# Fly Ash Stabilization of Decomposed Granite

## La Stabilisation de Granit Decomposé par des Cendres Volantes

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SYNOPSIS. The use of fly-ash as an effective way of stabilizing a sandy soil resulting from the decomposition of granite has been experimentally investigated. The self hardening properties of the fly-ash were analyzed by means of strength tests and X-ray diffraction analysis in an attempt to follow the development of new compounds. The gain in resistance observed in pure fly-ash and stabilized soil samples seems to be consistent with X-Ray diffraction results. Main findings of the investigation are : a) For Standard and half-Standard Proctor (in terms of energy of compaction) an optimum fly-ash content (10% by weight) has been found. Larger contents led to a decrease in strength due to swelling effects b) The effect of compaction delay after mixing is virtually non-existant despite other published results. c) The addition of small percentages of lime increases substantially the strength of the stabilized soil.

## INTRODUCTION

Fly-ash is a typical waste material of (pulverized) coal powered energy plants. It is a very fine granular material (similar to Portland cement) quite heterogeneous in physical and chemical properties according to the coal origin, the type of combustion and its degree of fineness. Fortunately, for a given coal and combustion type, the properties of the associated fly-ash remain approximately constant around its mean values. Basic components of fly-ash are $SiO_2$, $Al_2O_3$, $Fe_2O_3$, $CaO$ and C and, in smaller proportion, $MgO$, $SO_3$, $Na_2O$. Main crystals include mullite, quartz, magnetite and hematite. However, amorphous vitreous components predominate and they present (sometimes hollow) spherical shape. The most interesting property of fly-ash is its pozzolanic character, that is, its ability to combine with lime and form a hydraulic liant. This reaction is very sensitive to temperature fluctuations.

Approximately 3.5 millions of Tons of (lignite) fly-ash are produced every year in the North East area of Spain and only a small percentage is presently being used in practical applications. The growing interest in using waste materials in the construction industry has prompted an investigation into the possibilities of fly-ash as a stabilizing and strengthening agent for decomposed granite (a common and widely used material for road bases and embankments in certain areas of Cataluña).

## PROPERTIES OF FLY-ASH AND DECOMPOSED GRANITE.

The fly-ash analyzed is produced in the power plant of Serchs (Barcelona) which has a yearly production of 300.000 Tons. This is the nearest production plant to the city of Barcelona and its industrial area.

The fly ash is originated in the combustion of lignite and a typical chemical composition is : $SiO_2$ (44.6%), $Al_2O_3$ (17.9%), $Fe_2O_3$ (8.8%), $TiO_2$ (0.77%), $CaO$ (22%), $MgO$ (1.4%) $SO_3$ (2.4%), Ignition loss 0,31%, alkalis and not classified (1.82%). The free lime content, according to the spanish standard varies from 4 to 5.5%.

Due to the medium free lime content this fly-ash has setting properties when mixed with water. The evolution of compressive strength of fly-ash paste (at standard consistency : 16% water content, by weight) with time has been studied by means of 2:1 samples cured at 100% humidity and 20º C. An important increase in strength is observed after the first 14-28 days and, at the term of 90 days, strengths of 35 Kg/cm$^2$ are measured. An important expansion is registered during the first 28 days (See Fig.1). Only when the expansion phenomenon tends to halt, the strength begins to increase substantially.

By means of successive X-ray diffractograms the evolution of crystalline components of the fly-ash paste was established. The $CaO$ peak is well formed during the first three days. By the third day the $Ca(OH)_2$ peak begins to be visible. By the seventh day the $CaO$ peak has disappeared and, on the other hand, the $Ca(OH)_2$ peak has grown considerably. It is only after the 28 th day that the $Ca(OH)_2$ peak begins to reduce. Also, during the first 3-7 days the anhydrite peak is barely observable but disappears later on, being substituted by a peak in the 9-10º range, possibly belonging to ettringite. If this is confirmed, this compound may explain, at least in part, the observed expansions.

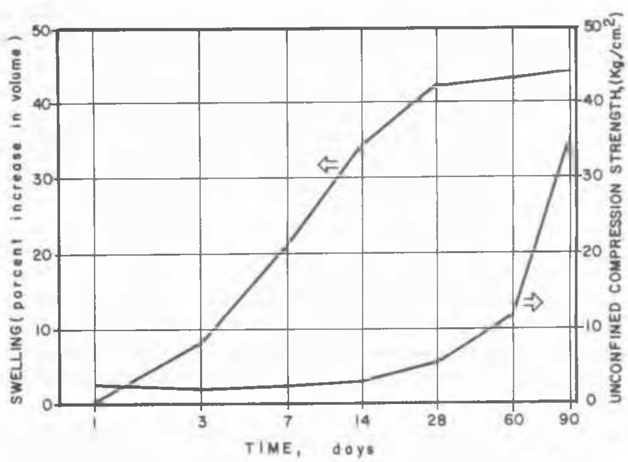


FIG.1 UNCONFINED STRENGTH AND SWELLING INCREASE WITH TIME FOR PURE FLY-ASH

It seems clear that the hydration of lime takes place during the first seven days and this reaction progresses slowly. The "pozzolanic" reactions do not seem to have significance before the first 14 days.

Temperature has a definite influence. Curing temperatures of 50º C give rise to strengths of 21 Kg/cm2 at 28 days (four times bigger than the strength for curing temperatures of 20º C).

The decomposed granite is a coarse to medium sandy soil without any plasticity. The grain size curve is shown in Fig. 2. Also shown is the effect of compacting the soil and the addition of

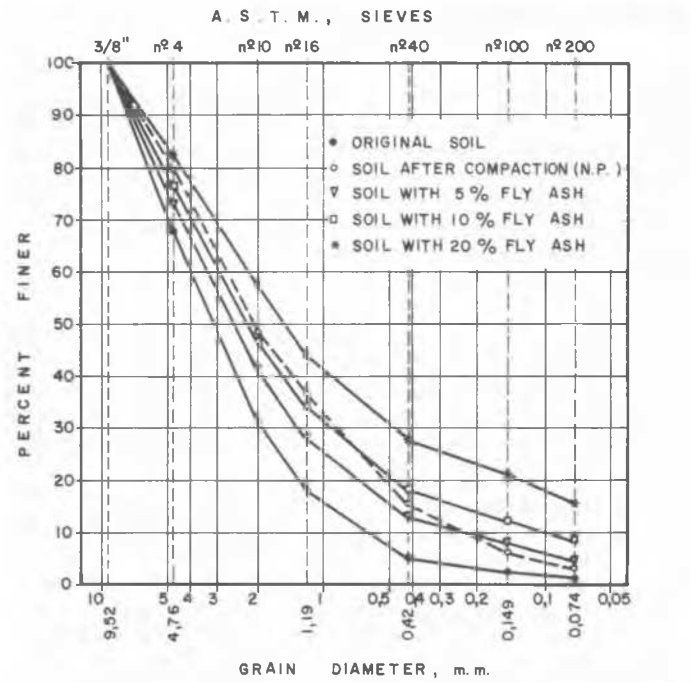


FIG. 2 GRAIN SIZE CURVES OF STABILIZED SOIL

fly-ash. A tendency towards a better grading of the curves is observed. This will result in denser materials for the same amount of compactive effort as Fig. 3 points out. In fact the increase in dry density for increasing amounts (by weight) of fly-ash is quite pronounced. In addition, there is a tendency towards reducing the optimum water content in accordance with the well known"workability" properties of fly-ash, derived from its microscopic structure. It should also be noted that the addition of fly-ash reduces the void ratio at the optimum point (e : 0.41 to 0.29 when fly-ash increases from 0% to 20%) and a parallel increase in degree of saturation (0.61 to 0.72).

RESULTS OF TESTS ON STABILIZED SOIL.

The tests presented and commented subsequently were performed on Proctor-size samples cured at 100% humidity and 20º C. All the tests were repeated five times in order to give a high reliability to the results. Only mean values are given (dispersion was small in general).

There was some interest in knowing the effect of delaying the initiation of compaction once the (wet) soil (with the optimum Proctor water contents) was mixed with the fly-ash. Previous results (Thornton and Parker, 1975) have shown that this delay may play an important role in final strength. (This fact would add

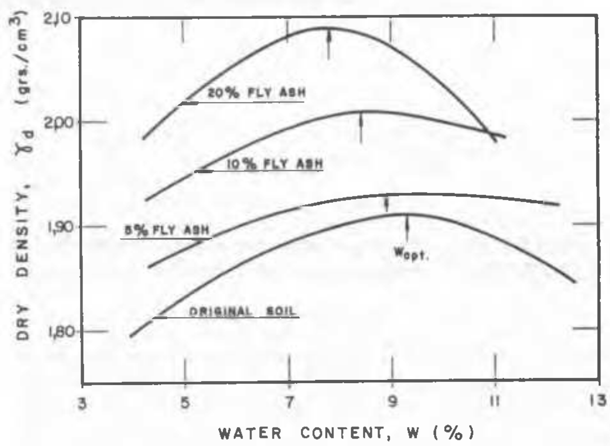


FIG. 3 PROCTOR TESTS ON SOIL MIXTURES WITH VARIOUS FLY ASH CONTENTS.

practical difficulties to stabilization works). According to Fig.4 no significant effect should be attributed, in this case, to this delay in terms of the 28-day compressive strength. In addition, no significant temperature increase was recorded during the mixing and subsequent setting period. Temperature was continuously monitored by means of thermocouple thermometers embedded in the soil mass.

The reason behind the reportedly rapid increase in temperature subsequent to the mixing of fly-ash with soil and water is the strong reaction of free lime with water to produce a hydrated lime. However in our case the (otherwise relatively abundant) calcium oxide seems to exist in a "dead burned" state due to the high coal combustion temperatures. In accordance with this hypothesis, hydration reaction rates are considerably reduced and the heat production takes place at a much more gradual pace.

Triaxial tests. Conventional drained triaxial tests on samples compacted at 95% of the optimum Proctor water content and later fully saturated, were performed for different fly-ash contens. At the test time the samples had an age smaller than one hour and, therefore, they represent an initial state, free from any setting effect of the fly-ash.Fig.5 shows normalized stress - strain volume change curves. The addition of fly-ash and subsequent compaction, has a distinct effect in increasing the deformation modulus and the tendency towards (positive) dilatancy. Also shown in Fig. 6 is the increase in strength as the fly-ash content increases. These results are associated with the density of the compacted sample achieved in each case. However as will be seen below, these trends are substantially modified at longer periods of time.

Evolution of unconfined compressive strength. A few stress-strain curves for samples with 10% fly-ash content and different ages are shown in Fig. 7. Both unconfined strength and elastic modulus show a parallel and important increase when the age to failure increases. In fact, the elastic modulus increases roughly ten times in three months (3 to 90 days) whereas the strength increases six times in the same period. The gain in strength with time is better displayed in the semilogarithmic plot of Fig.8. As usual, each experimental point in this graphic represents the mean of five samples tested. It is interesting to note that the effect of fly-ash additions is not homogeneous with

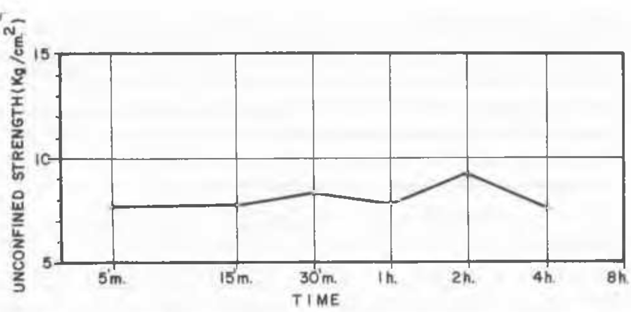


FIG. 4 28 DAYS UNCONFINED COMPRESSIVE STRENGTH FOR 10% FLY ASH CONTENT, AS A FUNCTION OF DELAY OF COMPACTION AFTER INITIAL MIXING.

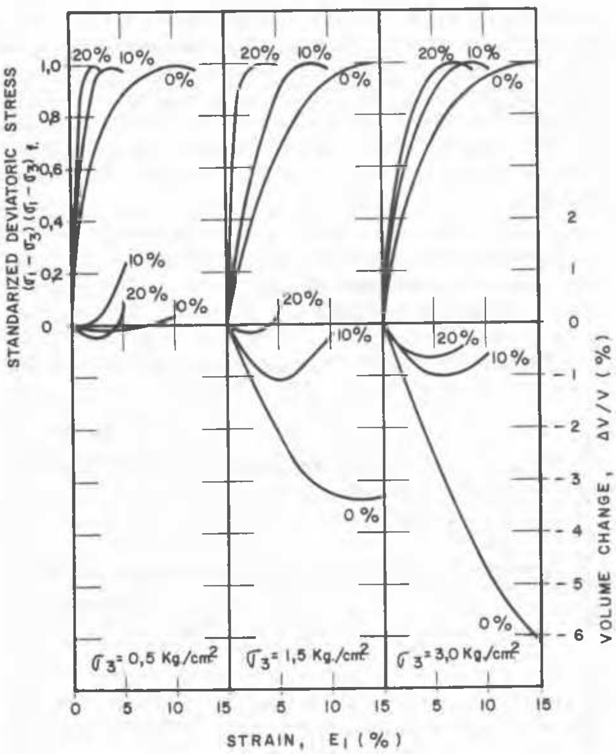


FIG. 5 CD. TRIAXIAL TEST ON SOIL SAMPLES WITH VARIOUS FLY ASH CONTENTS.

time, suggesting that the different "contributions" to the strength develop at different rates. Thus, the higher strength of the 20% fly-ash content samples during the first(5) days may be attributed to the denser structure of the mixed soil, not disrupted yet by the detrimental expansion effects of the fly-ash which counteracts the natural gain in resistance due to the formation of calcium-silicate compounds. Samples with 10% fly-ash content seem to represent an optimum compromise between detrimental expansion effects and gain in strength due to the self-hardening properties of fly-ash. The smaller influence of expansion in this case is explained by the larger amount of pore space available

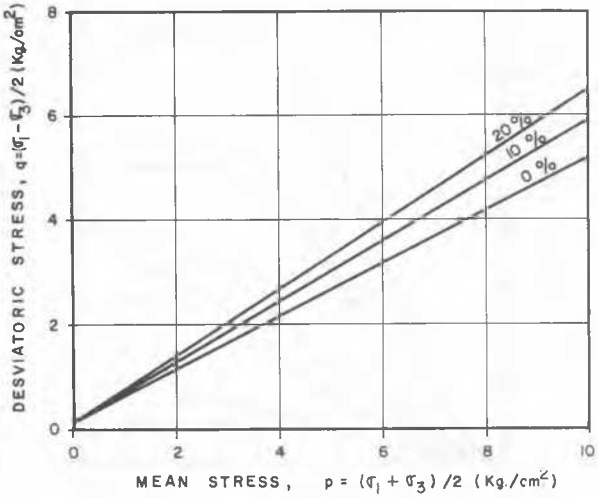


FIG. 6 STRENGTH ENVELOPES FOR SOIL SAMPLES WITH. VARIOUS FLY ASH CONTENTS (C.D. TRIAXIAL TESTS.)

once the compaction is finished and, of course, the smaller percentage of fly-ash. The influence of available pore space is better pointed out by comparing the results of standard Proctor and Half (in terms of compaction energy) Standard Proctor for the 20% fly-ash content samples. It can be seen that the "final" (28-90 days) strengths are very close to each other despite the initially denser structure of the Standard Proctor samples. The larger pore space available in the Half Standard Proctor samples may play in this case a befenicial role in allowing the expansion of fly-ash. This is also shown in Fig.9 which reflects better the influence of fly-ash content on strength (and obviously on associated elastic modulus) at 28 and 90 days. The optimum content seems to be close to 10%. However the figure also suggests that there is a tendency towards increasing the optimum fly-ash content when the energy of compaction decreases. This tendency is consistent with the previous discussion on pore space influence.

Expansion. Two series of expansion tests were performed on samples with different fly-ash contents and compacted at the optimum (Proctor) water content. The first one was aimed to find the radial 90 days unconfined expansion (a device similar to the Le Chatelier needle was used) of submerged samples at a constant temperature of 20º C. In the second one the vertical expansion of laterally confined samples into the (silicone greased) Proctor moulds was measured under identical circumstances.

Samples with 5% and 10% fly-ash contents showed small radial deformations (0,04% and 0.2% respectively) which developed only during the first 14 days. Similar figures were obtained for samples compacted at half the energy of the standard Proctor. Vertical expansion of confined samples was also small (0.30% was the maximum vertical deformation recorded) for the above mentioned fly-ash contents. On the other hand the Proctor compacted 20% fly-ash content samples showed (unconfined) radial expansion of 1.60% and vertical deformation close to 0.45% for the confined samples.

Parallel figures for the half energy samples were 2.24% and 0.6% All the 20% fly-ash content samples showed a well developed craking pattern unlike the other samples. As commented before this

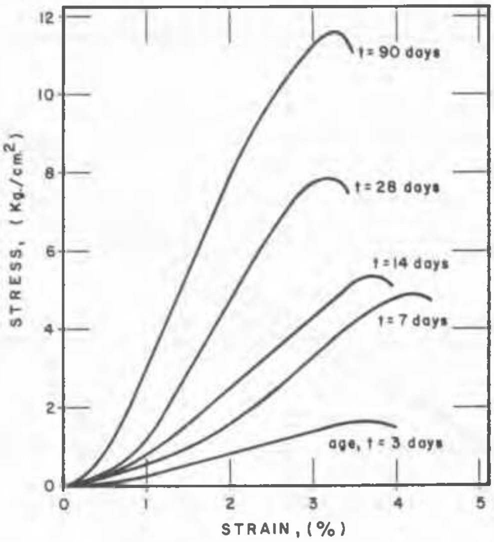


FIG. 7 UNCONFINED COMPRESSION TEST FOR 10% FLY-ASH CONTENT AND DIFFERENT CURING AGES

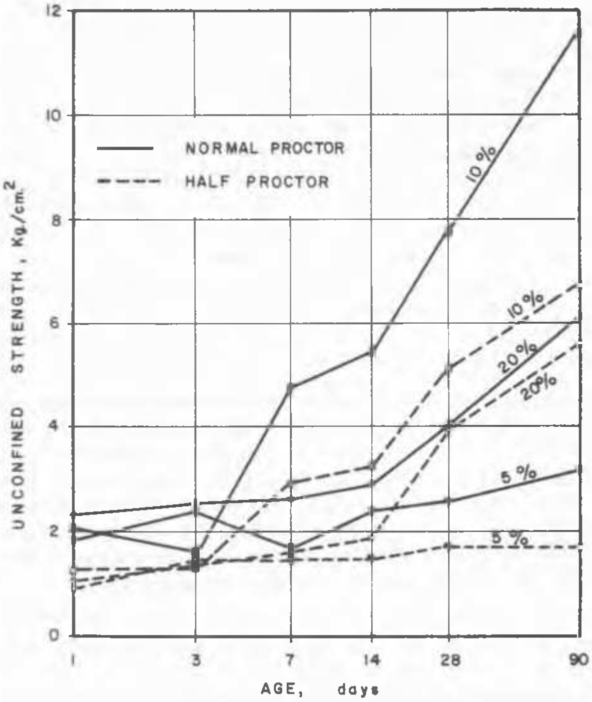


FIG. 8 EVOLUTION OF STRENGTH OF STABILIZED SOIL FOR DIFFERENT FLY ASH CONTENTS AND ENERGY OF COMPACTION.

expansion is, most probably, the reason for the decay in strength observed in the 20% fly-ash content samples.

MIXED LIME-FLY-ASH STABILIZATION

Several authors (Mateos and Davison, 1962, and Croft, 1964 ) have reported in the past the difficulties in finding an optimum lime content and recommend the addition of percentages ranging from 3% to 6% for sandy soils. The presence of free lime in the fly-ash studied here adds some further uncertainties in our case. Additions of 3% and 6% of line to the already mixed soil with 10% fly-ash and the optimum (Proctor) water content resulted in the strengths shown in Table I. Strengths

TABLE I. Strengths of lime-fly-ash stabilized soil($Kg/cm^2$)

| Compaction Energy | 3% lime + 10% Fly Ash | | | 6% lime+10% Fly Ash | | |
|---|---|---|---|---|---|---|
| | 7 days | 28 days | 90 days | 7 days | 28days | 90days |
| Standard.P | 4.2 | 14.8 | 4 2 | 4.6 | 9.5 | 41.1 |
| Half Standard | 3.6 | 11.7 | 29.5 | 51.3 | 12.8 | 31.2 |

are increased by 3–4 times if compared with the fly-ash stabilized soil at the same ages. However no significant improvement is obtained with larger amounts of added lime. On the other hand the measured expansions are larger than the expansions measured for the samples of the fly-ash stabilized soil (confined vertical deformation 0.49%; unconfined radial deformation 0.93%) but no visible cracks were recorded during the first 90 days of curing. Additional testes show that the increase in water content by 2% above the optimum Proctor does not have any influence on final strength.

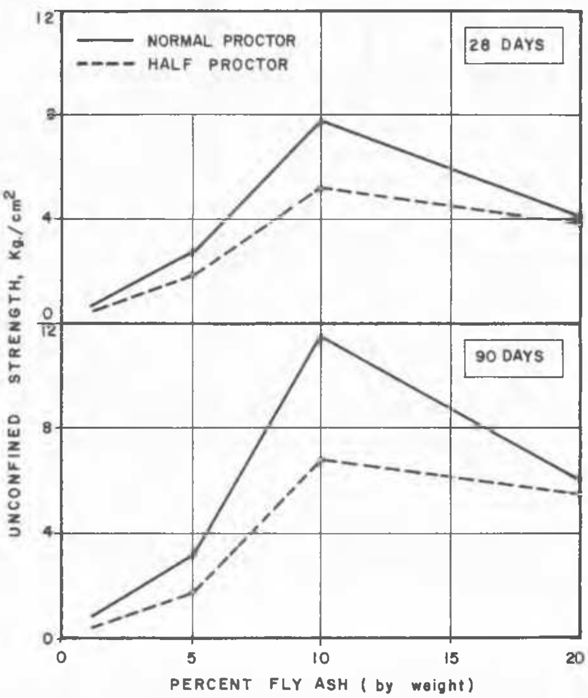


FIG. 9 INFLUENCE OF PERCENT FLY ASH, ON GAIN OF STRENGTH OF STABILIZED DECOMPOSED GRANITE ( SAULO )

CONCLUSIONS

The ability of self setting (due to the presence of free lime) fly-ash to effectively stabilize a sandy soil coming from decomposed granite has been investigated. The main setting mechanism and its development in time has been shown. Despite the strong ex pansion effects measured in pure fly-ash samples, high, unconfined strengths (35 Kg/cm$^2$) were measured (at ambient temperature -20º C - ) at 90 days.

An optimum fly-ash content (in terms of 28 and 90 days unconfined strength), very much conditioned by the fly-ash expansion effects and the available pore space of the soil, was found to be close to 10% (by weight) both for standard and half standard (in terms of compaction energy) Proctor. Strengths of 7,5 - 11,5 Kg/cm$^2$ and elastic modulus of 360/520 Kg/cm$^2$ were measured at 28-90 days for the stabilized soil.

The delay in compaction once the stabilized soil was prepared had no significant influence on final strength (at least for the first four hours). This result facilitates practical handling of fly ash in the field.

Lime addition by small percentages (3%) strongly increases the strength (by 3-4 times) over the 10% fly-ash stabilized soil. A slight increase in expansion is also measured (without crack formation) in this case.

These results confirm the possibilities of using these self-setting fly-ashes (either alone or accompanied by lime if larger strengths are required) as an effective agent to stabilize sandy soils.

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REFERENCES

Croft, J.B. (1964) "The pozzolanic reactivities of some New South Wales fly-ashes and their application to soil stabilizations." Australian Road Research Board Proc. Vol. 2, Part 2. Paper 120, pp. 1144-1168.

Mateos, M. and D.T. Davison (1962) "Lime and Fly-Ash proportions in soil-lime-fly-ash mix-tures and some aspects of soil-lime stabilization "Highway Research Board Bulletin, 335, pp 40-64.

Thornton S. and D.G. Parker (1975) "Fly ash as fill and base material in Arkansas Highway", Highway Research Project, 443, pp 4-43.