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Improved Performance of Soils Stabilized With FBC Ash

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ABSTRACT

The paper presents the results of the second phase of a project that studies the applications of Fluid Bed Combustion (FBC) ash in soil stabilization with particular application to forest roads. Two types of applications have been identified based on different types of soils which react differently with the addition of FBC ash. The first type application corresponds to those soils whose physical and mechanical properties are improved to a certain extent with the addition of FBC ash and may be used as an improved base course or an improved gravel road. The second type of application corresponds to those soils whose physical and mechanical properties are improved to a certain extent, but above an “x” percentage of FBC ash addition, they may swell and produce an adverse effect. The research work examines different procedures to further improve the performance of the second types of soils in order to make feasible its application on secondary type of forest roads.

Introduction

The forestry industry in Chile has experienced major growth during the last 15 years. This is reflected in the technical advancements reached in every one of the industry’s processes. In spite of the growth and development of the sector, the technologies applied to the construction and maintenance of the road network of forestry roads have not experienced the same progress, representing greater costs for forest production. For this reason, the industry is interested in finding new techniques that would make it possible to build and operate gravel roads without the need to implement traditional paving solutions. This is a challenge for road researchers, given that forestry roads present more adverse conditions than other types of roads mainly due to the lack of good road materials, the climate conditions (rainy), heavy traffic under extreme geometric conditions (slopes and horizontal curves). It has been proposed a research project in which soil stabilization techniques are going to be introduced for forest road construction. Among different chemical stabilizers FBC ash has been proposed to be one of the types of chemical stabilizer to be used. Coincidently, in Chile, one of the regions where most of the forest industry operation is concentrated operates a large combustion electric power plant which uses fluidized bed combustion (FBC) technology and produces between 60 to 80 tons per day of FBC ash in its operations. This ash is made up of 40% bottom ash and 60% fly ash. For this reason the project has another objective, which is the need to find a secondary use to all the FBC ash that is locally produce.

FBC ash differs from traditional fly ash mainly due to its low content of pozzolanic compounds (silica and alumina) and high content of lime and sulfates. Due to its lime content, FBC ash is self-cementing and thus serves to stabilize soils and granular materials. For the latter, previous research has shown the feasibility of their application however, when stabilizing soils containing large amounts of alumina, expansive reactions occur giving rise to hydrated calcium sulfates, ettringite in particular. The formation of these minerals after compacting produces soil heaving and loss of strength in the pavement [8]. Given that this is the type of subgrade soil that is most abundant in Chilean forestry farms, this research attempted to find alternatives to minimize swelling in soils stabilized with FBC ash and improved strength.

Ettringite Formation Mechanism

Four components are involved in the formation of ettringite in soil-FBC ash stabilizations: calcium, alumina, water and sulfates. Calcium is supplied by the lime in the FBC ash, alumina is added by the soil (especially clays), sulfates are also present in the FBC ash and sometimes in the soil and, lastly, water causes the cementation of the mix. The formation of ettringite and other similar minerals can be prevented by interrupting the supply of any of the four components [9].

Chemically, the reactions that occur are as follows [7]:

$$\mathrm{CaO} + \mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2} \quad (1)$$

$$\mathrm{Ca(OH)_2} \rightarrow \mathrm{Ca^{2+}} + 2(\mathrm{OH}) \quad (2)$$

$$\mathrm{Al_2Si_4O_{10}(OH)_2} \cdot \mathrm{nH2O} + 2(\mathrm{OH})^- + 10\mathrm{H_2O} \rightarrow 2[2\mathrm{Al(OH)^{4-}}4\mathrm{H_4SiO_4}] + \mathrm{nH_2O} \quad (3)$$

$$\mathrm{MxSO_4} * \mathrm{nH_2O} \rightarrow \mathrm{XM}^{\mathrm{Y}} + \mathrm{SO_4}^{2-} + \mathrm{nH_2O} \quad (4)$$

$$6Ca^{2+} + 2Al(OH)^{4-} + 3(SO_4)^{2-} + 26H_2O \rightarrow Ca_6[Al(OH)_6]_2 * (SO_4)_3 * 26H_2O \quad (5)$$

First of all, the lime in the FBC ash hydrates with the water (equation 1), and the calcium hydroxide becomes ionized (equation 2). This occurs due to the presences of calcium ions in the lime which replaces hydrogen and sodium ions in the clay, until the clay particles become saturated with calcium and the pH of the soil rises to 12.4 (pH of calcium-saturated water). At this pH level, the silica and alumina becomes soluble (equation 3), as do the sulfates (equation 4). All these reactions facilitate the formation of ettringite or gypsum, depending on the degree of hydration obtained. The formation and stability of the ettringite in the system is controlled by the pH, temperature, concentrations of dissolved CO_2 ions [7] and H_2O supply[3].

There are two theories that explain the expansion of the stabilized soil matrix [3], both of which have underlying different assumptions. The first theory postulates that the chemical mechanism to form ettringite produces an increase in pressure crystallization thus, causing the matrix to swell. On the other hand, researchers supporting the theory that ettringite is formed due to solution suggest that the absorption of water by the ettringite molecule is the cause of the swelling. The ettringite colloid in the matrix has a high surface area and a negative surface load that is capable of absorbing water and causing expansion. The combination of both mechanisms is also considered a cause for expansion. Regardless of the explanation, water is considered to be the main cause of the swelling.

Summary Research Objective

"To investigate the behavior of potentially expansive soils stabilized with FBC ash at a laboratory and field level". To meet this objective, the following specific objectives were proposed:

- Study a design a laboratory procedure that will make it possible to identify potentially expansive soils.
- Proposed mix design criteria to determine the optimal amount of ash.
- Investigate at a laboratory (and field) level different procedures to reduce the effect of swelling when stabilizing potentially expansive soils with FBC ash.

PS: Field laboratory investigation was under going while this paper was written.

Laboratory Program and Results

The laboratory program was divided into six stages:

a) Characterization tests: physical and chemical characterization of the materials and FBC ash and soils.

b) Initial Consumption of FBC ash: determine the initial percent of FBC ash to add to each soil.

c) Mix design criteria: was carried out adopting an improved version of mix design proposed by the first stage of the research (Vargas 2006).

d) Study the effect of free expansion reaction (mellowing): allow ettringite formation before the compaction. Swell reduction and strength variation of the stabilized soils were measured.

e) Study the effect of re-working a soil that has been already stabilized with FBC ash: Study the effect of re-stabilized with FBC ash in the final strength and swell test.

a) Characterization Tests

The ash used was taken from the power plant in October 2008. After performing chemical analysis on the FBC ash samples, it was to conclude that they are made up mostly of calcium oxide (CaO) and sulfates (SO_3), responsible for the formation of cementing agents (CSH and CAH) and expansive compounds, respectively. A low presence of polluting products such as nickel and vanadium was observed (Table 1).

Table 1. Chemical Composition of FBC Ash.

Element		% Weight
Sulfatos	SO3	40,6
Calcio	CaO	28,4
Sodio	Na2O	0,27
Silicio	SiO2	0,41
Vanadio	V2O5	0,33
Aluminio	Al2O3	0,26
Niquel	NiO	0,14
Magnesio	MgO	0,35
Hierro	Fe2O3	0,07
Cloruro	Cl	0,07
Titanio	TiO2	<0,01
Fósforo	P2O5	<0,01
Potasio	K2O	<0,01
PPC	1000°C/2 hours	29

The soils used were extracted from different forestry farms in the southern region of Chile. Table 2 presents a summary of the properties of the soils used.

Table 2. Characteristics of the Soils Used in the Research.

Soil	Clasification		PI	Optimal Humidity (%)	Dry Density (kg/lt)
	AASHTO	USCS			
A1	A-7-5 (16)	CH	42	20,4	1,7
A2	A-2-7 (0)	SM	13	15,9	1,77
A3	A-6 (4)	SC	21	9,9	2
B1	A-7-6 (15)	CL	21	22,6	1,63
B2	A-4 (4)	ML	7	22,7	1,57
B3	A-7-5 (34)	MH	33	29,6	1,45
B4	A-7-5(31)	CH	45	23,5	1,51
D1	A-6 (4)	SC	12	10,9	2,01

b) Initial Consumption of FBC Ash

To determine the minimum percent of FBC ash that produces pozzolanic reactions in soils, Eades and Grimm test method was used. Results are shown in Table 3.

Table 3. Initial Consumption of FBC Ash

Soil	Classification		Initial Consumption
A1	A-7-5 (16)	CH	5%
A2	A-2-7 (0)	SM	5%
A3	A-6 (4)	SC	7%
B1	A-7-6 (15)	CL	9%
B2	A-4 (4)	ML	6%
B3	A-7-5 (34)	MH	8%
B4	A-7-5(31)	CH	15%
D1	A-6 (4)	SC	6%

c) Mix Design Criteria

The criteria used to determine the optimum FBC ash content was the maximum Unconfined Compressive Strength (UCS) under saturated conditions keeping the Expansion Index lower than 50 (EI < 50) where, "EI" is determined by ASTM D 4829 – 88 (Standard Test Method for Expansion Index of Soils). The Expansion Index is calculated as follows:

$$EI = \frac{(Fh - Ih) * 1000}{Ih} \qquad (6)$$

Where,

EI: Expansion Index
Ih: Initial height of the test sample
Fh: Final height of the test sample

To complement the above criteria's and ensure that the FBC ash is an effective stabilizer, the use of the concept "Retained Strength Ratio" was proposed for the mix design process. Larger ratios are desirable, and they are calculated using the following formula:

$$RST\ (\%) = \frac{Saturated\ UCS}{Dry\ UCS} * 100 \qquad (7)$$

The optimum FBC ash content for the soils tested where:

Table 4. Optimal Ash Optimum Content

Soil	Classification		Optimum FBC Ash
A1	A-7-5 (16)	CH	Not Established
A2	A-2-7 (0)	SM	Not Established
A3	A-6 (4)	SC	20%
B1	A-7-6 (15)	CL	5%
B2	A-4 (4)	ML	5%
B3	A-7-5 (34)	MH	Not Established
B4	A-7-5(31)	CH	Not Established
D1	A-6 (4)	SC	Not Established

If none of the criteria's are met, it will not be recommended to use FBC ash. For soils that do not meet the "EI" criteria, different treatments were used to control the expansions. These treatments are analyzed in next paragraphs.

d) Free Expansion Reaction (Mellowing)

Free Expansion Reaction was achieved maintaining the mix moisture at ambient temperature and humidity for a specified period of time (24 and 48 hours) without compacting (mellowing process). According to the literature, this makes it possible to allow the expansive compounds to form prior to compacting. Then the material is reworked and compacted. Another recommendation drawn from the literature [5,6] to reduce the Expansion Index is to add more water than the OMC, during the mixing process. The effect of additional water was only analyzed in soil with higher content of sulfates and alumina [7].

Tests were run the clayey soil using two different maturating times (24 and 48 hours), and three percentages of additional water in the mix (0%, 3% and 5%). Each set of test was tested for unconfined compression and expansion index tests. The results are showing in Table 5 and Table 6.

Table 5. Results with 24 hours Mellowing Time – Soil A1

% FBC Ash	% Additional Water	UCS (Kg/cm^2)		RST	Expansion Index
		Dry	Sat.		
10%	0%	18.09	4.47	24.7%	87.48
	3%	28.09	3.07	10.9%	47.83
	5%	17.53	3.44	19.6%	80.34
20%	0%	27.81	13.63	49.0%	96.38
	3%	57.41	32.21	56.1%	87.04
	5%	45.62	24.72	54.2%	101.39

Table 6. Results with 48 hours Maturating Time – Soil A3

% FBC Ash	% Additional Water	UCS (Kg/cm^2)		RST	Expansion Index
		Dry	Sat.		
10%	0%	21.02	1.04	4.9%	36.48
	3%	7.58	0.69	9.1%	27.73
	5%	25.39	1.78	7.0%	61.01
20%	0%	44.83	5.97	13.3%	106.37
	3%	57.80	19.81	34.3%	79.29
	5%	42.38	14.76	34.8%	87.48

When adding 3% additional water to the mix, the results showed that in both cases, with 24 and 48 hours maturating time, the Expansion Index (EI) decreased by approximately 30% on average. However when adding 5% additional water Expansion Index increases again.

The results of the UCS tests show that with 3% water in excess of OMC, greater strengths are achieved for both maturation periods. With 5% water in excess of OMC the strength does not increase.

The Retained Strength Ratios (RST) also increases with the addition of 3% water, with the exception of the mix with 10% ash and 1 day's maturating time, where the ratio decreases by 10%. When maturing the mixes for two days, the RSTs decrease by approximately 20%.

After observing that the expansions decrease and that the unconfined compression strength increases with the addition of 3% additional water, it was decided to always recommend 3% additional water in excess of the optimal amount indicated by the Proctor test to all soils rich in sulfates.

In order to prove this last result two more soil high in sulfate content were tested with and without maturing time (0, 24 and 48 hours). The mixes were prepared with 3% more water than the optimal amount indicated by the modified Proctor test. The results of the Expansion Index are shown in .

Table 7. Results of the Expansion Test

Soils		% FBC Ash	Expansion Index		
			No Maturation	24 hours Maturation	48 hours Maturation
	A1	20%	99.61	87.04	79.29
	A3	5%	105.09	85.23	85.29
	D1	15%	73.31	48.92	39.26

The Expansion Index experiences a decrease in approximately 10% per day, which confirms that maturating time is a feasible way to reduce expansion. It was established that one day's maturating time is an acceptable range of time to prepare the mix prior to compacting in the laboratory and in the field.

In summary for those soils high sulfate content which may be highly expansive, the Expansion Index may be reduce by adding 3% on top of OMC and allowing the material to expand freely for 24 hour maturing time.

e) Double Stabilization or re-Stabilization

The hypothesis here is after mellowing time add additional FBC ash, reworked the material and compact. In this way it is expected that mechanical resistance will be improve as measured with the unconfined compression test.

Laboratory tests were conducted using the soil with higher Expansion Index and one with an intermediate Expansion Index. The first application of ash on both soils was 10%. These samples were left for 24 hours mellowing time and later 3% and 5% FBC ash was added. The additional water in the mix was also varied (0% and 3%). The EI and UCS were evaluated in both cases and the results are presented in Table 8.

Table 8. EI Results of Double Stabilization with FBC Ash

Soils		% Addit. Water	Expansion Index		
			0% Additional FBC Ash	3% Additional FBC Ash	5% Additional FBC Ash
	A1	0%	87.46	160.94	111.16
		3%	47.83	110.81	115.21
	D1	0%	50.43	48.22	39.91
		3%	41.5	38.71	37.75

The experience of double stabilization with FBC ash only achieved good results in soils with less expansion index, within the range of potentially expansive soils, this is maybe because in more clayey soils ettringite continued to form with the second addition of ash, and expansion increased when adding more water.

Recommendations for Mix Design Process

Step 1: To establish whether the soil to be stabilized is potentially expansive when reacts with FBC ash, the following is steps are recommended:

- Measure the sulfate and alumina content of the soil.
- Conduct an Atterberg Limits Test on the A PI higher than 15 is considered potentially may be an indication of an expansive soil.
- Determine the initial FBC ash consumption as per the Eades and Grimm Test
- Measure the amount of ettringite: Prepare mixes and measure ettringite as indicated in Appendix 1, starting with the percentage provided as the initial consumption for the test conducted previously and reaching a maximum of 15% (refer to sieve #40) at intervals of 3% to 5%, in the designer's judgment. At least four measurements are recommended. The maximum percentage of ettringite provided by the test is used as a reference (Table 9).

Table 9. Ettringite Percent Recommended

% Ettringite	LEVEL	EI
< 3%	No major expansion problems	EI < 50
3%-5%	Medium level expansion problems	50 < EI < 100
> 5%	Major expansion problems	EI > 100

Step 2: If the soil does not present any major expansion problems, i.e. it is at the first level of Table 9, design for the highest UCT.

Step 3: If the soil is at the second level of Table 12, showing medium-level swelling problems, it is recommended mellowing the mix for one day at ambient temperature, and adding 3% more water (on top of OMC), based on the Modified Proctor Test.

If the soil presents major expansion problems, it will be necessary to mellow it for one day and evaluate the reduction of expansion index with the optimum percent of FBC ash. If the EI isn't reduce lower than 50, lower percent of FBC ash it would be use.

Conclusions

FBC ash has characteristics that prove it to be a stabilizer with high self-cementing potential, due to the fact that it is made up of more than 27% free lime and contains pozzolanic components, mainly silica.

Domestic and national experiences show that the response of granular soils stabilized with FBC ash is satisfactory, increasing their strength considerably and without exhibiting any major expansion problems [2 and 10]. However, fine soils, such as clays and limes, may present expansion problems due to the fact that they contain a greater amount of alumina and sulfates, causing the formation of ettringite and other ettringite derivatives.

Base on the research work carried out, it is possible to conclude that, the soils stabilized with FBC ash can be treated prior the mix is compacted, achieving a reduction in the Expansion Index (EI). Although reducing EI may be reduced, strengths is also reduced, but even so their performance is better than that of natural soil.

Mellowing time is considered to be a good instrument to control expansion in soils with large amounts of dissolved sulfates and alumina. One day is recommended as the optimum maturation time for this type of soil, because it is feasible to carry it out it on site without increasing construction costs.

Adding 3% water in excess of the optimum amount proved to be a good approach for reducing expansion, because it causes greater dissolution of the sulfates in the soil.

The experience of double stabilization with FBC ash only achieved good results in soils with less expansion index, within the range of potentially expansive soils, because in more clayey soils ettringite continued to form with the second addition of ash, and expansion increased when adding more water. Conversely, in terms of the clayey sand studied (D1) the EI decreased to acceptable ranges.

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APPENDIX 1: MEASUREMENT OF ETTRINGITE CONTENT IN SOILS STABILIZED WITH FBC ASH

Test Protocol

This procedure has been used to measure the ettringite content in mixes of soil and FBC ash. It is based on the procedure used in research work carried out at Purdue University, West Lafayette, U.S.A., by Jody Tishmack and Richard Deschamp.

a) Scope

This procedure is applied to mixes of plastic soils with FBC ash, and makes it possible to measure the ettringite content on the basis of water loss above 60°C.

1. Materials and equipment used

- Metal capsules with a minimum volume of 100 ml.
- Oven capable of maintaining a temperature of 55°C with a precision of ± 2°C.
- Oven capable of maintaining a temperature of 110°C with a precision of ± 2°C.
- Scales with a capacity of 1000 g and precision of ± 0.001 g.
- ASTM #40 (425 µm) screen.

2. Procedure

i. Preparation of materials

The soil is sifted through a #40 screen and the retained material is discarded. The soil that passes through the screen is dried at 110 ± 5°C to constant mass.

FBC ash does not require any treatment prior to the test.

The water used should be potable, free of solids and impurities. However, if in any particular project a specific source of water is used, it is convenient to use a sample of that water in the test.

ii. Mix

In the capsule, weigh 100 ± 0,01 g of the mix prepared with the corresponding dose of water and ash as the same proportion that you use to dosaje. Record the mass of soil in the capsule as A and the mass of soil and ash in the capsule as B.

iii. Determination of ettringite

The capsule containing the hydrated mix is left in the oven at 55°C until constant mass is achieved, for a minimum of 24 hours.

Once the mix is dry, the mass is recorded as C and is placed in an oven 110°C, until it reaches constant mass, for a minimum of 12 hours. Once the mix is dry the mass is recorded as D.

3. Calculation and report

The report shall include the following:

- Identification of materials: Type of soil, type of ash.
- Ettringite content: $100 * 2 * (D - C) \big/ (100 + B - A)$