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Stabilization of loess soil with non-conventional reactive and cementing materials

Estabilización de suelos loéssicos con materiales reactivos cementantes no convencionales

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ABSTRACT: Loess soils cover approximately 35% of the Argentinian national territory. A metastable mechanical behavior and distinctive macro-porous structure characterize these sediments. Commonly, these sediments collapse when moisture content and/or applied stresses increase. Many places have loess-like sediments that are commonly used as construction material in various engineering projects like embankments, liners, and levees. For most of these cases, it requires to be stabilized. Common stabilization techniques consist of cement or lime addition, which are both related to industries responsible for significant greenhouse gas emissions. Nowadays, there is an increasing interest in finding new alternative binders, related to the need to reduce natural non-renewable resources consumption, implementing circular economy concepts, while reducing the climate change effects associated with carbon dioxide emissions incurred in the production of traditional binder materials. This paper evaluates the effectiveness of alternative binders such as steel slag, construction and demolition waste, biopolymer, and treated eggshells to improve the mechanical properties of compacted loess soil. The variables analyzed include the stabilization agent content, curing periods, and density. The results are analyzed by considering changes in stiffness and strength and by evaluating the sustainability of the different materials and their potential to replace lime to stabilize loess soils. The results obtained generate new possibilities for reducing frequently used binder consumption.

KEYWORDS: Loess, soil stabilization, mechanical behavior, climate change.

1 INTRODUCTION

Loessical soils cover approximately 10% of the Earth's surface. In Argentina, these sediments cover approximately 35% of the national territory, mainly distributed in the central area of the country. They constitute the primary regional soil in the Cordoba province. Its mineralogical composition differs from that of the rest of the world's loess deposits due to the presence of volcanic minerals and its alkalinity condition (Moll et al., 1988; Zárate, 2003; Francisca, 2010). This presence of minerals and volcanic particles is related to Andean volcanic eruptions, coming from volcanoes located in the Argentine Puna region, constituting the principal source of loess in the region (Zárate, 2007).

These soils have a macroporous structure with a high void ratio, with a predominantly fine granulometry with silt and clay fractions with significant influence on the mechanical behavior of the intergranular structure. Furthermore, they are represented by a poorly arranged structure, with particles the size of silt and a minor fraction of fine sand, linked together through cementitious agents such as precipitated salts, carbonates, silicates, and clay bridges (Reginatto, 1970). The strength and stability of the soil mass depend on the resistance of these joints and contacts between particles (Francisca et al., 2007).

The instability of the stratum itself is produced due to the presence of water, given that these precipitated cementitious agents dissolve and, therefore, the shear resistance between the silt particles decreases, causing the structure to collapse (Reginatto, 1970; Rinaldi et al. 2007). These loess sediments have metastable soil fabric, which generates the collapse of the macroporous structure due to changes in humidity (and degree of saturation), average acting stresses, pore pressures, or shear stresses (Jefferson et al. al., 2005; Terzariol, 2010; Feng et al., 2015).

1.1 *Loessical soil stabilization*

Loess sediments are abundant and consequently utilized as construction or support material in various engineering projects. However, due to their collapsibility, there is a need for soil stabilization in most cases. In this way, to solve or prevent the problems caused by collapsible loess, various researchers have studied and implemented several techniques to improve soil properties when used as a construction material.

Compaction, and therefore densification, is the most conventional strategy to improve the mechanical properties of the soil. This technique reduces the void ratio and compressibility and increases strength and stiffness (Zou et al., 2018; Kodikara and Shounthrarajah, 2018). Various properties of compacted clays, such as density, permeability, diffusion, and collapse, have been shown to depend on the moisture content of compaction, among other things, indicating that soil structure is affected by the compaction procedure. On a microscopic scale, compaction alters the original soil structure, destroying cutting planes and eliminating large pores, resulting in a more homogeneous soil structure generating an alignment of particles in the direction perpendicular to the one the energy is applied to the soil.

Chemical stabilization techniques require the addition of binding materials, such as cement or lime, which has been widely applied (Jefferson et al., 2008; Li et al., 2011; Metelková et al., 2012; Arrua et al., 2012). Hydration and hardening of Portland cement are responsible for complex physical and chemical changes that occur and allow for the effective improvement of the stiffness and shear resistance of the stabilized soil. These studies demonstrated that not only the risk of collapse is eliminated, but settlement is also reduced, maintaining its performance from the moment of stabilization. In these cases, the addition of cement is responsible for the reduction of macropores, leading to a more stable soil structure (Liu et al., 2014).

In the last two decades, researches were carried out to replace lime or cement with fly ash, geopolymers, and/or biopolymers. By adding fly ash and cement to loess silt, it is possible to improve durability against freeze-thaw cycles, eliminating capillary action that favors water infiltration into the soil (Zhang et al., 2019). Other studies have shown that adding biopolymer to soft soil samples promotes their strengthening (Chang et al., 2015; Sulaiman et al., 2022; Reddy et al., 2018; Chang et al., 2016), promising potential usefulness and applicability in soil stabilization.

Although the doses of these binder materials used in the stabilization processes are low (between 1 and 8%), it is considered that the total amount required of these agents is large concerning the total mass of improved soil (Daraei et al., 2019). The main impact of the production of these materials is the direct and indirect emissions of the process, which contribute to the carbon footprint (Gessa-Parera and González-Exposito 2017; Foteinis et al., 2022). This serves as a common foundation for assessing the quantity of gaseous emissions pertinent to climate change, which are linked to human production or consumption activities (Wiedmann and Minx, 2008). Emissions come mainly from burning fossil fuels (coal, oil, and gas), with significant contributions from forest clearing, agricultural practices, and other activities (Barceló et al., 2014).

In response to the imperative to mitigate greenhouse gas emissions contributing to climate change, ongoing efforts are directed towards achieving partial or complete substitution of both Portland cement and lime in these stabilization processes. This pursuit aims to identify environmentally sustainable alternatives.

The main objective of this research is to evaluate sustainable ways to achieve loess soil stabilization by reutilizing different materials such as steel slag, demolition wastes, eggshells, and biopolymers in an environmentally friendly way by studying their long-term mechanical behavior.

2 MATERIALS AND METHODS

Granular materials used in this investigation are loess soil, steel slag, eggshells, biopolymers, demolition wastes, and lime.

Typical loess from Córdoba, Argentina, was used in this study. This sediment was sampled at 8 m depth in an exploratory excavation near Córdoba city (31°31'13.3" S 64°13'59.4" W). Once sampled, a composite specimen was prepared by quartering and sieving to obtain a homogeneous sample. The obtained sample was tested to determine its main physical and mechanical properties. All tests were performed by following the ASTM Standard Methods, including granulometry and specific gravity tests ASTM D 854, liquid limit and plasticity index ASTM D 4318, unit weight ASTM D 4254, and unified soil classification ASTM D 2487-00 (ASTM, 2010).

Steel slag used in this study was supplied by the "Ternium Siderar" group in Argentina, which produces approximately 230,000 tons of hot-rolled steel per month, generating 45,000 tons of slag that is not reused within the production process nor sold, in part, to cement industries.

Demolition waste used in this investigation was provided by CORMECOR S.A., the sanitary landfill of Córdoba province. They are a product of the restoration of concrete pavements of the city, which were disposed of as waste for final disposal in the landfilling site.

In both samples, steel slag and demolition wastes, physical characterization tests were performed following ASTM standard methods to characterize the main properties of these granular materials, including granulometry (ASTM D 422-63) and specific gravity tests (ASTM D 854-02). Table 1 presents the main geotechnical characteristics of these granular materials.

The grain size curve for loess, SS, and DW is shown in Figure 1, from which the curvature (Cc) and uniformity (Cu) coefficients were obtained. According to the unified soil classification (USCS), loess sediment is classified as clayey silt of low plasticity (CL-ML), while the SS and DW as poorly graded sand with low content of fine particles (SP).

Table 1. Geotechnical characterization of Loessical silt, steel slag, and demolition waste.

Parameter	*L*	*SS*	*DW*
Specific gravity	2.64	3.16	2.77
Liquid limit	20.52	-	-
Plasticity index	1.86	-	-
Uniformity coefficient	20.00	10.50	10.00
Curvature coefficient	2.06	0.34	0.32
SUCS	ML	SP	SP

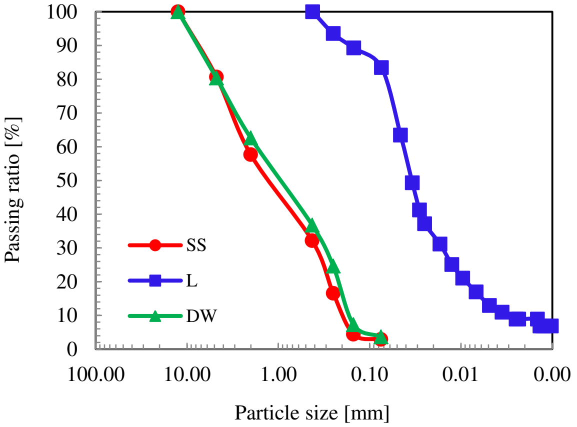

Figure 1. Particle size analysis of Steel Slag (SS), Loess (L), and Demolition Waste (DW).

The eggshell was prepared in the laboratory from crushing and grinding processes, obtaining a uniform sample through sieve #40. After obtaining a homogeneous sample, it was calcined in a muffle for 3 hours at 1100 °C generating a thermal activation process, resulting in a thermal activation process that yielded a high-purity material.

The biopolymer used in the present study is known as "Xanthan Gum" (XG), widely used in a spectrum of engineering applications (Reddy et al., 2018; Chen et al., 2019). XG is an anionic polysaccharide derived from bacterial fermentation of glucose or sucrose using the Xanthomonas campestris bacterium (Chang et al. 2015; Rosalam and England 2006). XG is reported to be hydrophilic, hydrocolloidal, has high stability under a wide range of temperatures and pH, pseudo-plasticity, insoluble in all organic solvents but soluble in water (Chang et al., 2015b; Dehghan et al., 2019; Mendoca et al., 2021)

Typical commercial lime for construction was used in this investigation, from selected high-purity limestone calcination process and controlled hydration process, from the Holcim industry. It was kept in an airtight box at room temperature in a laboratory to preserve carbonation when exposed to humidity.

Due to the characteristics of these last three fine materials (eggshell, lime, and biopolymer), the specific gravity determinations were carried out directly on the compensated samples (Sulaiman et al., 2022).

The pozzolanic index was determined for each material, following Luxan's method (Luxan et al., 1988). This indirect method allows for the characterization of different materials based on pozzolanic activity. The process involves evaluating the electrical conductivity variation that occurs after 120 seconds in a saturated 200 mL solution of calcium hydroxide, to which 5 grams of dry material are added. The solution is kept stirring during the measurement period. With this indirect method, a categorization of materials is achieved based on pozzolanic activity. According to this, materials can be classified as non-pozzolanic when PI < 0.4 mS/cm, with intermediate pozzolanicity if 0.4 < PI < 1.2 mS/cm, and as high pozzolanic material for PI > 1.2.

All materials were oven-dried at a temperature of 105 ± 1 °C for 24 hours until obtaining constant weight. Mixtures with different additions were prepared. The selection of the number of additions was defined from previous studies (Mozejko and Francisca, 2020; Francisca and Mozejko, 2022; Bell, 1996). The samples are designated as follows:

- Loessical soil (L)
- Loess + 12% SS (L+12%SS)
- Loess + 12% WD (L+12% DW)
- Loess + 3% Eggshell (L+3% E)
- Loess + 1% Biopolymer (L+ 1%B)
- Loess + 2% Biopolymer (L+2%B)
- Loess + 3% Lime (L+3%L)

Compaction tests were performed for each of these mixtures determining the maximum dry unit weight and the optimal moisture content. Specimens were compacted in a 50 mm in diameter and 100 mm in height cell, filling it in three layers by using the standard Proctor energy by following general recommendations of the ASTM D 4254 (ASTM, 2010).

Unconfined compressive strength (UCS) tests were conducted on the compacted SS-soil specimens to evaluate the mechanical properties of these mixtures. Compensated mixtures were prepared at the optimal compaction point determined from the compaction tests.

All samples were prepared with Type III distilled water, characterized by having an electrical conductivity of 4 μs/cm, according to what is specified by the ASTM D1193 standard. Twin specimens of each admixture were stored in a humid chamber until the moment of analysis. Curing times were defined as 0, 7, 28, and 56 days. Specimens having different curing periods were tested to evaluate the influence of time on changes at the particle level that arise at the macro-scale as modifications in the UCS and stiffness. During this period the samples were stored under controlled temperature and humidity conditions. To prevent contact with the oxygen present in the external environment of the sample, they were wrapped in plastic wrap, monitoring their weight.

3 RESULTS

Figure 2 shows the compaction curves for each tested sample. As presented, they show a single peak, coinciding with the results previously obtained by several authors. The shape of the curves, characterized by a single peak, can be attributed to the dominance of behavior controlled by the fine silty loess fraction in all cases, owing to the low proportion of additives in the mixtures. Results show that the maximum dry density of the mixtures is in the range of 14 kN/m^3 to 17 kN/m^3, while the optimum water content falls between 18% and 24%.

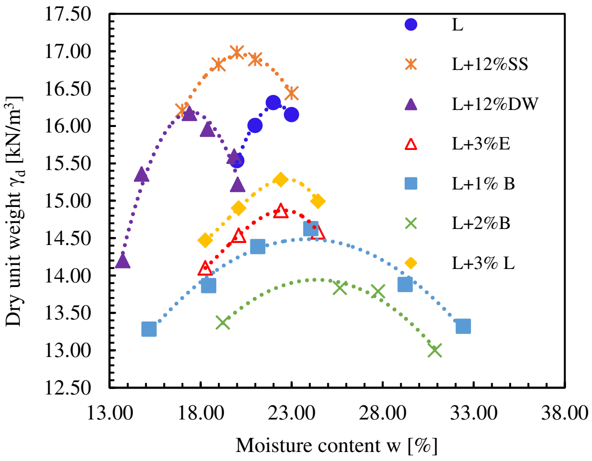

Figure 2. Influence of steel slag (L+12%SS), demolition waste (L+12%DW), eggshell (L+3%E), biopolymer (L+1%B and L+2%B) and lime (L+3%L) additions on loess silt compaction test.

As shown in Figure 2, the maximum dry unit weight obtained for loess soil is 16.4 kN/m^3 approximately. When adding SS, this value increases reaching 17.0 kN/m^3. The increase observed in unit weight can be associated with the higher bulk specific gravity of SS, which is greater than the one of soil (3.16 and 2.64, respectively). When adding demolition wastes, the dry unit weight remains at 16.0 kN/m^3 approximately, in agreement with the smaller difference between the specific gravity of loess (2.64) and demolition waste (2.76). However, in both cases, the optimum water content decreases due to the roughness of these granular particles.

Instead, the maximum dry unit weight decreases when adding eggshells, biopolymers, and lime. From the mixtures' specific gravity tests, it was possible to identify a decrease in these values: when adding 3% lime, a decrease from 2.64 to 2.53 was detected; when adding 3% eggshell, the decrease went from 2.64 to 2.61, and when adding biopolymers specific gravity lowers to 2.51 for 1% of biopolymer and 2.49 for 2% of biopolymer. These results indicate that lower dry unit weights are obtained when adding fine material with lower specific gravity. This corresponds with a slight increase in the optimum water content. Furthermore, the decrease in the specific gravity and the increase in the optimum water content achieved in the soil and XG mixture are caused by the bonding and rheology characteristics of the biopolymer (Chang et al., 2015). The decrease in the specific gravity obtained with the biopolymer can be attributed to the influence of the solution viscosity (Ayeldeen et al., 2016).

Figure 3 shows the peak values obtained from the UCS test of compacted specimens of L, L+12% SS, L+12% DW, L+1% B, and L+2% B after 0, 7, 28, and 56 days of curing. Specimens with and without additions, tested immediately after compaction, showed insignificant differences in their mechanical behavior. Loessical soil compacted sample shows a slight increase in its maximum strength with curing, reaching after 56 days 120 kPa. These results confirm that stabilization mechanisms are delayed over time. Nevertheless, all specimens that were stabilized developed higher strength with curing time. After 7 days of curing, the UCS of the specimen with 12% SS and 12% DW show a 100% increase in resistance terms. After 28 days SS sample reached 264 kPa, representing a 223% increase reaching 260 kPa after 56 days. DW sample reaches an increase of 293% after 56 days of curing reaching 265 kPa. Meanwhile, the increase is higher when adding biopolymers, reaching 468 kPa with 1% biopolymer addition and 400 kPa with 2% addition of this material after 56 days of curing.

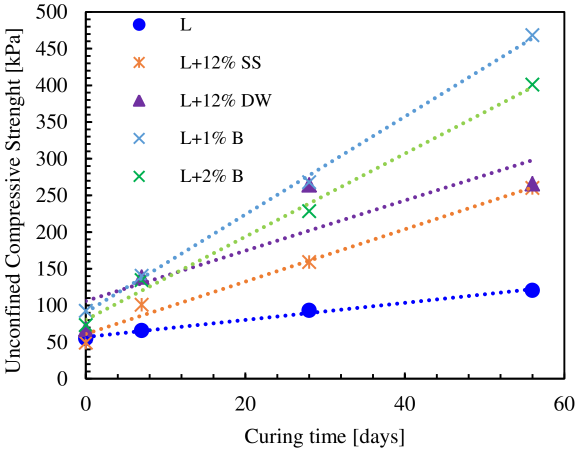

Figure 3. Influence of steel slag, demolition waste, and biopolymers contents on the unconfined compressive strength of compacted and stabilized loess soil samples.

Figure 4 shows the peak values obtained from the UCS test of compacted specimens when adding eggshell and lime to loessical soil after 0, 7, 28, and 56 days of curing. The improvements detected in terms of resistance of the samples stabilized with lime or eggshell are greater concerning the materials presented in Figure 3. Samples with eggshell (E) and lime (L) tested after preparation reached values of 123 kPa and 96 kPa, respectively, increasing with time until reaching 4080 kPa and 2800 kPa after 56 days of curing.

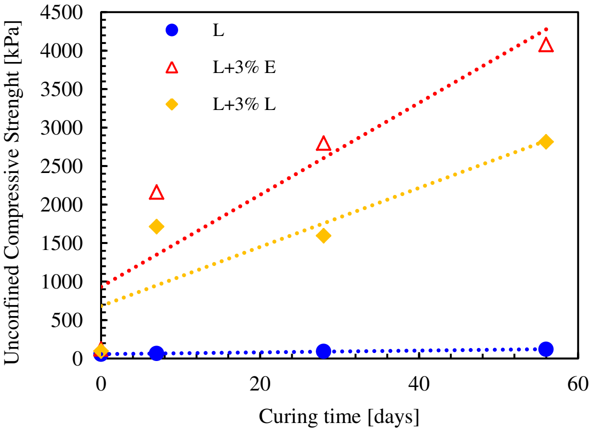

Figure 4. Influence of eggshell and lime content on the unconfined compressive strength of compacted and stabilized loess soil samples.

4 DISCUSSION

The results presented in Figure 3 and Figure 4 indicate that loess soil can be mechanically stabilized by adding selected materials.

Lime stabilization is implemented worldwide and the reactions that take place within soil samples have been extensively investigated by several authors. The lime-soil chemical reaction is mainly composed of two stages. The first, immediate or short-term, occurs a few hours or days after adding lime. This stage encompasses three main chemical reactions: cation exchange, flocculation and agglomeration, and carbonation. The second stage, the pozzolanic reaction, requires more time for its development (Latifi et al., 2018; Hezmi et al., 2019). Diverse studies inform that an eggshell is approximately 95% calcium carbonate, 3.5% organic compounds, and the remaining 1.5% are other minerals and nonmineral elements (Damaziak and Marzec, 2022). Because a high-purity material with a composition similar to lime is expected, results presented in Figure 4 were anticipated. This enables the identification of a similar reaction mechanism of stabilization taking place in eggshell and lime samples.

However, the resistances achieved in the mixture with eggshell are higher. This phenomenon can be attributed to the pozzolanic characterization of the material, presented in Table 2. As can be identified, both eggshell and lime may be classified as pozzolanic material due to the results obtained in which PI > 1.2 (PI = 1.67 and 1.56 mS/cm, respectively). Since eggshell material gives higher values of pozzolanic index, it can be inferred that there is a higher reaction rate in the second stage of stabilization in the L+3% E mixture. This indicates that the sample particles have a higher degree of cementation, which translates into a higher value in the maximum resistance achieved for the sample with lime.

Loessical soil by itself may be classified as a high pozzolanic material according to the adopted method. Hence, the increase detected on the sample, from 54 kPa up to 120 kPa is attributed to the natural cementation process that takes place between soil particles.

Previous studies demonstrated that the addition of SS particles in compacted silts favors the development of pozzolanic reactions by promoting an adequate environment for this type of reaction.

SS addition promotes an alkalization of the environment (SS pH = 12), favoring the reaction speed at which the cementation process occurs (Mozejko and Francisca, 2020; Francisca and Mozejko, 2022). As presented in Table 2, SS may be classified as non-pozzolanic material.

When adding DW instead, the increments on the unconfined compressive strength may be attributed to the medium alkalinization (DW pH = 9.30) but due to the presence of cement and lime typical of the mixture of this type of wastes as well. As shown in Table 2, the pozzolanicity of these wastes can be classified as variable (0.4 < PI < 1.2), higher than SS results. However, the mechanical behavior detected is similar to the SS mixture. In this sense, the contribution of the environment alkalinization, the presence of lime and cement, and the pozzolanicity of the material contribute to the development of cementation of particles during the curing process.

The addition of xanthan gum induces the formation of a gel structure in the soil matrix that fills the pores. The electric charges of the biopolymer enable direct interaction with the fine particles of the soil, facilitating the bonding of the particles. This provides firm biopolymer-soil matrices with high strength. The increment in the compressive strength over time is attributed to the dehydration of the hydrogel. Furthermore, it can be seen that the resistance is slightly higher with the addition of 1% rather than 2% of XG, showing that a high concentration of biopolymer does not guarantee higher strength. This effect can be attributed to the viscosity of hydrogel.

Table 2. The pozzolanicity index, obtained from Luxan's method, for all tested materials.

Sample denomination	*Pozzolanicity index (PI = mS/cm)*
Loess	1.28
Steel slag	0.14
Demolition waste	0.43
Biopolymer	0.72
Eggshell	1.67
Lime	1.56

5 CONCLUSIONS

This paper presents the evaluation of non-conventional stabilization agents to improve the mechanical properties of compacted loess. The main contributions are:

- Steel slag, crushed demolition waste, activated eggshells and biopolymers are effective for the stabilization of loess soils. The results show that soil stiffness and strength significantly increase over time due to the addition of these products.
- The main mechanisms involved in the observed stabilization is related to the development of pozzolanic reactions and hydrogels formation when the soil is mixed with steel slag, crushed demolition waste, and activated eggshells.
- Commercial lime was also used as a reference material for soil stabilization. The unconfined compression strength obtained when the soil is stabilized with the non-conventional products instead of commercial lime confirms the potential of using either steel slag, crushed demolition waste, activated eggshells, or biopolymers for loess soil stabilization.
- Xanthan gum has a significant strengthening effect on the treated soil. The increase in the mechanical properties over time is related to the dehydration of the hydrogels associated with the formation of a soil-xanthan gum matrix.
- A high concentration of biopolymers does not guarantee high soil strength. Adding a larger amount of xanthan gum, in this case 2% leads to a lower workability than 1%. One advantage of using a biopolymer as a binder is its effectiveness at low concentrations. The optimum biopolymer concentration may vary with the biopolymer type, soil type, and water content.

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