios of the lime to cement after 28 days.

3.3. Consolidation characteristics of the stabilized clay

A series of consolidation tests for the considered stabilized Egyptian clay specimens were carried out for all the considered contents of the additives and all lime to cement ratios. The specimens were subjected to axial stress up to 1600 kPa. It worth mentioning that this stress level is much higher than the working stress level on the deep mixing columns under earth embankments, that ranges between 500 to 600 kPa [14].

3.3.1. Void ratio (e).

Figure 4 shows the variation of void ratio (e) with the stress applied to the stabilized soil specimens. The figure delineates that, with the increase of the additives content, the soil compressibility slightly decreases. Whereas, the use of high proportions of cement in the additive, efficiently decreases the compressibility of the stabilized clay.

3.3.2. Volume compressibility (m_v).

The coefficient of volume compressibility (m_v) of the stabilized clay samples was estimated from the consolidation test results. Figure 5 presents the variation of the m_v -values with the applied stress level for the considered additive contents and for each of the lime to cement ratios. For a given stress level, the figure delineates that the m_v -values decreased with the increase of the cement proportion in the additive content. The figure illustrates, also, that with the increase of the additive content the m_v -values are decreased. In other words, the constrained modulus (E_c) of the stabilized clay ($E_c = 1/m_v$) is increased with the increase of the cement content and increase of the additive content.

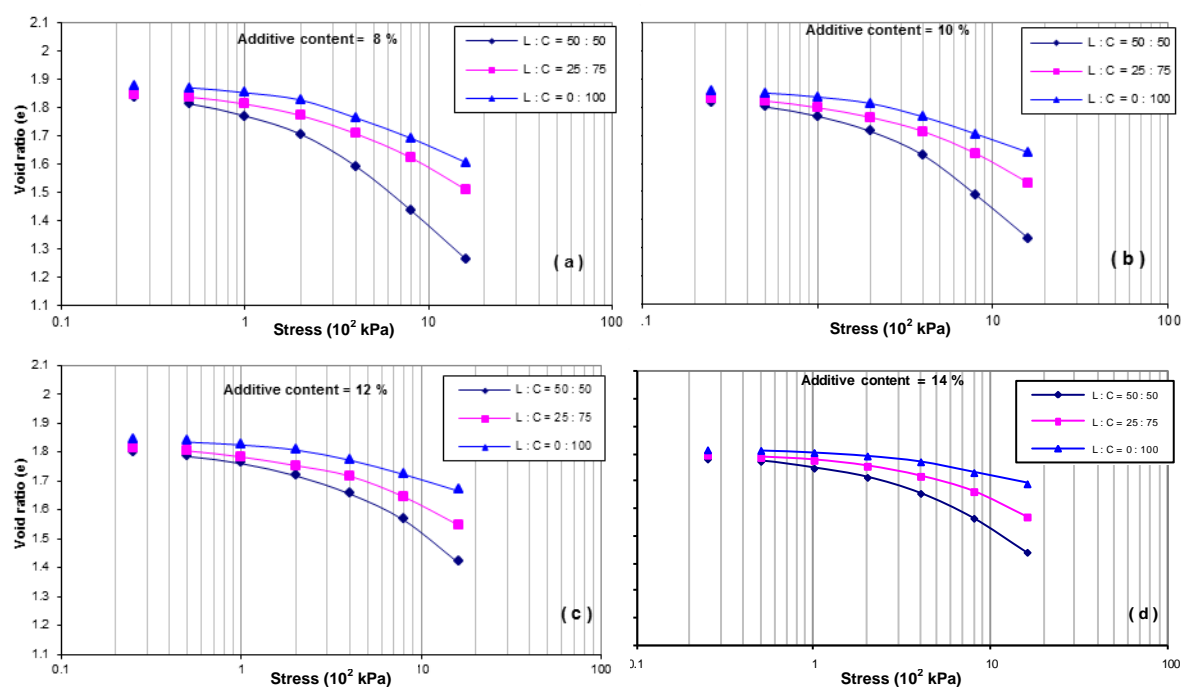


Figure 4. Variation of the void ratio with the applied consolidation stress at different additives content and different lime to cement ratios

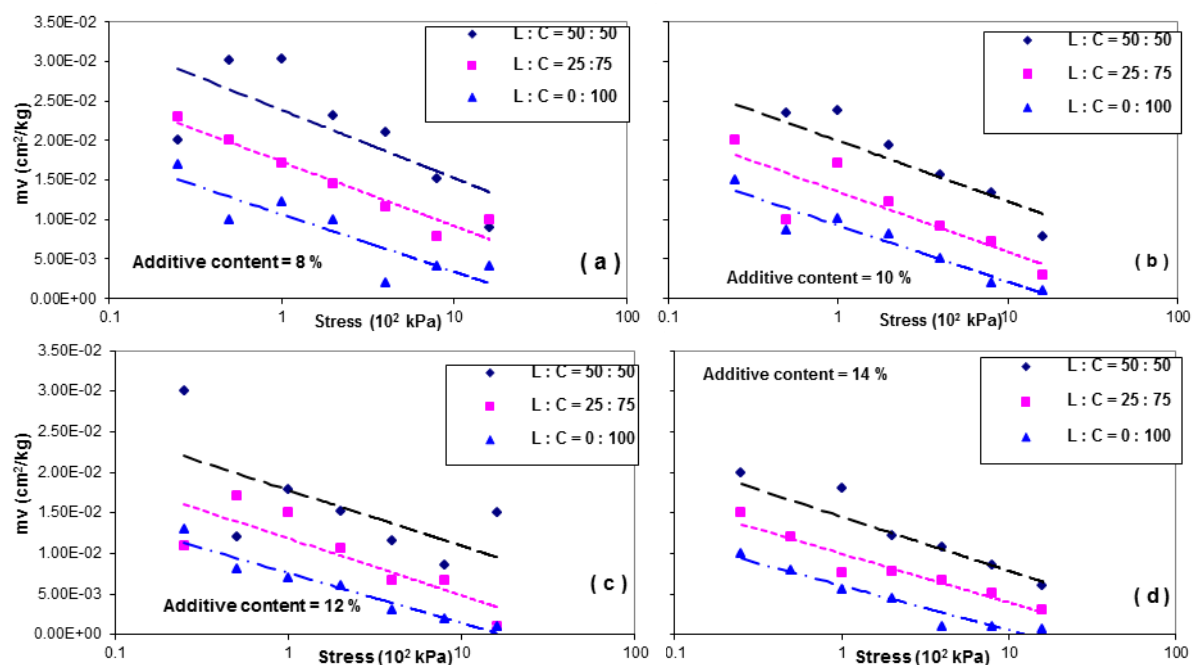


Figure 5. Variation of the volume compressibility coefficient with the applied stress at different additives content and different lime to cement ratios

3.3.3. Consolidation coefficient (c_v).

The results of the consolidation tests were analyzed using the square root of time method (Taylor's method) to assess the C_v -values of the tested specimens. In the current study, the loading progress was adopted to reach 1600 kPa. Figure 6 shows the variation of the C_v -values with the applied stress level for different additive contents and at each lime to cement ratios, after 4 weeks of curing. The figure shows that the C_v -values are generally increased with increasing the additive content. Whereas, the impact of the consolidation stress level on decreasing the C_v -values is insignificant. Therefore, table 3 proposes average values of the consolidation coefficient for the considered clay specimens.

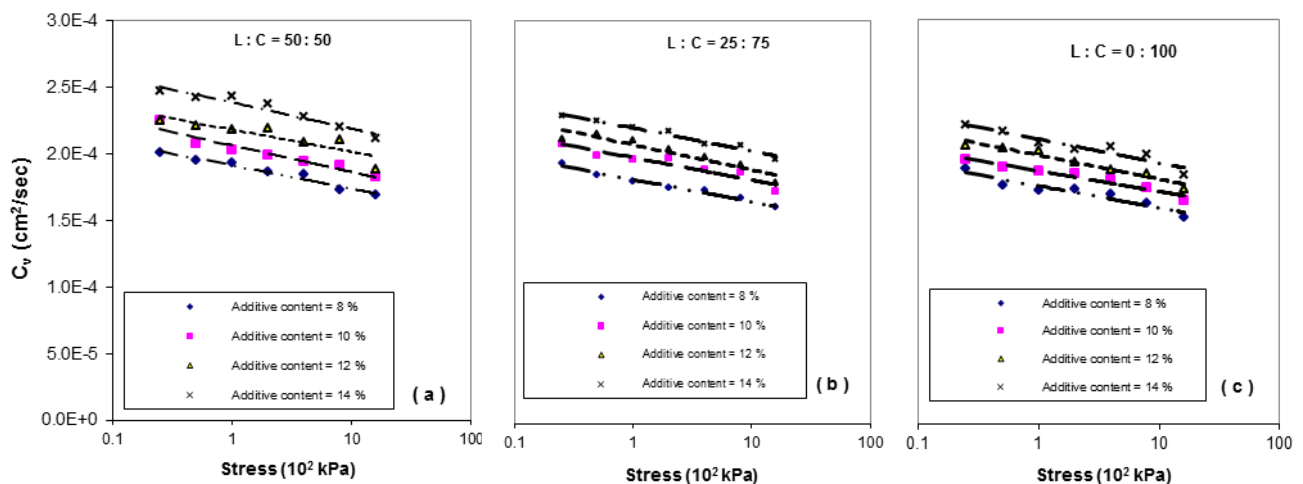


Figure 6. Variation of the consolidation coefficient with the applied level for different additive contents

Table 3. C_v -average values for a stress range of 25 kPa to 1600 kPa, after 4 weeks curing time.

Additive contents, dry weight (%)	Lime content (%)	Cement content (%)	Average value of the coefficient of consolidation (C_v) cm^2/sec
8	50	50	$1.83 \cdot 10^{-3}$
10	50	50	$1.97 \cdot 10^{-3}$
12	50	50	$2.10 \cdot 10^{-3}$
14	50	50	$2.30 \cdot 10^{-3}$
8	25	75	$1.74 \cdot 10^{-3}$
10	25	75	$1.90 \cdot 10^{-3}$
12	25	75	$2.00 \cdot 10^{-3}$
14	25	75	$2.13 \cdot 10^{-3}$
8	0	100	$1.70 \cdot 10^{-3}$
10	0	100	$1.81 \cdot 10^{-3}$
12	0	100	$1.94 \cdot 10^{-3}$
14	0	100	$2.06 \cdot 10^{-3}$

3.3.4. Coefficient of permeability (k).

Direct measurement of the permeability coefficient is not possible, it is calculated from the consolidation coefficient (C_v) and the volume of compressibility coefficient (m_v) obtained from the oedometer tests using the following relation:

$$k = C_v \cdot m_v \cdot \gamma_w \quad (1)$$

The permeability coefficient (k) of lime-cement stabilized samples were found for the considered progress of loading range. Figure 7 presents the variation of the k -value with the applied stress level for different additive contents and for each of the lime to cement ratios, after 4 weeks of curing. The figure delineates that k -value is generally decreases with increasing the applied stress. Also, the permeability coefficient of the samples stabilized with cement only is the least. In other words, addition of lime makes to increase the material permeability and this increase is proportional to the lime content.

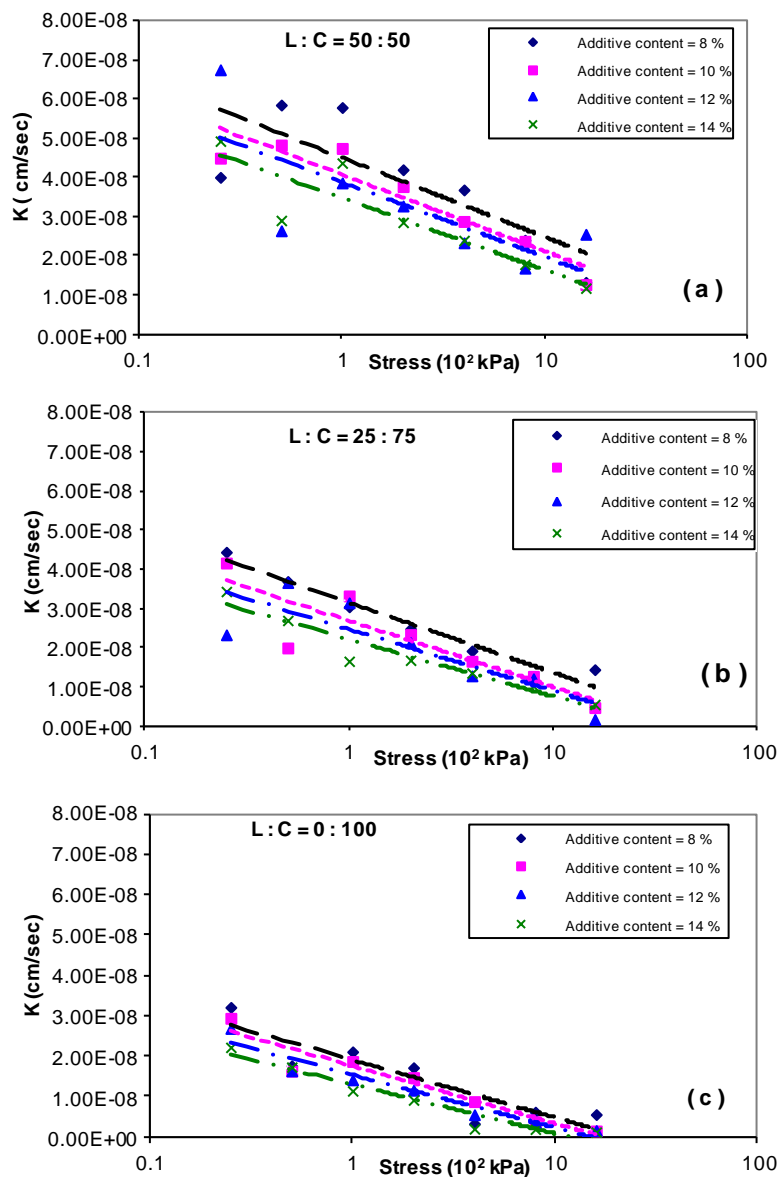


Figure 7. Variation of permeability coefficient with the applied stress level for different additive contents and different lime to cement ratios

4. Summary and conclusions

The work described in this paper is an attempt to identify the unconfined compressive strength as well as the consolidation characteristics of an Egyptian soft clay when mixing different contents of lime and cement at different proportions. From the results of the experimental work, the following conclusions can be obtained:

- The unconfined compressive strength and the stiffness of the treated samples increased with the increase of the additive contents.
- The addition of the cement significantly increased the unconfined compressive strength and the stiffness while the unconfined compressive strength and the stiffness are decreased when part of the cement is replaced by lime.
- The strength gain and the stiffness of the stabilized clay specimens increase with time.
- For the considered clay, additives contents of 12% and more are recommended to reach a significant increase in strength of the stabilized clay.
- With the increase of the additive content, the coefficient of volume compressibility (m_v) was found to decrease while the coefficient of consolidation (C_v) was found to increase.
- For the clay under consideration, it was found that as the lime proportion increased (in comparison to the cement proportion), the coefficient of volume compressibility, the coefficient of permeability (k) and the coefficient of consolidation (C_v) were increased.
- For the clay under consideration, it was found that with the increase of the consolidation pressure, the void ratio, volume compressibility coefficient, permeability coefficient, and the consolidation coefficient, were decreasing.

In general, the trend of the current research results compared well with the results introduced by previous studies. However, researches showed that, the type of the treated clay was of major impact on the values of the improved characteristics [11], [15]. Therefore, the additive content and lime/cement ratio should be optimized for each individual clay formation to attain the desired strength. It was recorded by [16] that, the optimized cement content value required to improve compressibility features of an investigated clay, was 15%, which is near the percentage of additive content got in this research (12%). As concluded in the current work, lime stabilized clay possessed higher increase of permeability coefficient. Whereas cement mixed specimens exhibited slightly lower permeability [11].

5. References

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