Physicochemical stabilization of soil, a lab methodology for its evaluation, case Cd. Hermosillo, Sonora, Mexico

Israel Miranda Pasos* / Salvador Aguayo Salinas**
Jesús Leobardo Valenzuela García*** / Jorge Ramírez Hernández****
Juan Arcadio Saíz Hernández*****

Fecha de envío: 13 de julio de 2008.
Fecha de aceptación: 7 de noviembre de 2008.

Abstract

In cities in development air pollution by dust, due to the lack of paved streets, is an ongoing problem. Although there are advanced technological products directed to mitigate this problem, in most of the cases their acquisition is not economically feasible.

This research propounds a methodology to evaluate common regional products to be implemented as soil stabilizers. Some of these products are: hydrous lime, natural zeolite, calcium lignosulfonate and lime. The evaluation is carried out by means of the strength parameters to direct load and saturation-immersion test. The latter one with the aim of evaluating if mixture is liable to be easily weaken by humidity as the ground critical condition. In the particular case of the named products, the mixture of hydrous lime and zeolite (natural zeolitic tuff) showed a better behavior when combined with studied ground which was classified as sand with fine argillaceous slime.

The evaluating methods include the soil characterization by means of traditional ground mechanics test in addition with instrumental techniques like: x-ray diffraction, electronic microscopy of sweeping and petrography, as well as ground mineralogical characterization techniques. The aim of these techniques incorporation is to get a more precise soil characterization as well as a better understanding of the physicochemical stabilization behavior.

Keywords: methodology, techniques, weak, compression, saturation.

* Department of Civil Engineering and Mines, University of Sonora. Blvd. Luis Encinas and Blvd. Rosales, Hermosillo, Sonora. Correo electrónico: imiranda@dicym.uson.mx

** Department of Chemical Engineering and Metallurgy, University of Sonora. Blvd. Luis Encinas and Blvd. Rosales. Hermosillo, Sonora. Correo electrónico: saguayo@iq.uson.mx

*** Department of Chemical Engineering and Metallurgy, University of Sonora. Blvd. Luis Encinas and Blvd. Rosales. Hermosillo, Sonora.

**** Institute of Engineering, Autonomous University of Baja California, Mexicali, Blvd. Benito Juárez and calle de la Normal S/N. Mexicali Baja California.

***** Department of Civil Engineering and Mines, University of Sonora. Blvd. Luis Encinas and Blvd. Rosales, Hermosillo, Sonora.

Estabilización físico-química de un suelo, una metodología de laboratorio para su evaluación, caso Cd. Hermosillo, Sonora, México

Resumen

En la actualidad, en las ciudades en desarrollo, la contaminación debida al polvo por falta de pavimento vial es un problema. Existen productos de tecnología avanzada encaminados a mitigar este problema; sin embargo, la adquisición de ellos, en la mayoría de los casos, no es factible económicamente.

La presente investigación propone una metodología con el fin de evaluar productos regionales comunes para su aplicación como estabilizadores de suelo: cal hidratada, zeolita natural, lignosulfonato de calcio y cal viva. La evaluación se realiza mediante los parámetros de resistencia a carga directa y prueba de saturación-inmersión; esta última con el fin de evaluar si la mezcla es susceptible de ser fácilmente deleznable a la humedad como condición crítica de un suelo. En el caso particular de los productos señalados, la mezcla de cal hidratada-zeolita (toba zeolítica natural) presentó mejor comportamiento en combinación con el suelo en estudio, clasificado como arena con finos limo arcilloso.

Los métodos para la evaluación incluyen la caracterización del suelo mediante pruebas y ensayos tradicionales de mecánica de suelos y, adicionalmente, por medio de técnicas instrumentales, difracción de rayos X, microscopia electrónica de barrido y petrografía, así como técnicas de caracterización mineralógica de suelos. La incorporación de éstas está encaminada a una caracterización más precisa del suelo, así como a una mejor comprensión del comportamiento de la estabilización físico-química.

Palabras clave: metodología, técnicas, deleznable, compresión, saturación.

Introduction

The growth and development of cities increase the number of cars on streets demanding the construction of appropriate roads or the improvement of existing ones. Different types of problems arise when is not possible meet roads infrastructure demand. As it is stipulated in the diagnostic presented by the H. City Council of Hermosillo by means of the Municipal Program of Urban Development (PMDU, 2003), many of these problems are related with air pollution by soil dust.

In desert cities dust pollution becomes a big problem that is mainly attributed to lack of humidity in the ambient and can be defined as a thin layer of tiny particles that pollutes air causing illnesses.

This problem has always been present in Mexico and has been increasing along with the development of different states such as the state of Sonora, in particular Hermosillo. This is a city that presents the anthropogenic pollution as a result of this development. One of them is due to the dust emission that has been growing since the 80's and, because of the lack of pavement on streets and avenues, is getting worst at the present time especially in the north and west areas of the city (PMDU, 2003). There are several ways of classifying the different sources that pollute air, some of them are: linear (streets or heavy traffic roads and frontal lines of forest fire), by number (simple or multiple sources) and by area (stationary or mobile sources) (Cruz, 2005).

Dust is classified as a particle-type primary polluting agent that represents a compound mixture of organic and inorganic substances. In the urban ambient its mass and composition tend to be divided into two main groups: thick and fine particles. The barrier of these two fractions is usually found between 1 and 2.5 microns. However, the limit between thick and fine particles for measurement purposes is sometimes fixed by convention at 2.5 microns in aerodynamic diameter (PM 2.5). The smallest pieces contain the secondarily formed aerosols, combustion particles as well as re-condensed organic and metallic vapor. The biggest ones usually contain soil material and fugitive dust from roads and industries (Cruz, 2005).

Methods and materials

Area of study

The City of Hermosillo, Sonora, Mexico belongs to the municipality of Hermosillo (figure 1) which is bordered to the north by the municipalities of Pitiquito, Carbó and San Miguel de Horcasitas; to the east by the municipalities of San Miguel de Horcasitas, Ures, Mazatan, La Colorada and Guaymas; to the south by the municipality of Guaymas and the Golfo de California; and to the west by the Golfo de California and municipality of Pitiquito. The City is located at 29°04'23'' north latitude and at 110°57'33'' west longitude, at 200 m. altitude above sea level (INEGI, 1997). The zone of study belongs to street in the residential areas: Solidaridad and Villas del Cortijo located in the northwest zone of the city.

Sampling

Two field sampling were carried out in February and October, 2006, six samples were collected (M1 to M6) one for each lane of avenue selected in the zone of study (table 1). The soil samples were collected by direct digging from the running surface first 40 cm. (NMX-C-030-ONNCCE) and put inside 60 kilograms capacity transparent plastic bags. The samples were taken to the laboratory where they were dried at ambient temperature for 48 hours. Subsequently, representative samples were obtained using the cracking method NMX-C-170-ONNCCE, for test and research analysis.

Figure 1. Area of study

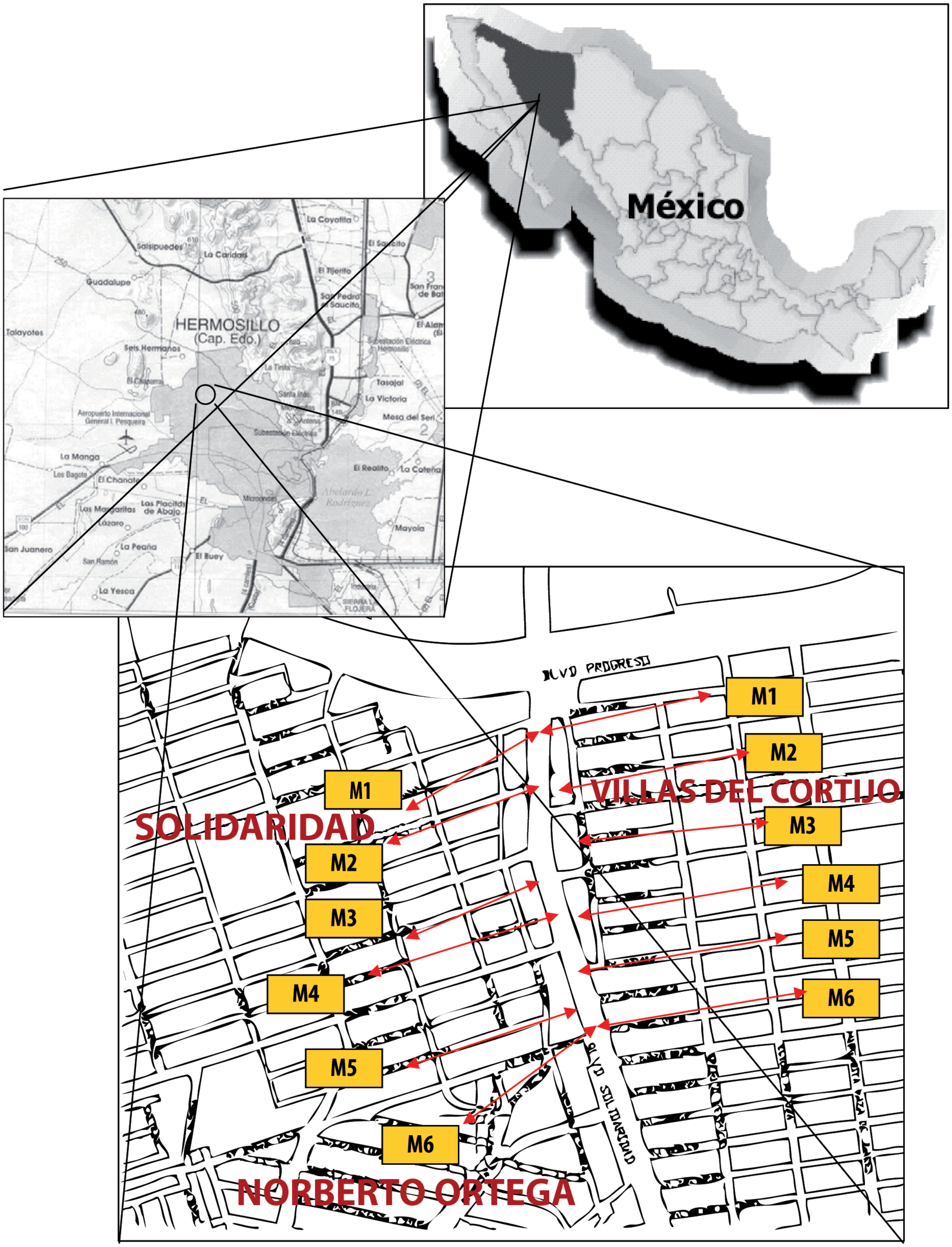


Table 1. Sampling Avenue Lanes

Simple	Avenue's Name
M1	Cofre de Perote - Campo Verde
M2	Campanero - San Nicolás
M3	Sierra de Tepehuanes - Adivino
M4	Ajusco - Tecoripa
M5	Sierra de Baja California - Topahue
M6	Juan José Ríos - Rancho Viejo

Characterization

The soil was characterized by means of the unified system of soil classification (SUCS) (ASTM-D-2487) (Badillo-Juárez and Rodríguez-Rich, 2003), the proof or consistency limits or Atterberg limits (ASTM-D-4318) and the sieves method (ASTM-D-422, ASTM-C-136).

Consistency limits classify the soil in its fine fraction through plasticity chart when getting the liquid and plastic limits.

The mineralogical part was carried out using the following instrumental techniques: X Rays Diffraction, Sweep Electronic Microscopy (SEM) and Petrography. An equipment Broker model D8 Advance provided with Cu (Kα) x rays tube, with 1.5 A° wavelength from 35 Kv to 25 mA radiation was used for x rays diffraction; in the sweep electronic microscopy it was used an equipment Joel model 5410 LV, with radiation from 40 Kv to 20 mA, with a sweep speed of 2° per minute; and for the petrography analysis a microscope Nikon Eclipse model E 400 POI.

The test in cationic capacity exchange was developed in the chemical analysis in order to identify the group of clay which the fine part of soil belongs. The method corresponds to the Mexican Standard NOM-021-RECNAT-2000.

Specimens production or test tubes

Soil was mixed with: lime, hydrous lime, zeolite and calcium lignosulfonate in different combinations with each one (table 2). Two tests were made for each one of them, including a core or blank (soil without product). Specimens or test tubes were made by assay or Proctor test (ASTM-D-698) that consists in compressing the soil applying load depending on the specific humidity content (Ralph *et al.*, 1995). The test tubes obtained from the soil-product and the core were kept at ambient temperature, between 20° and 30° C, to be tested at direct compression at 7, 14 and 28 days and a fourth one to be subjected to saturation immersion proof after reaching the 28 days.

Assessment parameters

Tests to simple compression (ASTM-D-2166), where the load supported by the soil was directly measured until the failure point, were carried out to evaluate the behaviour of the soil mixed with the following products: lime, hydrous lime, zeolite and calcium lignosulfonate. The equipment used corresponds to the brand CONTROLS type MULTISPEED model 82-PO336/O with console to data capture brand CONTROLS type DIGIMAX plus model 76-00802/CZ. The load was applied for a deformation-penetration speed of 6.62 mm/min. Once the optimum soil humidity and the combination with the products are known, the test tubes are obtained by the standard Proctor test, procedure ASTM-D-698. Test tubes were prepared to be proved at three different ages: 7, 14 and 28 days and a fourth one is subjected to saturation after 28 days.

The saturation test is a no desirable boundary condition to which a soil can be subjected. It reproduces the condition of humidity saturation simulating a rain or a water spilling eventuality. Saturation evaluates the permanence condition of the form through direct observation of the test tube in water immersion and the disintegration capacity (friability). Mixtures (test tubes) that resist this proof are submitted to a dry process, 110 ± 5 °C for 24 hours and they are subsequently tested to direct simple compression. The scale of nominal values determined to evaluate the saturation test is in terms of the test tube cracking time, this is: at day 1 or less the result is *null capacity* to humidity; more than 1 day but less or equal to seven days, the result corresponds little capacity to humidity. For more than seven days and less or equal to 14 days, it is considered as a *good* capacity to humidity; and more than 14 days has an excellent capacity to humidity.

Simple compression results are statistically validated by the application of multiple regression analysis in order to obtain the coefficient statistical of multiple determinations R^2 and evaluate the relation between variables involved and their interaction (Montgomery, 2006). The regression equations for each of the mixtures design were obtained in their different combinations as well as their respective R^2.

RESULTS Y DISCUSSION

Characterization and soil identification

The consistency limits show liquid limit values lower than 27% and plastic limit lower that 22% with Plasticity indexes between 2 and 6, as well as fines content higher than 12%. According to the Unified System of Soils Classification (SUCS by its acronym in Spanish), (table 3), it is mainly classified as SM type; it corresponds to slimy sand, sand mixture, and low plasticity argillaceous slime (Badillo Juárez and Rodríguez Rico, 2003). The granulometry (ASTM-D-422, ASTM-C-136) corresponds to a sand-type soil with fines. In the analysis of cationic exchange capacity (CIC) results show a range of 5-15 Cmol (+) Kg^{-1} and, taking into account results and comparison with the tables showed by the standard NOM-021-RECNAT-2000, the type of clay belongs to the kaolinites group and regards to the weathering degree it goes from very low to low, it is located in the horizon B, having found secondary minerals such as kaolinitic-type and free oxides. Results are summarized in table 2.

Table 2. Results of the Cationic Exchange Study carried out to the samples of the soil

Sample	Sample $cmol(+)kg^{-1}$	Type of clay; group	Weathering Degree; type
MI	5.6	Group Kaolinitas	Very low-Low
M2	7.4	Group Kaolinitas	Very low-Low
M3	5.2	Group Kaolinitas	Very low-Low
M4	6.6	Group Kaolinitas	Very low-Low
M5	5.8	Group Kaolinitas	Very low-Low
M6	6.0	Group Kaolinitas	Very low-Low

The x rays diffraction analysis presents the following phases in common: quartz, albite, riebeckite, muscovite which are found in samples M2, M3, M4, M5 and M6. In sample M1 it was also found the phase of the calcite and shadlunita.

Figure 2. Results of the x rays diffraction analysis carried out in sample M 4

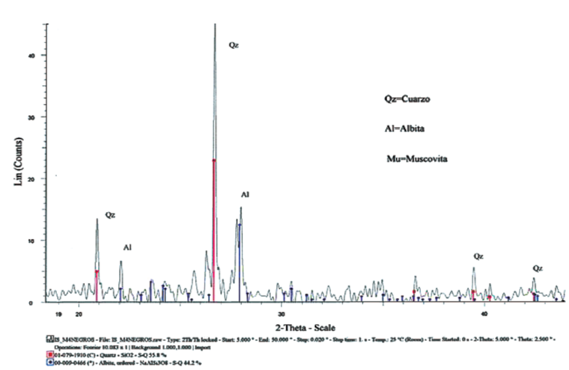


Table 3. Results test indexes for soil samples identification

S a m - ple	Depth (m)	Granulometry			Consistency Limits			SUCS	W_{Opt}(%)	δ_{dOpt}.kg/m³
		Gravel (%)	Sand (%)	Fines (%)	LL (%)	LP (%)	IP (%)			
M1	0.0-0.30	0.00	75.82	24.18	20.00	INA*	---	SM	9.5	2005
M2	0.0-0.30	0.00	71.92	28.08	24.30	21.97	2.33	SM	9.0	2010
M3	0.0-0.30	0.00	71.36	28.64	24.20	19.72	4.48	SM-SC	10.5	1990
M4	0.0-0.30	0.00	68.98	31.02	26.52	20.62	5.90	SM-SC	10.0	1960
M5	0.0-0.30	0.00	76.50	23.50	23.45	20.77	2.68	SM	10.0	1980
M6	0.0-0.30	0.00	71.60	28.40	23.04	20.31	2.73	SM	10.8	1985

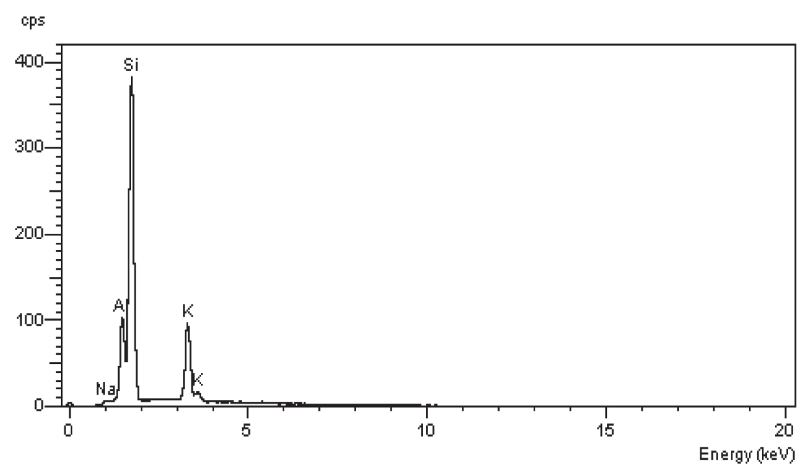
LL= Liquid Limit
Lp= Plastic Limit
IP= Plastic Index
W_{Opt} = Compressing optimum humidity content
δ_{dOpt}.= Material optimum density
SUCS = Unified System of Soils classification
SM = Slimy sand
SC = Argillaceous sand

Table 4 shows the main minerals found through the sweep electronic microscopy analysis in samples M1, M4 and M6. Results indicate that quartz and feldspars such as orthoclase and plagioclase like albite predominate. Figure 3 shows sample 4 diffractogram that corresponds to quartz, orthoclase-type feldspar and albite-type feldspar.

Table 4. Results of the Sweep Electronic Microscopy Analysis

Sample	**Kind of mineral** (Type of mineral)
M1	Quartz, orthoclase-type feldspar, iron and illite impurity
M4	Quartz, orthoclase and plagioclase (albite) types feldspar
M6	Quartz, orthoclase and plagioclase (albite) types feldspar

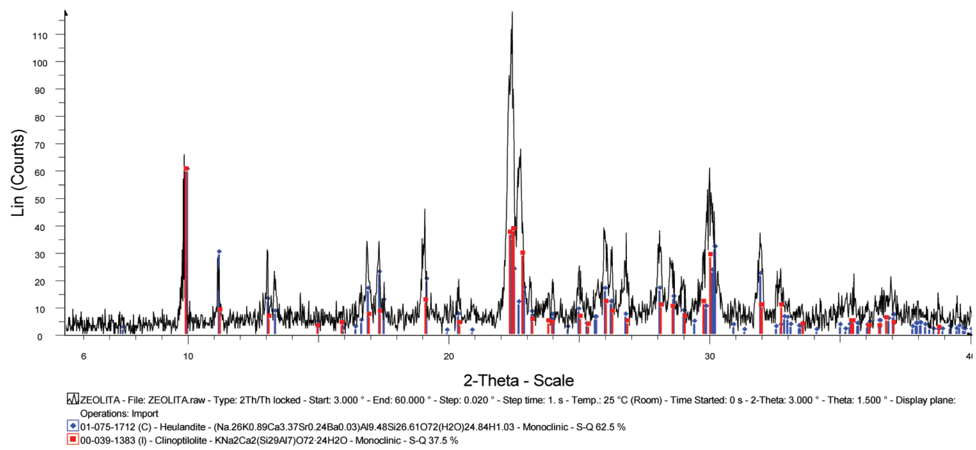
Figure 3. Phase graphic of minerals in sample M4



The Petrographic analysis corroborates the classification carried out through the unified system of soils classification (SUCS). It was classified as a low plasticity argillaceous sand compound by quartz-feldspar, orthoclase, plagioclase and microlite as main minerals. Microlite was found as a mineral adhered to biotite and calcite.

The zeolite used in this study was commercially produced. According to the mineralogical study, where instrumental techniques were used, (figure 4) it belongs to a zoelitic tuff where the kind Heulandite at 62.5% and Clinoptilolite at 37.5% predominates. In regards to the lime it is commercial-type, calcium hydroxide (Ca(OH)2 or hydrous lime and lime or calcium oxide. The calcium lignosulfonate used is commercial-type solid (dust).

Figure 4. X rays diffractogram of the commercial zeolite used



Direct Test of Simple Compression

In order to make the mixtures, the six samples of soil corresponding to the same type were homogenized in equal parts to obtain only one and this way mix it with the products as follows:

- **Simple mixture (blank)**: Soil with optimum humidity.
- **Double mixture**: Soil-lime, soil-hydrous lime, soil-zeolite and soil-calcium lignosulfonate.
- **Triple mixture**: Soil-lime hydrouos-zeolite, soil-lime hydrous-calcium lignosulfonate and soil-zeolite-calcium lignosulfonate.
- **Quadruple Mixture**: Soil-lime hydrous-zeolite-calcium lignosulfonate.

The mixtures were made combining 4, 8 and 12% of the product(s) weight plus the soil to complete the unity.

The results observed by mixture for compression variable are:

- **Soil mixture with optimum humidity (blank).** With the aim of establishing a point of reference, the soil was subjected to the proof of simple compression without mixing with any other products. In figure 5 the values at age of 7, 14 and 28 days are observed.

- **Double mixture**. The mixture of soil with calcium lignosulfonate in combination 96-4%, respectively, has the better behavior in terms of strength; nevertheless, it has the inconvenience that at early age, 7 days, the values are far too low than the rest of the products. Taking into account time and strength of the soil mixture plus zeolite in combination 96-4%, respectively, it has the better behaviour in the case of both signed variables (figure 6).

Figure 5. Result of soil simple compression with optimum humidity

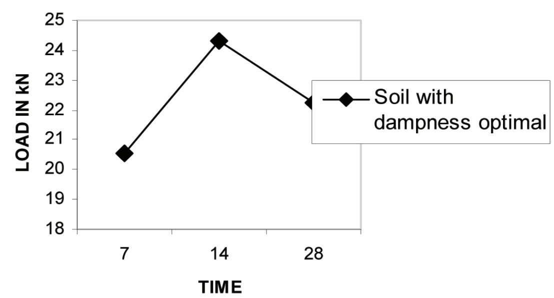
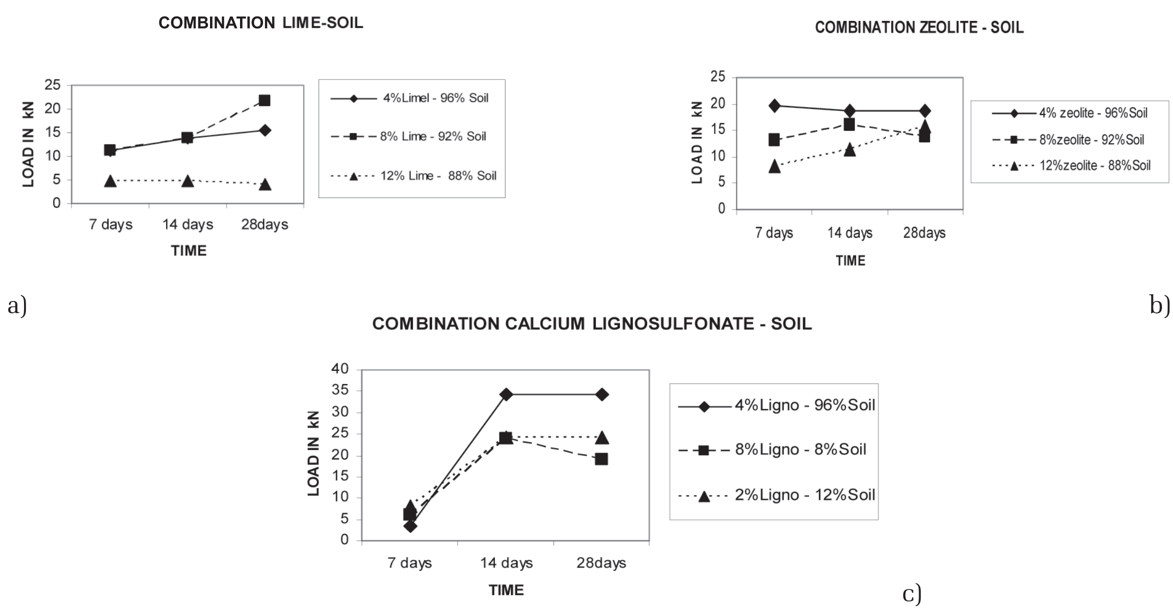


Figure 6. Double mixtures (soil-product)



- **Triple mixtures**. Taking into account variables of time and resistance, the mixture of soil-lime hydrous-zeolite in combination 84-8-8%, respectively, shows better results (figure 7).

- **Quadruple mixture**. Since strength values are very low and will not be able to substantially improve with the time, the combination soil-lime hydrous-zeolite-lignosulfonate is not suitable to be considered as a possible stabilization alternative (figure 8).

Figure 7. Triple mixtures (soil-two products)

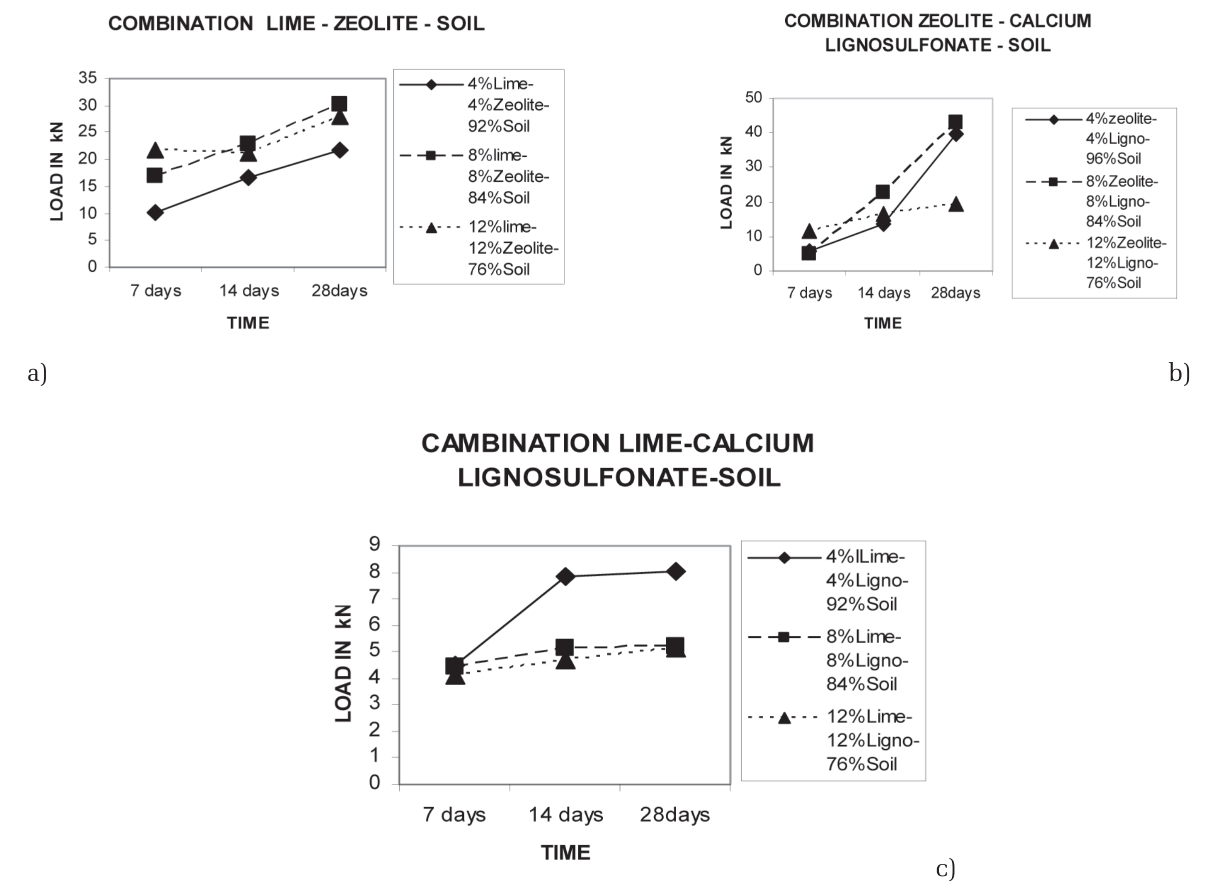
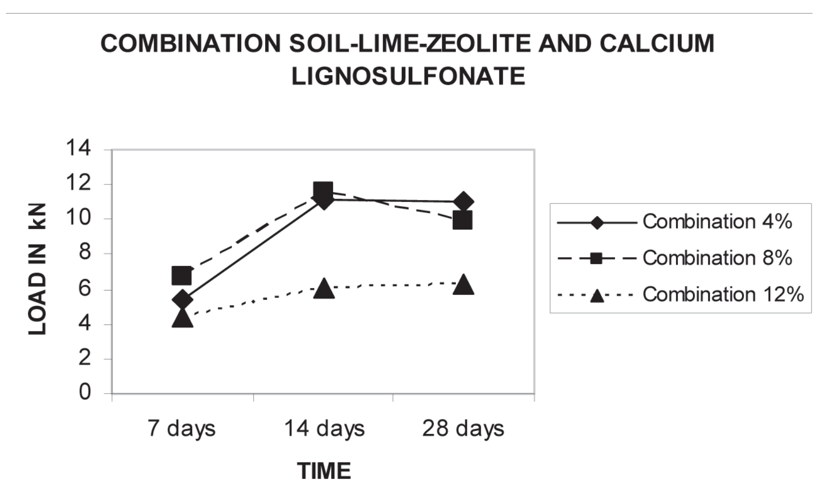


Figure 8. Soil-lime hydrous-zeolite-calcium lignosulfonate mixture



Experimental results validation

Results of the simple compression were statistically validated applying the multiple regression analysis. The regression equation (prediction model) and the respective values of R^2 for each design of mixture in their different combinations were calculated to obtain the coefficient statistical of multiple determinations R^2 and evaluate the relation between the introduced variables and their interaction (Montgomery, 2006). Values obtained show that experimentation results are reliable (table 4).

Table 4. Summary of results of the multiple linear regression analysis and the regression variance

Mix	Value of R^2 $0 < R^2 < 1$			Observations
	7 days	**14 days**	**28 days**	**Better R^2**
Double	**0.8918**	**0.8839**	0.6438	A 7 y 14 Days
Double-Triple	**0.8202**	0.7370	0.6889	A 7 Days
Cuadruple	**0.7472**	0.7258	0.6237	A 7 Days

Regarding to reality, prediction models at 7 and 14 days show acceptable values for R^2, this is, we expected values of about 73 to 89% of the real value. Double and double-triple mixtures presented less variation in the prediction model, for 7 and 14 days. The values of R^2 at 28 days are lower; nevertheless, among them there is uniformity so the models are suitable.

Saturation test

Soil-lime hydrous-zeolite is the mixture that showed an excellent behaviour before saturation and load capacity (table 5). Mixtures like soil-lime hydrous-calcium lignosulfonate and soil-lime hydrous-zeolite-calcium kept their shape stable; however, their load capacity reduced down below the expected mean values regarding the core or blank (table 6). Mixtures like soil-lime, soil-zeolite, soil-calcium lignosulfonate and soil-zeolite-calcium lignosulfonate presented instability to keep the shape before humidity, showing easiness to become crumbly.

Interaction analysis

According to a mineralogical analysis, kaolinita present in the soil resulted to be little sensitive to lime (Rosell *et al.,* 2007) as well to the rest of the handled products, reason why the mixtures of soil plus hydrous lime, soil plus zeolite and soil plus calcium lignosulfonate did not significantly improve their load capacity.

The mixture of soil-lime hydrous-zeolite corresponds to the one with the better behaviour with regards to the two tests carried out. The reaction of silex and zeolite alumina as acid components with lime is present in this mixture. This reaction is considered for exchanging; nevertheless, it has been found that calcium silicates and hydrous aluminates with well defined crystalline structure, and not a calcified zeolite, are formed in a long term (Rosell *et al.,* 2007).

In triple mixtures, calcium lignosulfonate is observed as a product that absorbs and holds water. This property influenced the reduction of interaction between the hydrous lime and the zeolite, this is why it is showed as the inhibitor agent of the reaction between the hydrous lime and the zeolite.

Conclusion

From the mixtures that were carried out, the mixture based on soil-lime hydrous-zeolite showed the better behaviour before the simple compression assay and the proof of saturation-immersion. This mixture in its different combinations presented good physical mechanical and chemical stability. Physical mechanical because of the loading capacity presented above the mean of the blank, and chemical by showing an excellent behavior to be crumbly at the presence of humidity and its increase of the load capacity.

The saturation-humidity processes works like a catalyst checking this way the puzzolanity reaction between the hydrous-zeolite lime and the cationic exchange with the soil. This reaction is proved by the increase in the loading capacity at direct compression after being submitted in saturation for more than 28 days.

Because of its behavior, the mixture soil-lime hydrous-zeolite reaches such stabilization degree that makes it more resist to abrasion than natural soil, which results in a lower releasing of particles into the environment.

Results of the instrumental techniques show the presence of kaolin as fine element in the soil coming from the weathering of feldspar quartz grain, which is little sensitive to lime, confirming with results the low loading capacity of the soil-lime hydrous mixture and its null capacity to saturation. In regards with zeolite, it contains heulandite, followed by clinoptilolite, at 67.5% and 32.5% respectively, being these minerals which react with the lime and the soil. This interaction appears when presenting better loading capacity and excellent behaviour to saturation.

Although at present time techniques like mineralogical instrumental analysis, x rays diffraction, sweep electronic microscopy and petrography are not used as established procedures in the area of soil mechanics, the incorporation of these techniques as soil characterization techniques allow the better understanding of the soil's behavior, as is shown in this case.

Finally, a methodology at lab level is suggested in order to evaluate the physic-mechanical and chemical stabilization of a soil.

Acknowledgments to

Dr. Francisco Brown Bojórquez, Department of Polymers, University of Sonora.

Geologist, Abraham Mendoza Cordova, Department of Geology, University of Sonora.

M. Sc. Elizabeth Araux, Department of Civil and Mines, University of Sonora.

M. I. Carlos Anaya Eredias, Department of Industrial Engineering, University of Sonora.

Dr. Agustin Gómez Álvarez, Department of Chemical Engineering and Metallurgy, University of Sonora.

Dr. Dagoberto Burgos Flowers, Department of Civil and Mines, University of Sonora.

For their valuable cooperation in the realization of the research.

Table 5. Summary of behavior of saturation tests and strength to soil combinations loads plus the product(s)

Combination		Values scale				Observations	Loading Capacity compression dry condition (oven dried 24 hours at 110° C ± 5 °C)
	Product	Null	Little	Good	Excellent		
Soil	Soil	**X**				Crumbling during the first minutes and disintegration before 24 hours	Null
	Lime	**X**				Crumbling during the first minutes and disintegration before 24 hours	Null
	Zeolite	**X**				Crumbling during the first minutes and disintegration before 24 hours	Null
	Calcium Lignosulfonate	X				Crumbling during the first minutes and disintegration before 24 hours	Null
	Lime-Zeolite				X	Specimens null disintegration, strength to scratching when pressing with the finger, compression hardness kept.	The loading capacity increased after saturation (see table No. 2).
	Lime-Calcium Lignosulfonate			X		Crumbling and disintegration in combinations lower than 8%, little strength to scratching with the finger and softening to contact during the 60 days.	Down below to the one obtained before saturation.
	Zeolite-Calcium Lignosulfonate	**X**				Crumbling and specimens disintegration during the first minutes.	Null
	Lime-Zeolite-Calcium Lignosulfonate			X		Did not present crumbling or disintegration during the 60 days of saturation, in the opposite presented softening to contact.	Down below to the one obtained before saturation.

Scale of assessment: NULL: Until 24 hours of saturation, LITTLE: between 24 hours and 7 days, GOOD: between 7 and 14 days, EXCELLENT: more than 14 days.

Table 6. Failure load comparison before and after saturation test

Combination	**Key**	**Failure load 28 days (no saturation) (kg)**	**Failure load 60 days (saturation-dry) (kg)**	**Difference (kg)**	**Increase of loading capacity after saturation (%)**
Soil - lime - Zeolite	ICZ02%	1922.93	609.28	-1313.65	**-68**
	ICZ04%	2208.15	4,283.69	2075.54	**93**
	ICZ06%	2793.06	5,424.00	2630.94	**94**
	ICZ08%	3082.97	5,700.00	2617.03	**84**
	ICZ10%	3174.61	9,150.00	5975.39	**188**

(-) = Decrease of loading capacity.

ICZ = Identification of soil-lime hydrous-zeolite mixture, followed by the quantity of product, weight percentage.

Bibliography

ASTM-C-136 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.

ASTM-D-4318 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.

ASTM-D-698 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3)).

ASTM-D-2166 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil.

ASTM-D-2487 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).

ASTM-D-422. Standard Test Method for Particle-Size Analysis of Soils.

Badillo-Juárez y Rodríguez-Rico. *Mecánica de suelos.* Tomo I "Fundamentos de la mecánica de suelos". Ed. LIMUSA-Noriega Editores, 2003.

Cruz, M. "Evaluación de la calidad del aire respecto de partículas suspendidas totales (PST) y metales pesados (Pb, Cd, Ni, Cu y Cr) de la ciudad de Hermosillo, Sonora, México, tesis de Maestría en Ciencias, 2005.

INEGI (Instituto Nacional de Estadística, Geografía e Informática). Cuaderno de Estadística Municipal, Hermosillo, Sonora, 1997.

Montgomery, D. *Diseño y análisis de experimentos*. Segunda edición. Editorial LIMUSA WILEY, 2006.

NOM-021-RECNAT-2000. Establece las especificaciones de fertilidad, salinidad y clasificación de suelos. Estudios, muestreo y análisis.

NMX-C-170-ONNCCE. Cuarteo y reducción de las muestra de agregados obtenidas en el campo.

NMX-C-030-ONNCCE. Muestreo de agregado en banco o almacén.

Rosell L., Mercedes y Ganoso B., Regino. *Utilización de la zeolita como material de construcción. Una experiencia cubana.* 2007

Ralph B., Peck, Walter E. Hanson, Thomas H. Thornburn C. Ingeniería de Cimentaciones. México: Ed. Thomson Learning, 2001.

PMDU. "Programa Municipal de Desarrollo Urbano". H. Ayuntamiento de Hermosillo, Sonora. México, 2003. Consultado en marzo de 2005. <http://www.implanhermosillo.gob.mx/>.