Technical and Environmental Assessment of an Alternative Binder for Low Traffic Roads with LCA Methodology

Alejandra Balaguera Quintero, Diana Gómez Cano, Gloria Carvajal Peláez and Yhan Paul Arias

Abstract Currently, low traffic roads in most countries are made up of unpaved roads; therefore, to increase the bearing capacity and durability of soils, using stabilizers such as lime and portland cement is required. In this paper, the results obtained from the addition of alternative binder materials based on industrial by products such as alkali activated coal ashes that work as soil stabilizers with sustainability criteria and are assessed through Life Cycle Assessment (LCA); this process is approached from the preparation, packaging and storage of binder material, its activation and finally the application in test sections obtaining unconfined compressive strengths of the order of 2 MPa; which represented an increase in resistance above 300% for the same soil without stabilization.

Keywords Alternative binder · Life cycle assessment · Soil stabilization

Introduction

Alternative binders are formed from two components, the powdery materials of alumina-silicates nature and alkaline activator, usually sodium or potassium hydroxide comprise materials with microstructures similar to Ordinary Portland Cement (OPC). These material have been known since the last three decades as geopolymer [1–3] or alkali cements [4, 5], and its use in construction industry ranges from cements, mortars and concretes [6, 7]; among others. Alkali cements produced from industrial by-products like fly ash, blast furnace slag, thermally modified clays, and others such as metakaolin, are used due to their chemical

A.B. Quintero · D.G. Cano · G.C. Peláez
Facultad de Ingeniería, Universidad de Medellín, Carrera, 87 N° 30-65, Medellín, Colombia

Y.P. Arias (✉)
Facultad de Arquitectura, Universidad Nacional de Colombia, Cl. 59a #63-20, Medellín, Colombia
e-mail: ypariasj@unal.edu.co

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composition and reactivity as precursors for the manufacture of unconventional cementitious materials [8]. Materials with high contents of alumina Al_2O_3 and reactive silica SiO_2 or fly ashes, have been used successfully for decades as a partial replacement of OPC, thus contributing to the improvement of physical-mechanical properties and durability compared to traditional materials [9, 10].

The production of a ton of OPC generates approximately between 0.87 and 0.97 t of carbon dioxide gas CO_2 [1, 11, 12] where the construction industry accounts for 7% of anthropogenic emissions worldwide, this due to the use of fossil fuels [13]. According to *The Colombian National Administrative Department of Statistics*, the cement production is on the rise, in 2009 6.97 Million Metric ton (MMt) and in 2015 13.15 MMt were produced, generating an increment of nearly double the production in six years. This increase is linked to population growth and strong demand in the construction industry.

In 2012 it was found that coal is the second source of main energy due to its abundance and the policies adopted by industrialized countries, which produce about 80% of the energy required from fossil fuels; coal production worldwide exceeds 6185.85 MMt per year; Colombia particularly presented an annual coal production from 34 to 77 MMt, being the tenth largest producer of coal, with 74.35 MMt [14]. Fly ashes from coal combustion are generated in large volumes, approximately 10,000 t per year [15]. In addition, in the production of palm oil Colombia ranks first in America and fourth worldwide [16], with a production of 5.4 MMt per year, this shows that 5% ashes are a product of biomass processing. Therefore, the use and reuse of these materials represent significant advantages, since their production and use have a positive environmental impact by reducing anthropogenic CO_2 emissions over conventional cementitious materials that have in their production a high consumption of energy and natural resources [17].

In most developing countries the roads are not paved and have high levels of deterioration due to the susceptibility of the soil and the water regime to which they are exposed, hindering proper operation, especially during the rainy season [18]. To this problem it is added the financial inability to pave the entire network of this type of roads, which means the need for rehabilitation and maintenance in tertiary network with techniques that contribute to their stability and proper functioning.

In Colombia the *research network and technological innovation in new materials and construction processes for road infrastructure INNOVIAL* has integrated coal ash as an alternative material in soil stabilization for low traffic roads, showing significant improvements not only technical but also environmental and social for the sustainable development in the construction business [19]; however, the material conditions for stabilizing the soils and the processes associated with their manufacture and initial processing of raw materials for their production is a subject without enough research, because it is not considered a commercial product yet and there are not systems for optimal storage to preserve their properties. The materials used for packaging and subsequent storage in addition to moisture conditions and storage times directly influence the physical, chemical and mechanical properties of the stabilizer and therefore stabilized soils; from the economic point of view it is evidenced a high cost in the types of packaging used for storage, which is revealed in the increase of environmental impacts at the time of production and marketing. This statement implies exploring into new stabilizer products for unpaved roads from industrial waste management from the manufacturing process, packaging, storage and environmental assessment.

Materials and Methodology

Materials

Silty-clay soil from Colombia that comes from a low traffic road unpaved was extracted for stabilization with fly ash and Na(OH). The used soil had a plastic index of 17.5% with characteristics AASHTO A-7-5, and contents of SiO_2 and Al $(OH)_3$. Modified proctor tests were performed in the soil and the stabilized soil to determine the optimal soil moisture. See Table 1.

The stabilization or improving of the mechanical properties of the soils that are the study object were performed with the use of fly ashes product of the coal combustion in a thermoelectric process of a Colombian textile industry.

The ashes used had mass contents of $SiO_2 + Al_2O_3 + Fe_2O_3$ around 82.35% and CaO of 4.46%, which makes it an F type ash. The quantity of burned coal was 3.9%, see Table 2.

Through DRX Rietveld analysis [20], it was determined that 72.25% in mass of the coal ash corresponds to a vitreous phase, the rest of the mineral components of crystalline character represent 27.75% of the ashes, see Table 3.

The ashes particle size is described in Fig. 1, with a d_{80} of 45 µm, which allows classifying it as an F Type fly ash.

Table 1 Materials

Soil (% in mass)	Fly ash (% in mass)	Optimum moisture (%)	Maximum density (kN/m^3)
100.00	0.00	25.75	14.66
86.00	14.00	22.50	14.70

Table 2 FRX of fly ash (%) in mass

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	SO_3	Loss on ignition 110–1000 °C
46.2	31.4	4.75	4.46	1.82	3.63	0.68	3.9

Table 3 Mineralogical phases for fly ash (%) in mass

% mullite	% quartz	% hematite	% vitreous phase
17.49	9.01	1.59	72.25

Fig. 1 Stabilizer product

a) Stabilizer Mixture of NaOH and fly ash   b) Packed Stabilizer Product

Alkaline Activator

Activation of the fly ash, it has been made whit solid flakes of Na(OH) for the necessary concentration of 4 M. NaOH 98% purity was used.

Methodology

A design of experiment (DOE) methodology was proposed to assess factors that may modify the final conditions of the stabilizing packaged product. The packed stabilizer corresponds to the mixture of fly ash and Na(OH) solid flakes, see Fig. 1.

The experimental matrix is presented Table 6, where:

F I: Packaging Material
F II: Type of seal
F III: Baling Moisture
F IV: Storage humidity.

F I with two levels: *cellulose* (C) and *polyethylene* (PE). Vacuum sealed (*Vacuum*) and (*simple*) sealed without vacuum were considered for *F II*. Moisture packaging material *F III* included kiln (*dried*) fly ash and (*standard*) humidity conditions. Finally, the *F IV* was evaluated by storing the packed stabilizer to (*standard*) and above 90% humidity. For all measures of the experimental matrix 14% mass of stabilizer product and 86% of soil was used. In each experimental run the stabilizer packaged product was stored for 14 days and the effectiveness of the soil stabilizer was measured by its response to *Unconfined Compressive Strength* (UCS). Similarly, it was performed at 28 days of storage. To assess the response to UCS test pieces of 50 mm of diameter and 100 mm high were used, cured in a sealed container for 7 days at 25 °C. The compressive test of the samples was conducted in 3000 Humboldt equipment with a load cell of 45 kN.

Finally, for environmental valuation the life-cycle assessment (LCA) methodology was used through the following stages, according to the ISO-14044 standard.

Stage 1. Goal Definition and Scoping

The quantification of environmental impacts generated during the processes of stabilizer preparation, activation, packaging and storage, was from gate to gate LCA, because the analysis was carried out from the acquisition of raw materials for manufacturing until obtaining the stabilizing product, using as a functional unit 25.0 kg of stabilizing product manufactured and stored. Table 4 shows the impact categories considered.

Stage 2. Life Cycle Inventory

Resources consumption and waste generation and emissions attributable to product life-cycle were identified, according to information gathered, depending on the input and output variables of the evaluated processes (see Table 5).

Stage 3. Impact Assessment and Interpretation

According to ReCiPe methodology, the evaluation was carried out in three consecutive phases: *classification* of the impacts for each impact category; *characterization*, involving the assessment of the real impact of each category by characterization factors; and finally, *normalization* where multiplicative weighting factors.

Table 4 Definition of impact categories

Categoría de impacto
Use of fossil fuel (MJ)
Energy consumption (MJ)
Breathable inorganics (SO_2)
Climate change (CO_2)

Table 5 Variable definition of input and output

Variables de Entrada		Variables de Salida	
Distance	Lengths traveled for transporting materials	Emissions (CO_2–SO_2)	Generation of emissions in relation to fuel emission factors (ACPM—Diesel) and energy (kWh)
Fuel/energy	Type and amount of consumption in relation to performance of vehicle/equipment and usage times		

Results and Discussion

Technical Assessment of the Stabilizer

The technical results of the stabilizer were performed by *analysis of variance* ANOVA. The null hypothesis indicates that the factors evaluated have no difference or a significant effect on UCS, i.e. arise in changes in the properties of the stabilizers do not arise. The confidence level (β) is defined as 95%, therefore, the significance level (α) is 5% ($\alpha = 0.05$). Under these conditions if the *p*-value is less than α, the null hypothesis is rejected (see Table 6). Experimental matrix and results are presented.

The *p*-values obtained for 14 days and 28 days of storage age, indicated that none of the factors or double interactions between them influenced the response variable. See Table 7.

Although the results Fig. 2 reported an average increase of 400–600% of the UCS on the soil with stabilizing product with respect to the unstabilized soil. It was observed that there is a variation of properties depending on the time of stabilizer storage.

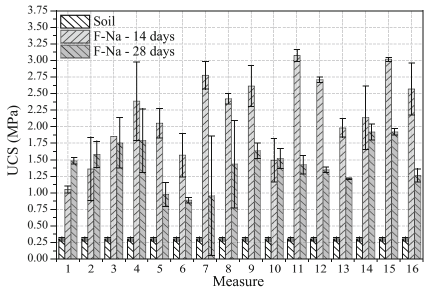
Table 6 Comparing UCS means

Measure	Main factors				UCS (MPa) for age store		t_0	*Hypothesis*
	I	*II*	*III*	*IV*	14 days	28 days	$t_{\alpha/2} = 4.3$	*Ho*: $Ux = Uy$
1	C	Vacuum	Dray	Std.	1.05	1.48	11.22	Rejected
2	PE	Vacuum	Dray	>90%	1.36	1.58	0.82	Accepted
3	C	Vacuum	Std.	>90%	1.85	1.76	0.63	Accepted
4	PE	Simple	Dray	Std.	2.38	1.79	2.30	Accepted
5	PE	Simple	Dray	>90%	2.05	0.98	7.16	Rejected
6	C	Vacuum	Std.	Std.	1.57	0.89	4.50	Rejected
7	PE	Simple	Std.	Std.	2.78	0.95	2.73	Accepted
8	C	Vacuum	Dray	>90%	2.42	1.43	3.01	Accepted
9	C	Simple	Std.	Std.	2.61	1.64	9.92	Rejected
10	C	Simple	Std.	>90%	1.49	1.52	0.15	Accepted
11	PE	Simple	Dray	Std.	3.07	1.42	23.32	Rejected
12	PE	Vacuum	Dray	Std.	2.71	1.35	64.50	Rejected
13	PE	Vacuum	Std.	>90%	1.98	1.21	14.80	Rejected
14	PE	Simple	Std.	>90%	2.13	1.92	1.31	Accepted
15	C	Simple	Dray	>90%	3.02	1.92	58.19	Rejected
16	PE	Vacuum	Std.	Std.	2.57	1.26	10.78	Rejected

Table 7 ANOVA

Factor	Value—*p*	
Main factors	*14 days*	*28 days*
Packaging material (A)	0.321	0.268
Type of seal (B)	0.124	0.189
Baling moisture (C)	0.774	0.733
Storage humidity (D)	0.425	0.278
Double integration		
Packaging material*type of seal (A*B)	0.741	0.852
Packaging material*baling moisture (A*C)	0.444	0.064
Packaging material*storage humidity (A*D)	0.124	0.190
Type of seal*baling moisture (B*C)	0.537	0.083
Type of seal*storage humidity (B*D)	0.556	0.127
Packaging material*storage humidity (C*D)	0.600	0.761

Fig. 2 Unconfined compression strength



Environmental Assessment of the Stabilizer

The results of the environmental assessment are summarized in two stages of the product life-cycle: *preliminary* and manufacturing. Table 8 shows the overall results during the life cycle, obtained by processing input and output variables. In fuel consumption and emissions, a considerable excess was found for the manufacturing stage; because at this stage it was required higher power consumption unlike the preliminary stage, where only transportation was needed to move the materials to the gathering site and using local material.

In Table 9, the contribution by life cycle stage for each impact category is showed. It is notably highlighted the effect generated by the manufacturing stage with a contribution in all cases greater than 90%, this represents a contribution of 92.21% of the total impact generated throughout the life cycle evaluated. For the preliminary stage of the contribution only reached 1%. Moreover, the impact category that has affected the most is the availability of fossil fuels mainly in relation to the activities carried out for the manufacturing stage, while other categories had lower involvement close to 0%.

Table 8 Life cycle consumption and emissions

Stage	Activity	Consumption fuel vehicle (gal)	Emissions CO_2 vehicle (kg)	Emissions SO_2 vehicle (kg)
Preliminary	Transport materials	1.28E+00	3.88E−01	9.78E−04
	Transport packaging	2.91E+01	8.74E+00	2.22E−02
Stage	Activity	Power consumption equipment (kWh)	Emissions CO_2 equipment (kg)	Emissions SO_2 equipment (kg)
Manufacturing	Preparation of materials	1.36E+02	3.51E+01	5.32E−01
	Dosage	4.44E+01	1.50E+02	2.26E+00
	Mixed and packed	9.90E+00	8.72E+01	1.32E+00
	Storage	5.24E+02	1.42E+02	2.15E+00

Table 9 LCA results of the impact categories

Etapa	Fossil fuel use (MJ)	Global Warming CO_2 (DALY)	Inorganic respirable SO_2 (DALY)	Health damage (DALY)
Preliminaries	4.63E+02	6.46E−16	2.90E−11	1.74E−11
Fabricación	5.49E+03	6.45E−12	1.73E−06	1.04E−06

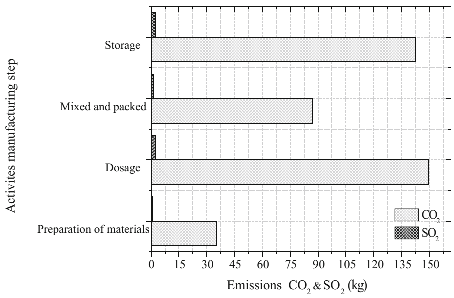


Fig. 3 Contribution of CO_2 and SO_2

Finally, it was found that the greatest impact for all categories in the manufacturing stage was caused by the composition and storage activities representing 98% more CO_2 emissions compared to SO_2 for all the activities (see Fig. 3).

Conclusions

The factors: **F I**, **F II**, **F II** and **F IV** have no statistical influence on the response variable, this indicates that the condition of fly ash material with a moisture of 0.15% is suitable to design the stabilizing product, allowing to decrease the energy required by the processes like drying.

It is recommended for Kraft paper and high density polyethylene packaging a simple or vacuum sealed and a moisture of fly ash below 0.15% so that the stabilizer product can be stored at humidities above 90%.

For environmental purposes laminated kraft paper and biodegradable represents the best packaging material for the stabilizing product, although it should be noted that the storage time tested was less than 30 days. It is recommended to assess it for longer periods.

By using the LCA methodology for assessing environmental impacts, it became clear that the packaging process has high impacts due to the energy required during the manufacturing stage associated with composition and storage. From the foregoing, it is proposed as future research, standardize processes, using alternative energy to optimize electricity consumption.

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