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MODIFICATION OF CLAYEY SOILS' PROPERTIES WITH THE ADDITION OF LIME AND FLY ASH

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ABSTRACT
Samples of swelling soils from sites in Rhodope Peripheral Unit (former prefecture) were stabilized using lime and fly ash and the alteration of engineering properties such as the plasticity, the relation between moisture and density and the compressive strength has been investigated in the laboratory. It is established that lime is a very good stabilizer, acting beneficially not only on the strength characteristics, but on the optimum moisture and maximum dry density as well. The pozzolanic properties of the fly ash are mainly responsible for the improvement coming upon the characteristics of the tested soil materials. The role of specimen's curing time is important, more specifically in the case that lime is used as additive. By investigating a large number of soil materials, it is feasible to establish suitability criteria for their use in stabilized subgrade and roadway layers.

KEYWORDS: soil stabilization, lime, fly ash, compressive strength.

INTRODUCTION
Construction of roadways over soft subgrade is one of the most frequent problems for highway construction in many parts of the world. A usual approach to soft subgrades stabilization is the removal of the soil and its replacement with stronger materials likes crushed rock, a rather costly procedure emphasizing the need for alternative construction methods [1, 2] on soft subgrades. Clay stabilization with cement or lime has a lower cost. Fly ash can also be used.

Changes in soil's engineering properties are attributed to cation exchange, flocculation, and pozzolanic reactions [3]. Ultimate cured strength development is gradual but may continue for several years [4, 5]. Carbonation reactions are harmful to the long-term strength and durability of the lime-stabilized soil. Using sufficient amount of lime (to provide enough alkalinity) compaction of the soil to high density and prompt placement after mixing lime with soil can minimize potential carbonation problems.

The effect of lime on soil's plasticity is immediate. Calcium ions from the lime replace other exchangeable ions, causing flocculation and reduction of the samples plasticity, making them more friable and easily workable [6].

When lime is added to a clay soil, it must first satisfy the affinity of the soil for lime, that is, ions are adsorbed by clay minerals and are not available for pozzolanic reactions until this affinity is satisfied [7, 8]. Because this lime is fixed in the soil and is not available for other reactions, the process has been referred to as lime fixation

Soils that react with lime to produce substantial strength increase (greater than 3.5 kg/cm^2 following 28-day curing at 23ºC) are termed as reactive [9]. Soils with lesser strength increases are called non-reactive. This terminology does not imply that lime modification does not take place.

Fly ash is useful in many construction applications because it is a pozzolan, meaning it is a siliceous or alimino-siliceous material which in itself possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties [10]. Fly ash is a by-product of coal burning power plants. The use of fly ash as a soil-stabilizing agent is beneficial for improving the engineering properties of the soil, while at the same time it provides an opportunity for the utilization of an industrial waste that will otherwise require costly disposal [11].

The improvements in the engineering properties of soils as fly ash is added can be explained by two reactions: short-term reactions (cation exchange and flocculation), and long-term reactions, involving pozzolanic activity.

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Three soil materials from the Rhodope Peripheral Unit were tested in the laboratory in order to investigate the effect of lime and fly ash addition on their engineering properties, such as their strength. A series of tests were conducted for the natural properties (Atterberg limits) and their variation. The effect of stabilizers was shown through with their placement in the soil classification system. The effect of additive's content and curing time was investigated through unconfined compression strength tests.

MATERIALS AND METHODS

The soils were collected at sites where the thickness of swelling materials varied from a few to tenths of meters. Most of clay layers in Rhodope Peripheral Unit contain high amounts of sand and conglomerates of the parent rock. The clay content also varies from site to site. Clays S1 and S2 have a dark grey color, while S3 is brownish.

The fly ash was furnished from the Public Power Corporation's power station in Ptolemaida. This unit uses lignite rich in $CaCO_3$. The fly ash has a low grade of crystallization and it's therefore more active. The pulverized fly ash is rich in CaO. The lime used as additive for the stabilization of soil samples was a typical commercial lime with high content of CaO (65.25%).

Atterberg limits were determined in accordance to the ASTM D 4318-83 procedure. Quantities of the soil fraction passing the No. 40 sieve were thoroughly mixed with different amounts of lime and fly ash.

The standard Proctor method (AASHTO T99) has been employed in order to define the moisture-density relation. For each moisture-content, a new specimen was compacted using new soil sample. The procedure was repeated several times to draw a smooth dry density-moisture content curve.

With the unconfined compression test (AASHTO T 208) the compression strength of soil samples was determined. Air-dried soil material passing the No. 4 (4.75 mm) sieve was mixed with lime or fly ash. The required amount of soil for each specimen was determined for the optimum moisture and maximum dry density of the sample. Three 50x100 mm specimens were prepared for each additive-content. Specimens remained in a chamber with constant temperature and moisture for 7, 28 and 90 days. Loadings were applied through a steady deformation rate of 1.27 mm/min to fracture. For each soil or soil-stabilizer mix, 3 specimens were fractured, with the mean value of fracture limits to represent the unconfined compression strength.

RESULTS AND DISCUSSION

According to the AASHTO classification system, the soils tested belong to group A-7-5(20), A-7-6(20) and A-7-6(17) for soil samples S1, S2 and S3, respectively. According to Unified Classification System samples S1 and S2 fall in class CH and soil sample S3 in CL class. The suitability of such soils for pavement construction is judged moderate to bad.

Tables 1, 2 and 3 give the variation of Atterberg limits as compared to those of the natural soils (with a negative sign denoting reduction of the property), following their mixture with various additive contents.

Table 1. Atterberg limits variation as a function of the additive's content (Soil sample S1)

Percent additive (%)	Liquid Limit LL		Plasticity Limit PL		Plasticity Index PI	
	Value	Variation (%)	Value	Variation (%)	Value	Variation (%)
0	77	0	33	0	44	0
Fly ash						
4	71	-7.8	31.5	-4.5	39.5	-10.2
8	64	-16.9	34	3.0	30	-31.8
12	58	-24.7	36	9.1	22	-50.0
16	54	-29.9	37	12.1	17	-61.4
Lime						
2	66	-14.3	35	6.1	31	-29.5
4	62	-19.5	39	18.2	23	-47.7
6	60	-22.1	43	30.3	17	-61.4
8	57	-26.0	46	39.4	11	-75.0
12	53	-31.2	46.5	40.9	6.5	-85.2

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Table 2. Atterberg limits variation as a function of the additive's content (Soil sample S2)

Percent additive (%)	Liquid Limit LL		Plasticity Limit PL		Plasticity Index PI	
	Value	Variation (%)	Value	Variation (%)	Value	Variation (%)
0	76	0	29	0	47	0
Fly ash						
4	69	-9.2	32	10.3	37	-21.3
8	64	-15.8	35	20.7	29	-38.3
12	59	-22.4	39	34.5	20	-57.4
16	56	-26.3	41	41.4	15	-68.1
Lime						
4	68	-10.5	39	34.5	29	-38.3
8	59	-22.4	42	44.8	17	-63.8
12	53	-30.3	43	48.3	10	-78.7

Table 3. Atterberg limits variation as a function of the additive's content (Soil sample S3)

Percent additive (%)	Liquid Limit LL		Plasticity Limit PL		Plasticity Index PI	
	Value	Variation (%)	Value	Variation (%)	Value	Variation (%)
0	51	0	23	0	28	0
Fly ash						
4	50	-2.0	33	43.5	17	-39.3
8	47	-7.8	37	60.9	10	-64.3
12	45	-11.8	40	73.9	5	73.9
Lime						
4	49	-3.9	NP	--	NP	--
8	46	-9.8	NP	--	NP	--
12	42	-17.6	NP	--	NP	--

In all samples, flocculation has caused an increase of the plasticity limit, when the lime or fly ash content increased. The increase rate was more pronounced with lime, because of excess cations accumulation on the clay. Soil S3, with the addition of 4% lime, became non-plastic. An increased plasticity limit shows that the stabilized material has the capacity to maintain its stability when the moisture content increases.

The addition of stabilizers caused a reduction in the liquid limit. For the samples S1 and S2 a clear reduction of liquid limit has reached the 17% and 16% respectively, when mixed with 8% fly ash or 31% and 30% respectively, when the lime content was 12%.

The plasticity index of all three soils was reduced on the addition of lime or fly ash to medium or low plasticity levels. Lime influenced more severely the reduction of plasticity index. In all cases, the reduction of the plasticity index is due to the reduced values of liquid limit. With the stabilization, the reduction of liquid limit and plasticity index changes the soil characteristics and modifies their behavior, when used as highway construction materials. The group index in AASHTO classification system was reduced. In cases of high additive content the engineering behavior of the materials is proportional to that of soils in groups A-4 and A-5.

In tables 4, 5 and 6, the AASHTO group index for the samples and mixtures with lime and fly ash is given. The most characteristic change is that of soil sample S3, which turns from the group of high plasticity (A-7-6) to group A-4, typical material of which is a non-plastic silty soil with over 75% passing the No. 200 sieve. Addition of up to 10% lime to soil sample S1 has influenced only the group index, while it changed the group of soil sample S2.

High fly ash content was needed to alter the group index of soil S1, (at least 12%). Samples S2 and S3 are classified as group A-7-5 after the addition of 4% fly ash. With all other fly ash contents a reduction in group index was found.

Soil sample S1 presented the lower maximum dry density while soil sample S3 the highest one. The higher optimum moisture has been found in soil sample S1 and the lowest in soil sample S3.

Addition of lime has led to immediate reduction of maximum dry density and increase of optimum moisture content for the same compaction effort.

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Table 4 AASHTO Classification of stabilized soil (Sample S1)

Additive (%)	LL	PI	<No. 200	AASHTO Classification	
				Group	Index
0	77	44	95.4	A-7-5	20
Fly ash					
2	75	44	--	A-7-5	20
4	71	39.5	--	A-7-5	20
6	67	34	--	A-7-5	20
8	64	30	--	A-7-5	20
12	58	22	--	A-7-5	16
16	54	17	--	A-7-5	14
Lime					
2	66	31	--	A-7-5	20
4	62	23	--	A-7-5	17
6	60	17	--	A-7-5	15
8	57	11	--	A-7-5	12
12	53	6.5	--	A-5	11

Table 5. AASHTO Classification of stabilized soil (Sample S2)

Additive (%)	LL	PI	<No. 200	AASHTO Classification	
				Group	Index
0	76	47	75.7	A-7-6	20
Fly ash					
4	69	37		A-7-5	20
8	64	29	--	A-7-5	19
12	59	20	--	A-7-5	16
16	56	15	--	A-7-5	13
Lime					
4	68	29	--	A-7-5	19
8	59	17	--	A-7-5	14
12	53	10	--	A-5	10

Table 6. AASHTO Classification of stabilized soil (Sample S3)

Additive (%)	LL	PI	<No. 200	AASHTO Classification	
				Group	Index
0	51	28	83.8	A-7-6	17
Fly ash					
4	50	17	--	A-7-5	13
8	47	10		A-7-5	9
12	45	5	--	A-7-5	9
Lime					
4	--	NP	--	A-4	--
8	--	NP		A-4	--
12	--	NP	--	A-4	--

Fly ash had a similar effect on compaction characteristics. The way fly ash and lime contents influence the maximum dry density and optimum moisture content of soil admixtures with the additives is presented in figures 1 and 2, respectively.

With all additive contents, the maximum dry density of soil-fly ash mixtures is greater than that of soil-lime mixes. This is due to lower unit weight of lime. The unconfined compression strength values of the three soil samples were low -typical of clay soils- and they do not meet the highway construction subgrade suitability

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criteria. When different by weight percentages of lime and fly ash were added to the natural soils, the stress-deformation characteristics were dramatically improved. Especially important for the strength increase was the role of curing time of the compacted specimens.

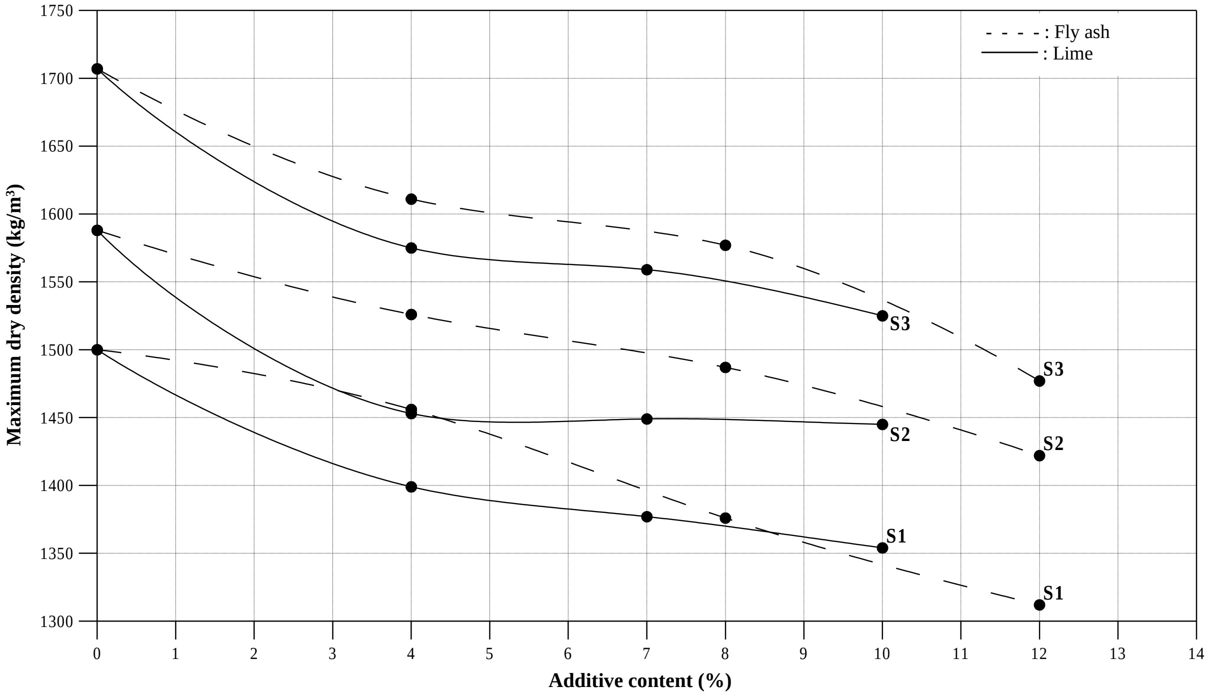

Figure 1: Maximum dry density as a function of the percentage of additive.

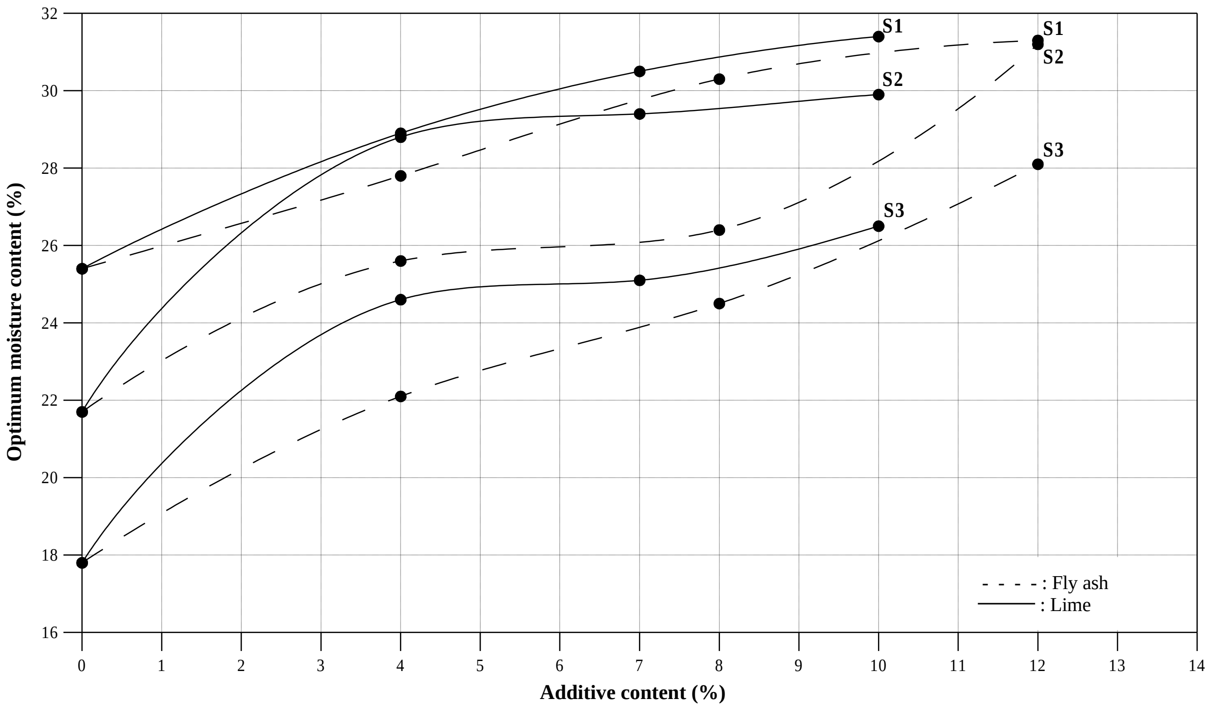

Figure 2: Variation of optimum moisture content as a function of the percentage of additive.

The way fly ash and lime content influenced the unconfined compression strength of soil sample S1 is shown in table 7.

The influence of ash and lime content on the mixture strength is depicted in table 8 for soil samples S2 and S3,

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for all curing times.

Table 7. Influence of additive's content on the strength of the mixtures (Soil sample S1)

Unconfined Compression Strength (kg/cm^2)							
Additive Fly Ash				Additive Lime			
Percent (%)	7 days cure	28 days cure	90 days cure	Percent (%)	7 days cure	28 days cure	90 days cure
0	1.84	2.52	2.71	0	1.84	2.52	2.71
4	3.76	4.42	5.30	3	4.21	6.66	18.66
8	4.27	5.88	7.75	6	6.13	17.85	23.21
12	5.31	7.34	10.19	9	6.71	23.16	30.11
16	7.26	9.21	14.57	12	5.26	21.76	28.29
20	9.84	12.17	17.97	15	4.97	19.37	25.18

Table 8. Influence of additive's content on the strength of the mixtures (Soil sample S2 and S3)

Percent Additive (%)	Soil Sample S2			Soil Sample S3		
	Unconfined Compression Strength (kg/cm^2)			Unconfined Compression Strength (kg/cm^2)		
	7 days cure	28 days cure	90 days cure	7 days cure	28 days cure	90 days cure
0	1.28	1.45	1.65	2.26	2.88	2.97
Fly ash						
4	4.29	4.49	5.55	3.76	4.27	4.48
8	6.41	7.17	7.90	6.57	7.90	9.19
12	7.59	8.79	9.51	8.75	9.53	12.43
Lime						
4	6.03	9.64	13.64	3.51	5.66	8.46
7	6.50	11.7	22.90	3.90	5.84	8.98
10	7.43	13.53	16.43	3.90	5.97	8.44

For the development of compressive strength, the fly ash content in all soil mixtures constitutes a more critical factor compared to the time of specimen curing. The exactly opposite result appeared for lime mixtures, where the curing time contributes a lot in the improvement of strength. This is verified by the values in tables 9 for soil sample S1 and 10 for soil samples S2 and S3, which present the ratios of the strength of soil-fly ash and soil-lime mixtures to the strength of natural soil for curing times 7, 28 and 90 days.

Table 9. Mix strength to soil sample strength ratio (Soil sample S1)

Additive Fly Ash				Additive Fly Ash			
Percent (%)	7 days cure	28 days cure	90 days cure	Percent (%)	7 days cure	28 days cure	90 days cure
0	1.00	1.00	1.00	0	1.00	1.00	1.00
4	2.04	1.75	1.96	3	2.29	2.64	3.20
8	2.32	2.33	2.86	6	3.33	7.08	8.56
12	2.89	2.91	3.76	9	3.65	9.19	11.11
16	3.95	3.65	5.38	12	2.86	8.63	10.44
20	5.35	4.83	6.62	15	2.70	7.69	9.29

CONCLUSION

Several engineering properties of clay soils from areas in the Rhodope Peripheral Unit have been amended with the admixture of lime and fly ash. Lime in soil samples generated reactions which are difficult to understand or be predicted.

Laboratory tests on three clay soils with the admixture of lime and fly ash have shown different improvement rates. From a road function point of view, the strength increased. Despite the small number of tested samples, the findings could be applicable in soil types and testing conditions similar to those adopted in this research.

Table 10. Mix strength to soil sample strength ratio (Soil samples S2 and S3)

Percent (%)	Soil Sample S2			Soil Sample S3		
	7 days cure	28 days cure	90 days cure	7 days cure	28 days cure	90 days cure
0	1.00	1.00	1.00	1.00	1.00	1.00
Fly ash						
4	3.35	3.10	3.36	1.66	1.48	1.51
8	5.01	4.94	4.79	2.91	2.74	3.09
12	5.93	6.06	5.76	3.87	3.31	4.19
Lime						
4	4.71	6.64	8.27	1.55	1.97	2.85
7	5.08	8.07	13.88	1.73	2.03	3.02
10	5.80	9.33	9.96	1.73	2.07	2.84

Soils with high clay content and high plasticity index, like those dominating in the area, require larger quantities of lime in order to achieve the non-plastic condition. The initial lime admixtures are more effective in reducing the plasticity, while with the increase of the additive’s content the result is less beneficial.

The admixture of lime or fly ash results in a gradual reduction of the maximum dry density indicative of the increased resistance offered by the flocculated structure to the compaction effort as well as in an increase of the optimum moisture content which is derived from the excess water hold in the open structural units of the flocculated structure.

The results show that the optimum strength obtained for a soil is directly associated with the moisture content and the concentration of lime. However, it is not easy to explain the way the soil properties affect the reaction mechanism. Soil samples with comparable liquid limits haven’t behaved similarly. Because of the pozzolanic reactions, mineralogy is the only parameter associated with the development of strength.

The maximum compressive strength has been achieved with the optimum moisture content. The aforementioned finding means that both the maximum compressive strength and the maximum dry density could be achieved if the specimens are compacted with the optimum moisture content.

The increase in compressive strength as a function of the curing time and the fly ash content could be attributed to the time-dependent pozzolanic activity of the Ptolemaida’s fly ash. The self-hardening and pozzolanic properties of the fly ash can ensure the long-term stability of soils in that group, if soils are mixed in appropriate proportions with fly ash.

Based on the present study, fly ash could be recommended as an effective agent for the improvement of swelling soils. Using fly ash in such a manner it would also have the benefit of depositing an industrial by-product without negatively affecting the environment.

The laboratory testing findings point out the need for a thorough study of clay soils’ characteristics, if these soils are intended to be used in highway construction works. The stabilization process is proved to be a fiscally effective and environmentally successful solution for construction works of such an extent and importance.

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