Use of additives to improve the engineering properties of swelling soils in Thrace, Northern Greece

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Abstract

Highway construction engineers often face the need for more stable, durable and, at the same time, more economic road structures. This is nowadays true because of increased traffic volumes and heavier loads on the roadways. As a consequence, enhanced pavement structures and improved subgrades is a necessity. The international highway "New Egnatia" crosses areas in Thrace, Northern Greece with abundant clayey soils having poor technical properties.

The treatment of physical soils with some substances could bring up new materials, which would operate better under the traffic and environmental conditions. This has led to the decision to investigate the possibilities of improving the existing soil materials using chemical additives. Soil samples were collected from the abovementioned area and mixed with lime and fly ash, in various proportions. The modification of the soil properties with special emphasis on their strength has been examined in the laboratory after different curing periods.

The experimental results have shown that the unconfined compressive strength increased as a function of both the percentage of additive in the mixture and the time of curing. The improvement depended upon the soil mineralogy and the kind and quantity of exchangeable cations. This holds true when the influence of the kind and quantity of the additive is taken into account. The effects of lime on the swelling clayey soils tested were more beneficial than those of fly ash.

The soils after their treatment could be used as a subgrade or even as a subbase layer in roadway pavements.
Keywords: stabilization, lime, fly ash, engineering properties, unconfined compressive strength, optimum moisture.

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1 Introduction

The continuous growth of the traffic volume and of vehicle's size, has made obvious the need for more stable, durable and, at the same time, more economic road structures. Consequently, a requirement exists for improved properties of the pavement structure as well as of the physical subgrade. The treatment of physical soils and base materials with some substances could bring up new materials, which would operate better under the traffic and environmental conditions. In this procedure, called soil stabilization, such substances as Portland cement, bituminous materials, lime, fly ash or alkali salts could be used.

It has been recognized by numerous investigators (Bell [1], Zhang and Cao [2]) that the addition of lime and/or fly ash to soil materials may cause various beneficial changes to the engineering properties of fine-grained soils, such as the reduction of plasticity, the reduction of shrinkage-swelling potential and the improvement of strength characteristics.

Roadways have a high potential for large volume use of the fly ash stabilized soils. Arora and Aydilek [3] investigated the use of Class F fly ash amended soil-cement or soil-lime as base layers in highways. Unconfined compression, CBR, and resilient modulus tests were conducted. Required base thicknesses were calculated using the strength parameters. The strength of a mixture is highly dependent on the curing period, compactive energy, cement content, and water content at compaction. Lime treatment didn’t provide sufficient strength for designing the mixtures as highway bases.

The strength of soil-lime-fly ash mixtures could be estimated by various methods such as unconfined compression, CBR, the Hveem stabilometer and triaxial tests. The most commonly used method is the unconfined compression test, not necessarily being the most appropriate for all purposes. The strength of soil-lime or soil-fly ash mixtures depends on many variables such as the soil type, the lime and fly ash content, the additive type, the time and method of curing (temperature and humidity), the water content, the unit weight and the time interval between mixing and compaction (Çokça [4]).

The addition of lime, fly ash, and lime/fly ash to three clayey soils led to a reduction of the plasticity index and contributed to an increase in the optimum moisture content and a decrease in the maximum dry density (Hesham [5]). The optimum lime content ranged from 3 to 5%, while the optimum fly ash content between 16 and 35%. The optimum lime/fly ash content for the three soils was (2.5%L+8%FA), (2%L+12%FA) and (3%L+20%FA). The UCS, E_{secant}, CBR, and the Velocity of ultrasonic p-waves, Vp, values increased slightly with an increment of the dry density of the untreated compacted soils (due to the compaction process) and strongly due to the addition of the chemical stabilizing agents (lime, fly ash, and lime/fly ash) whereas the formed cementitious compounds (as a result of the chemical reactions between the silica and the alumina and the additives) joined the soil particles.

Basic studies on pozzolanes and on the pozzolanic properties of fly ash have been carried out by Adu-Gyamfi [6] and Brooks [7]. Considering the nature of the lime used in the mixtures, many investigators such as Ingles and Metcalf [8], have shown that calcarious limes gave higher strength results than those given by dolomitic limes.

In Greece, many roads have been built using stabilization techniques for the subbase materials. The behaviour of these roads has been judged as fairly satisfactory. The scope in some of these trials was the use of large quantities of fly ash per surface unit, in order to take advantage of the surplus of this material. However, the cost of transporting the material from places of its production or deposition to the areas of the projects under consideration, which are located to a relatively small distance from the power stations, is a very restrictive factor.

The Research Centre of Public Works (KEDE) has carried out significant studies on the stabilization of aggregates and clayey soils, mainly with Portland cement and with lime and fly ash since 1982. The exploitation of Megalopolis fly ash and its applications in highway construction in adjacent areas has been examined by Marsellos et al. [9]. Further studies have been undertaken by Greek Universities, the Technical Chamber of Greece, and other researchers.

The main objective of this work is to test the capability of lime and fly ash in improving the engineering properties of clayey soils from the areas of Thrace, in order to use them as stabilized layers in road construction and to apply more economic processes in constructing new pavements or improving existing ones.

2 Materials and methods

The soils used in this study have been sampled near the villages Aetolofos and Aetokorifi of the Rhodope prefecture in Thrace. The soils are pleio-pleistocene fluvio-lacustrine deposits resulted by the alteration of andesitic tuffs and tuffites of the Zonaia Mountains surrounding the basin. These clayey soils are of black colour near the surface, but they turn to grey or yellowish in the deeper horizons. In some places they are intercalated by lenses or layers of sand and gravels.

Disturbed samples were taken from an excavation about 1 m deep in two different locations, near the New Egnatia highway. The soil "S_1" is a fine-grained black clay, while the soil "S_2" is a brown clay. Cation concentrations of Mg and Ca 5.76 meq/l and 19.21 meq/l, respectively, have been determined for S_1. The respective values for S_2 were 8.84 meq/l and 92.32 meq/l. The chemical properties of the soils are summarized in Table 1.

Table 1: Chemical composition of the soils tested.

	Black Soil (S_1)	Brown Soil (S_2)
Loss on Ignition	11.62 (%)	14.95 (%)
SiO_2	64.18 (%)	57.25 (%)
Al_2O_3	12.73 (%)	11.97 (%)
Fe_2O_3	5.43 (%)	5.43 (%)
CaO	1.55 (%)	7.28 (%)
MgO	1.50 (%)	1.16 (%)
K_2O	1.80 (%)	1.55 (%)
Na_2O	0.70 (%)	0.21 (%)

The soils were air-dried and pulverized, in order to pass the No. 4 (4.75 mm) sieve. The grain size distribution of the representative soil samples is presented in Table 2.

Table 2: Properties of natural soils.

Properties	Soils	
	Black Soil (S_1)	Brown Soil (S_2)
Specific gravity (kg/cm^2)	2.5	2.7
Liquid Limit (%)	76	51
Plastic Limit (%)	29	23
Plasticity Index (%)	47	28
Linear Shrinkage (%)	13.3	10
Free Swell Index (%)	95	51
Maximum Dry Density (kg/m^3)	1588	1707
Optimum Moisture Content (%)	21.7	17.8
Grain Size Distribution		
Sand and Gravels (%)	24.3	16.2
Silt (%)	22.7	35.8
Clay (%)	53.0	48.0
Classification		
AASHO	A-7-6	A-7-6
USCS	CH	CL
Unconfined Compressive Strength (kg/cm^2)	1.5	2.7

The basic properties of the soils were determined from representative samples and for the soil fraction passing the No 40 (425 μ) sieve. The liquid limit of these soils was found using the Casagrande method.

The grain size distribution of the soils has been determined by both the dry method (AASHTO T-27) and hydrometer analysis. The physical properties of the soils studied and their unconfined compressive strength (UCS) are presented in Table 2.

Both soils are classified as Group A-7-6 according to the AASHO classification system, while, according to the Unified Classification System, are classified as CH and CL respectively. Soil samples passing the No 4 (4.75 mm) sieve were used in order to find the dry density-moisture content relation with the standard Proctor compaction test. The soils were thoroughly mixed with different moisture contents (14% to 30%) and were cured in a moisture room for 24 hours before they were compacted, for uniformity purposes. The maximum dry density and the optimum moisture content are shown in Table 2.

The lime used in this study was a typical commercial hydrated calcitic lime, having a high CaO content (65.25%). It was supplied by the AIMOS Lime Company, Drama, Greece which has a 200 ton daily production. The chemical composition of this lime is shown in Table 3.

The term fly ash represents the fine-grained ash residue produced from pulverized coal combustion and carried away by the hot gases comes out of the chimney. This residue is usually collected with appropriate filter put along the chimney. The fly ash used for the preparation of the laboratory specimens was supplied by the Ptolemaida Power Station (6,000,000 ton/year). The chemical composition of the fly ash is shown in Table 3.

Table 3: Chemical composition of lime and fly ash.

Properties	Lime	Fly ash
Loss on Ignition	33.25 (%)	13.90 (%)
SiO_2	0.01 (%)	29.95 (%)
Al_2O_3	0.01 (%)	10.85 (%)
Fe_2O_3	0.11 (%)	4.57 (%)
CaO	65.25 (%)	20.00 (%)
MgO	0.50 (%)	1.90 (%)
K_2O	0.01 (%)	0.95 (%)
Na_2O	0.01 (%)	0.32 (%)

3 Treatment of soil samples with lime and fly ash

The air-dried soil materials passing the No. 4 (4.75 mm) sieve, were mixed in different proportions by weight with lime (in powder form) and fly ash. Water was added until the optimum moisture content was reached and the mixing process continued till a visually uniform product was achieved. Cylindrical specimens 50 mm in diameter and 100 mm high were then formed in special moulds. The material was placed in the mould in three layers of equal thickness.

The quantity of the material for each sample was determined by the optimum moisture-maximum dry density relationship. The compaction to the maximum dry density Proctor was achieved by compressing the required mass in the given volume with an automatic hydraulic press. After their extraction from the mould, the specimens were weighted and sealed in polyethylene bags, in order to keep the moisture content constant during the curing period.

For each percentage of additive a set of three specimens was prepared. Care was taken to cure the specimens under stable temperature and moisture conditions. The specimens for the unconfined pressure test were cured for 7, 28 and 90 days before their testing.

The additive–soil weight ratios used were:

a) for the lime: 4–100, 7–100, 10–100 for both soils.

b) for the fly ash: 4–100, 8–100, 12–100.

Specimens were also prepared with lime–flyash–soil ratios: 1–3–100, 2–6–100 and 1–5–100 by weight.

For each discrete ratio, the optimum moisture content was determined using the standard Proctor method according to the AASHTO T99 61 specification. The specimens were tested in an unconfined compression machine with strain rate 1.25 mm/min.

An X-Ray Diffraction analysis showed that soil S_1 had more swelling clay minerals, while soil S_2 had more kaolinite and calcite.

4 Results and discussion

The Atterberg limits, the optimum moisture content and the maximum dry density of the soil-lime, soil-fly ash and soil-lime-fly ash mixtures are presented in Tables 4 and 5 for the black soil S_1 and the brown soil S_2 respectively. In the same tables the unconfined compressive strength after 7, 28 and 90 days of curing is shown.

The addition of lime resulted in a reduction of the liquid limit in comparison with the natural soil. This fact complies to the results obtained by other investigators (Sridharan et al. [10], Akoto [11], Athanasopoulou [12]) who have observed a significant reduction in the LL of fine-grained soils following their treatment with additives. The admixture of lime rapidly initiates flocculation and cation exchange reactions, leading to a reduction of the specific area of the soil. The reduction of the thickness of the diffused double layer causes the reduction of the liquid limit. This reduction was smaller (12% with fly ash and 18% with lime) for the brown clay, in comparison to the black soil (22% with fly ash and 27% with lime) due to higher concentration of calcium and magnesium exchangeable cations and the lower percentage of swelling clay.

The admixture of lime and fly ash resulted in a reduction of the maximum dry density (MDD) of the soils. On the other hand, an increase in optimum moisture content (OMC) was observed for the same compaction effort (Tables 4 and 5). The reduction in maximum dry density, following the treatment with lime and/or fly ash, reveals the increased resistance to the compaction effort offered by the flocculated soil-structure.

Table 4: Alteration of properties of black clay treated with lime and fly ash.

Materials			Atterberg Limits			Compaction Characteristics		UCS (kg/cm^2)		
Soil g	F.A G	Lime g	LL %	PL %	PI %	M.D.D. Kg/m^3	O.M.C. %	7 Days	28 Days	90 Days
100	0	0	76	29	47	1588	21.7	1.5	1.5	1.5
100	4	0	69	32	37	1526	25.6	4.3	4.5	5.6
100	8	0	64	35	29	1487	26.4	6.4	7.2	7.9
100	12	0	59	39	20	1422	31.2	7.6	8.8	9.5
100	0	4	68	39	29	1453	28.8	6.0	9.6	13.6
100	0	7	60	41	19	1449	29.4	6.5	11.7	22.9
100	0	10	55	43	12	1445	29.9	7.4	13.5	16.4
100	3	1	66	34	32	1476	28.2	3.3	4.1	5.0
100	6	2	65	48	17	1453	29.4	7.9	9.3	11.7
100	5	1	59	42	17	1468	28.8	3.8	4.3	4.3

The OMC increased as a consequence of the excess of water retained in the voids of the flocculated soil-structure (formation of soil aggregates), which results from the soil-additive interaction. For all the percentages of additive, the mixtures with fly ash showed greater MDD values than those with lime, due to the smaller apparent unit weight of lime.

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Table 5: Alteration of properties of brown clay treated with lime and fly ash.

Materials			Atterberg Limits			Compaction Characteristics		UCS (kg/cm^2)		
Soil g	F.A. G	Lime g	LL %	PL %	PI %	M.D.D. kg/m^3	O.M.C. %	7 Days	28 Days	90 Days
100	0	0	51	23	28	1707	17.8	2.7	2.7	2.7
100	4	0	50	33	17	1611	22.1	3.8	4.3	4.5
100	8	0	47	37	10	1577	24.5	6.6	7.9	9.2
100	12	0	45	40	5	1477	28.1	8.8	9.5	12.4
100	0	4	49	NP	--	1575	24.6	3.5	5.7	8.5
100	0	7	47	NP	--	1559	25.1	3.9	5.8	9.0
100	0	10	42	NP	--	1525	26.5	3.9	6.0	8.4
100	3	1	46	43	3	1604	22.6	5.3	6.1	7.1
100	6	2	43	42	1	1558	24.9	8.4	11.7	12.6
100	5	1	40	39	1	1573	23.9	6.3	7.5	8.9

The change of OMC and MDD was gradual when fly ash was used, whereas with the admixture of lime a rapid change existed with small percentages of additive and remained almost constant thereafter. This could be attributed to the reaction rate between the clayey soil and lime, as well as to its quick flocculation due to quick exchange of soil cations with Ca^{++} from the lime and depression of the double layer. On the other hand, the end change of these properties is greater with fly ash than with lime due to the reaction of the soil with the constituents of fly ash other than CaO, like SiO_2, Al_2O_3 and MgO.

Considering the strength change of the soils, the UCS increased both with the percentage of the additive and with the time of curing as it is demonstrated in figures 1 to 4. In the case of lime addition, a dramatic increase occurred in the strength of the soil (more than 10 times) with addition of only 4% lime. This high rate of increase in soil strength was reduced with the increase of lime content and at some 8-10% of lime the UCS remained more or less constant or started to decrease (point of soil satisfaction). This percentage is recognized as the lime modification optimum (LMO) of the soil. The same trends hold true for the fly ash, though the rate of increase was lower and there was no point of soil satisfaction. The strength increased in an almost constant rate when the percentage of fly ash in the mixture was increased. As it is shown in figures 1 to 4 the rate of strength gain and the ultimate strength were different for both the additive and the soil. Lime proved to be much more effective than the fly ash in the case of the soil S_1; the opposite has been observed for the soil S_2.

The difference in the soil behaviour is certainly due to the differences in the mineralogy of the soil and the kind of the exchangeable cations present. The brown soil S_2 is almost saturated by Ca^{++} cations, therefore the addition of lime has little effect on the exchangeable cations of the soil. It is well-known that lime has a more pronounced effect on swelling clay minerals (illite, caolinite) due to the greater depression of the double layer. For the same reasons, fly ash yielded a little better results in soil S_1 than in the brown soil S_2.

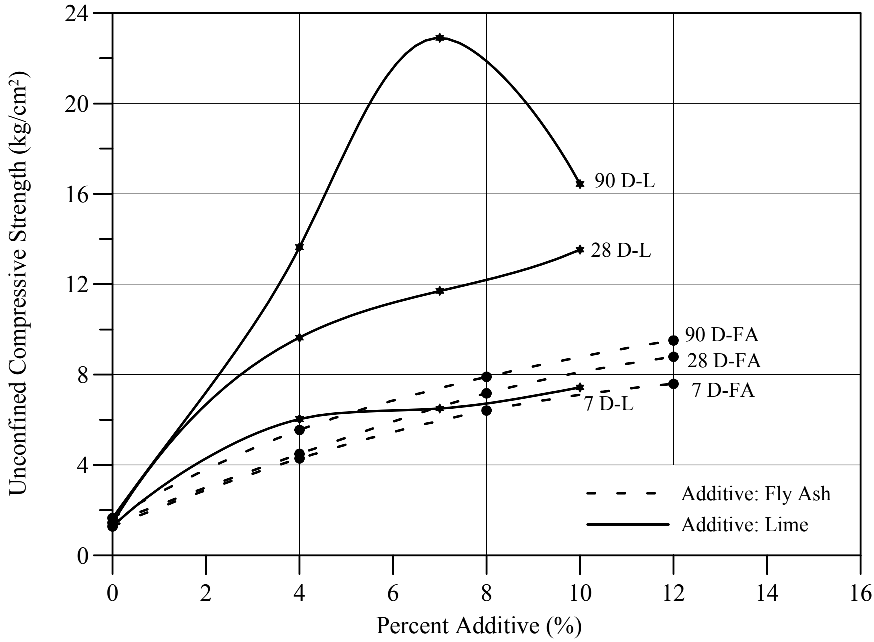

Figure 1: Variation of UCS with the percentage of additive (Black clay, S_1).

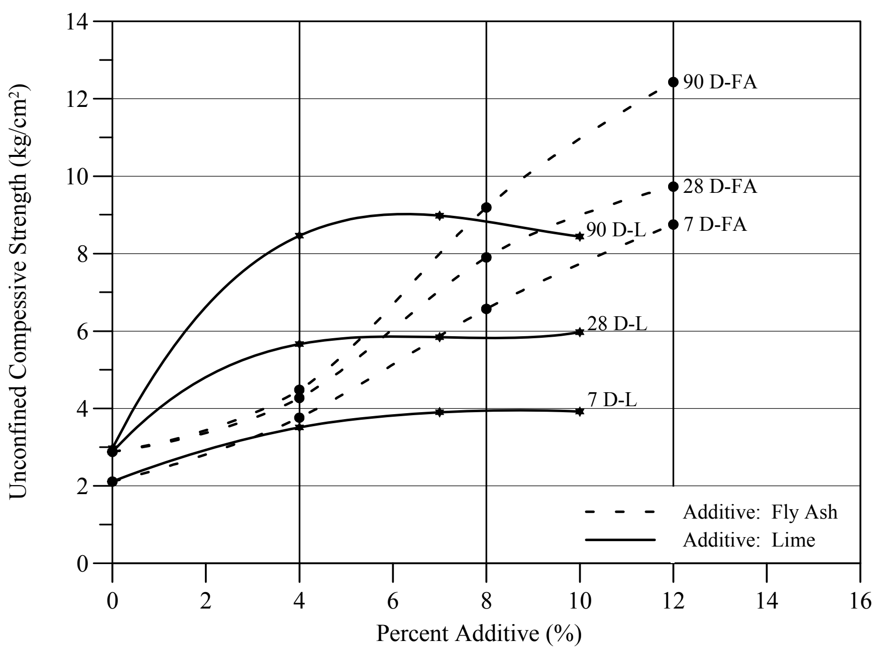

Figure 2: Variation of UCS with the percentage of additive (Brown clay, S_2).

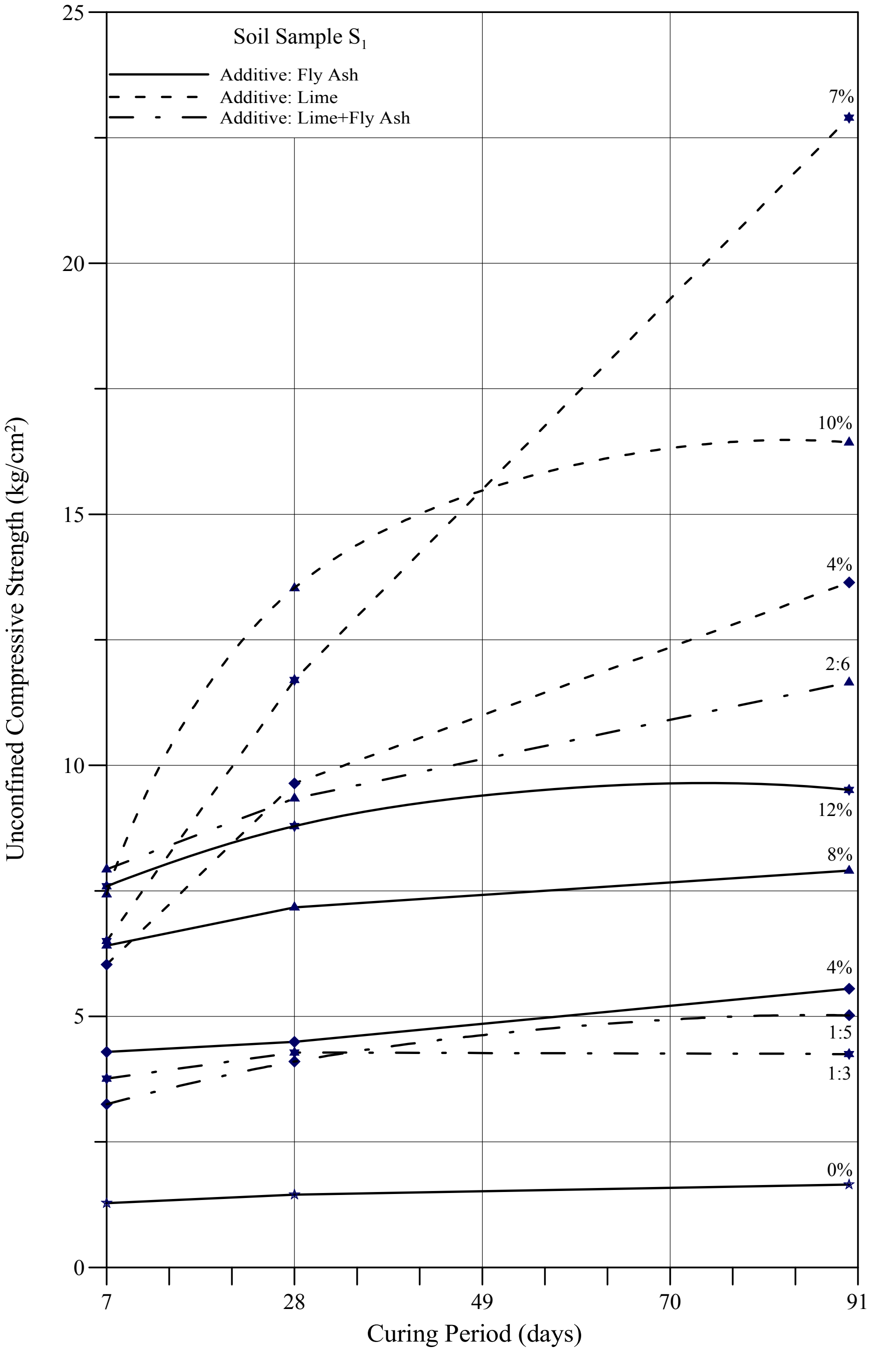

Figure 3: Variation of strength values for mixtures after different curing periods (Black clay, S_1).

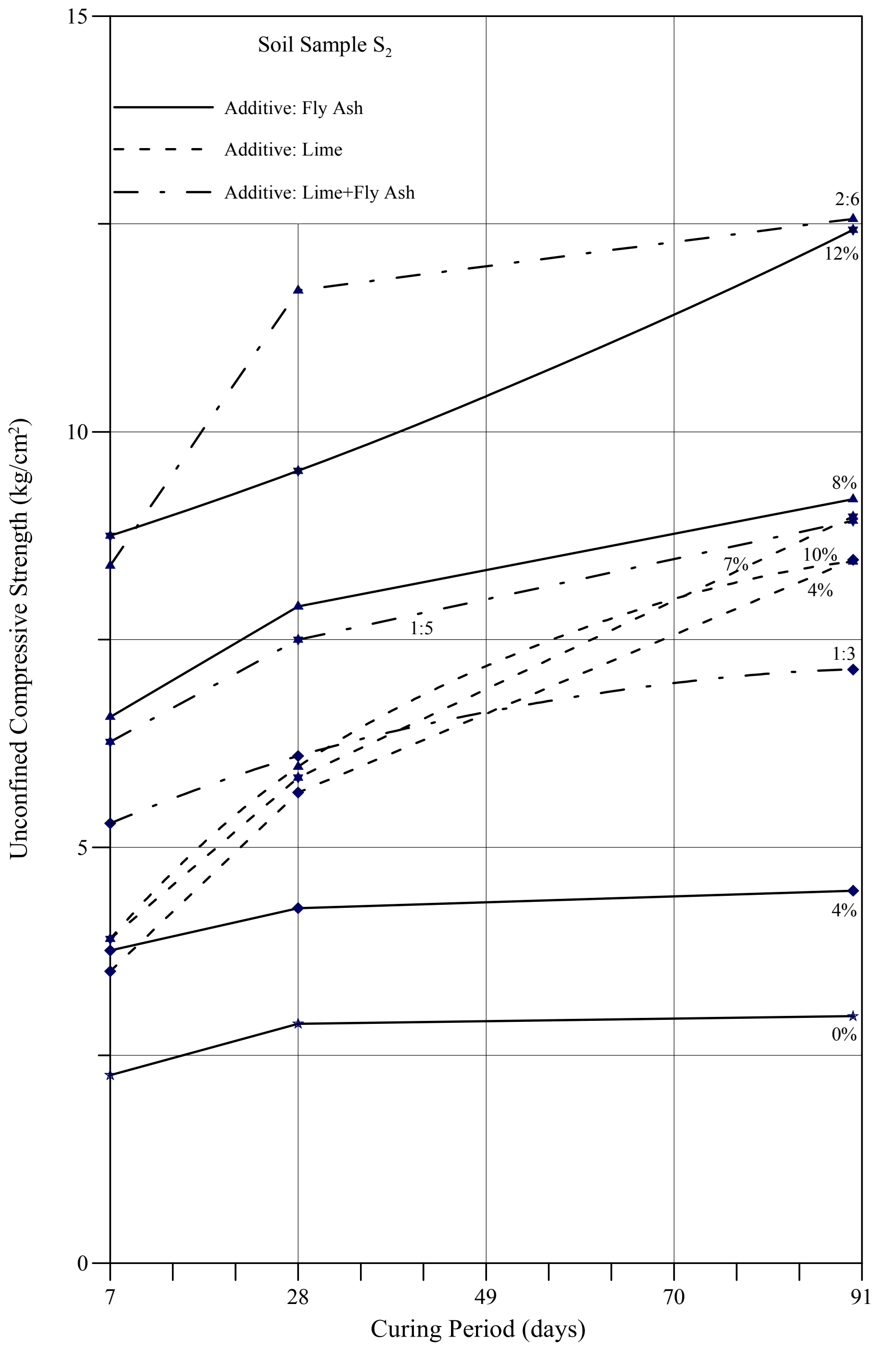

Figure 4: Variation of strength values for mixtures after different curing periods (Brown clay, S_2).

Considering the effect of the curing period, the results followed the same general pattern as with the percentage of additive. That is, for soil S_1, the effect of time was more significant in the case of lime than in the case of fly ash, whereas in soil S_2 the UCS value raised much more with the curing time when fly ash was added than in the case where lime was used.

This difference could also be attributed to the abundance of swelling minerals in soil S_1. The more the swelling minerals, the more lime is precipitated in the clay surface and the more cementitious materials ($CaCO_3$) are formed. The increase of strength in swelling minerals is due rather to cation exchange (flocculation of the clay) and to the cementitious reaction than to the pozzolanic one (Xeidakis [13], Baykal et al. [14]).

Soil mixtures having lime–fly ash ratios of 1–3 and 2–6 have given a little higher strength values than those of the mixture with each additive alone. So, the 2–6 lime–fly ash ratio resulted to a strength two times and 1.5 times greater than that with the addition of fly ash alone and lime alone, respectively (figures 3 and 4). The soil-lime-fly ash mixtures exhibited final strength values intermediate to those found for the soil-lime and soil-fly ash mixtures.

5 Conclusions

The admixture of lime and fly ash to two expansive clays have led to a significant decrease of the liquid limit probably due to the depression of the diffuse double layer thickness associated with the clay particles, the aggregation of the clay and the coating by $Ca(OH)_2$.

A progressive reduction in maximum dry density and increase in optimum moisture content has been observed with the addition of these materials. The decrease of maximum dry density of clay soils, after their treatment with lime and fly ash, is an indication of the increase of the strength of the soil and the increase of its bearing capacity.

The strength of the mixtures tested was much higher than that of the natural soils, in all cases. In general, the strength of soil-fly ash and soil-lime mixtures increased with an increase in the additive content, for all curing periods. For both soils and additives, an increase in curing period resulted to an increase in strength.

The increase of the UCS for the soil S_1 was greater with the addition of lime (up to 20 times greater than the original), than with the addition of fly ash. The best results obtained when 7% lime was added to the soils and a 90 days curing period followed the compaction of the specimens. This is attributed to less Ca^{++} and a greater percentage of clay minerals in this soil. The strength increase in soil S_2 was greater with fly ash than with lime. This may be due to a higher content in Ca^{++} and caolinite, as well as to a lower content in swelling minerals.

The results showed that the mineralogy of the soil plays a decisive role in the stabilization process and greatly affects the ultimate strength of the mixture.

The ultimate strength of the soil after its improvement is adequate for the soil to be used as subgrade or embankment material in main roads, or even as subbase in some secondary roads.

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