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# Soil improvement with the addition of natural materials, such as cactus mucilage

## Introduction

Improving soil simply means making the ground intended for construction stronger and firmer, ensuring that buildings do not collapse or experience other problems (De la Cruz Vega & Cornelio, 2022). In some places, the soil is very soft or cannot support much weight, therefore some materials need to be used to strengthen it. Usually, products like lime or cement are used, but those can be quite expensive and harmful to the environment (Alarcón et al., 2020).

Growing concern about pollution has encouraged the search for more natural and sustainable alternatives in many industries, including the construction sector. Accordingly, interest in natural materials has increased, as they help protect the environment and encourage a reconsideration of the ways in which buildings and infrastructure are designed and constructed (Silva et al., 2020). In recent decades, they have reemerged in sustainable architecture and engineering, driven by their

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renewability, lower environmental footprint, and the rediscovery of techniques that improve their mechanical performance and durability (Przybek, 2025).

One of the natural materials used is cactus mucilage – a sticky, gel-like substance derived from the cactus *Opuntia ficus-indica* (More & Gogate, 2019). This gel improves soil by increasing soil particles cohesion and by promoting healthy conditions in the soil (More & Gogate, 2019). This makes the soil less water-permeable, as well as stronger and firmer, which is highly beneficial for construction purposes and also for protecting the environment (Luna-Zapién et al., 2023).

To evaluate the effectiveness of this gel, a test was conducted to measures soil compaction, which is important for the safety of constructions (Medina-Torres et al., 2000). Before the test, basic soil properties, such as particle size and sieve retention, were checked (Medina-Torres et al., 2000). After adding the gel, the soil exhibited improved compactability (Bacchetta et al., 2024). This effect was observed because the gel, when mixed with water, enhances the soil's workability (Soto Juscamayta, 2023). In very wet soil, the gel makes the cohesion of fine particles, such as clay, more effective and allows them to deform without fracturing (Luna-Zapién et al., 2023). However, if the soil becomes too soft or sticky, its workability can decrease,, which can lead to construction problems, such as excessive settlement or structural damage (Kulshreshtha et al., 2022).

A study by Campos (2022) investigated the effects of cactus mucilage affects on soils used in road subgrades. Three different concentrations were tested 25%, 35%, and 40% using the Proctor method together with an assessment of natural soil conditions. The results showed a clear improvement in soil properties, starting with a reduction in the plasticity index to 3% after incorporating 40% cactus mucilage. In turn, the optimal moisture content was reduced by 8.3%, while the maximum dry density increased to 2.168 $g \cdot cm^{-3}$, indicating that mucilage may represent a good option for improving road subgrades, especially for clayey soils. Huamán Roca and Reaño Quiespe (2022) conducted a similar study on the Huilcarpay highway, with similar objectives, adding San Pedro cactus mucilage, using concentrations of 0%, 30%, 60%, and 90%. The study showed the maximum dry density achieved with the addition of 90% mucilage was 1.45 $g \cdot cm^{-3}$, and the plasticity index was 30.87%, suggesting that San Pedro cactus mucilage improves the physical and mechanical properties of the soil. Aranda-Jiménez and Suárez-Dominguez (2014) chose to use the following concentrations: 0%, 0.5%, 1%, 1.5%, 2%, and 2.5%, and the dry density increased from 1.85 $g \cdot cm^{-3}$ in the undisturbed soil to 1.91 $g \cdot cm^{-3}$ with the highest dose of 2.5%, indicating that small doses of mucilage can improve soil densification, facilitating soil handling.

Finally, Tanta (2022) analyzed cactus mucilage in the subgrade of the Rosario–Sivia highway using mucilage concentrations of 0%, 3%, 6%, and 9%. The maximum dry density of the natural soil without mucilage was 1.655 $g \cdot cm^{-3}$; with 3% mucilage, the density was slightly lower (1.600 $g \cdot cm^{-3}$). The optimal moisture content was 25.3%, indicating that cactus mucilage is effective in reducing soil plasticity. This background demonstrates that cactus mucilage has the potential to significantly enhance the soil properties, enabling its use in conditions that would otherwise be unsuitable for road subgrades.

# Material and methods

## Type of research

This research is applied in nature, as it uses scientific knowledge to address a specific problem within the field of geotechnical engineering. According to Torales and Barrios (2023), this type of research transforms theoretical principles into practical solutions oriented towards real-world contexts. Similarly, Cordero (2009) explains that its purpose is to generate concrete impacts in technical, social, and operational areas, extending beyond theoretical contributions. In this study, cactus mucilage is used as a natural additive to improve soil properties, representing a sustainable, economical alternative aligned with current environmental protection demands. As noted by Olivera Granada (2022), the incorporation of natural materials in civil engineering enhances both the technical performance and the sustainability of projects, strengthening the transition toward more responsible construction practices.

## Research design

The study adopts a quasi-experimental design, characterized by the manipulation of a variable – in this case, the dosage of cactus mucilage –  without requiring the random assignment of treatments. According to Zurita-Cruz et al. (2018), this design enables the analysis of cause-and-effect relationships in situations where full control of the study conditions is not feasible. Ramos-Galarza (2021) states that this approach is suitable for measuring effects while maintaining some degree of internal control, even in the absence of strict randomization. Likewise, Manterola and Otzen (2015) indicate that this design is particularly useful in applied research where external factors cannot be completely controlled, but results with practical

validity are still desired. In the present investigation, samples were distributed without random assignment and were subjected to different proportions of mucilage under carefully controlled laboratory conditions to ensure the consistency of the results.

## Research approach

A quantitative approach was used, which involved working with numerical measurements to analyze the relationship between the variables under study (Sánchez Flores, 2019). This approach relies on standardized instruments and precise procedures that allow for objective and replicable results (Hernández Sampieri et al., 2014). As emphasized by Huamán Rojas et al. (2022), it is essential in quantitative research to formulate clear hypotheses and test them through verifiable procedures in order to generate valid and generalizable conclusions. In this case, laboratory tests, such as the Standard Proctor test, were conducted to rigorously evaluate the effect of cactus mucilage on the soil's mechanical behavior.

## Research methods

The methodological process consisted of several stages, each designed to ensure the validity, reliability, and reproducibility of the results. These stages were conducted in accordance with technical criteria and internationally recognized standards, ensuring the overall quality of the research.

### Soil collection

The soil used in the study was collected from Luzuriaga street in the Barranca District, selected for its representativeness of the study area. The sample was extracted through a shallow excavation, with care taken to avoid disturbing or altering its natural properties (Agostini et al., 2014). The amount of material to be collected was determined in accordance with established technical guidelines to ensure representativeness. The entire process was carried out in accordance with national and international standards, primarily ASTM specifications (ASTM International, 2012).

### Initial soil analysis

The collected soil underwent characterization tests, including granulometry, Atterberg limits, and specific gravity, in accordance with applicable ASTM and AASHTO standards. These analyses established a baseline of the physical

and mechanical properties of the natural soil, enabling subsequent comparison with the samples treated with mucilage.

*Preparation and analysis of cactus mucilage*

The mucilage was extracted from fresh cladodes, followed by a controlled process that preserved its physicochemical properties. Parameters such as viscosity, density, and pH were evaluated, as these directly influence how the mucilage interacts with soil particles. Additionally, X-ray analysis was used to determine its chemical composition, providing insight into its potential as an additive capable of modifying soil structure.

*Preparation of soil–mucilage mixtures*

Mixtures were prepared with varying the proportions of mucilage added to the soil. Environmental variables such as humidity, temperature, and resting time were controlled to ensure comparability between samples. This control made it possible to attribute any observed differences in the results could be attributed specifically to the mucilage rather than to external factors.

*Compaction and mechanical behavior tests*

The mixtures were subjected to the standard Proctor test to determine optimum moisture content and maximum dry density (Flores et al., 2020; Guevara Lopez & Canaza-Rojas, 2023). With these data, compaction curves were generated – an essential tool in geotechnical engineering for understanding how soil density varies with moisture content and with the inclusion of additives. This analysis is fundamental for the design and construction of civil works, as it helps engineers to predict soil behavior under applied loads (American Association of State Highway and Transportation Officials [AASHTO], 2001).

*Comparison and analysis of results*

Finally, the results obtained from the natural soil samples were compared with those from the mixtures treated with cactus mucilage. This comparison made it possible to evaluate the influence of the natural additive on the compaction properties, optimum moisture content, and mechanical behavior of the soil, thereby determining its potential as a sustainable alternative for soil improvement.

# Results and discussion

## Cactus mucilage

Table 1 shows the names of cactus mucilage by scientific name, country, and species. This information makes it possible to identify how its nomenclature varies in different regions (Villa Uvidia et al., 2020), which is useful for understanding references from other locations, facilitating knowledge sharing, and supporting its application in diverse contexts.

TABLE 1. Names of cactus mucilage used in other countries

| Scientific name | Country | Plant common name | Mucilage common name |
|---|---|---|---|
| *Opuntia ficus-indica* | Mexico | Nopal | Nopal mucilage |
| | Peru | Cactus | Cactus mucilage |
| | Argentina | Tuna | Prickly pear mucilage |
| | Chile | Tuna | |
| | Ecuador | Tuna | |
| | Bolivia | Tuna | |
| *Opuntia* spp. | United States | Nopal | Nopal mucilage |
| | Colombia | Nopal | |
| | Venezuela | Nopal | |

Source: own work.

Table 1 presents to the elemental composition of cactus mucilage determined using the Ed XRF technique, a practical and well-known technique for accurately identifying the mineral components present in the mucilage. This method provides a clear characterization of mucilage's structure and composition, which is essential for properly understanding its chemical and physical properties and for supporting its use in various industrial or research applications (Vargas Mamani et al., 2019).

Figure 1 shows a world map highlighting the regions or countries where the use of cactus mucilage in soil compaction has been applied or explored. The areas marked in green include parts of Latin America, North and East Africa, West Asia, and India, suggesting that this method is relevant mainly in arid or semi-arid regions where cactus species are common and accessible.

FIGURE 1. Regions where cactus mucilage is used for soil compaction
Source: own work.

The results of cactus mucilage chemical analysis (Table 2) reveal a high water content (96.43%), suggesting its primarily aqueous nature. Significant levels of potassium, calcium, and magnesium were found among the inorganic components, present both in elemental and oxide forms, suggesting their involvement in the structure of the mucilage and its water-retaining capacity. Other elements were also detected, including phosphorus, iron, zinc, manganese, and copper, but in smaller proportions, which could indicate their role in the chemical stability and bioactive properties of the mucilage. This water-rich composition, with a diverse mineral fraction, makes the mucilage a suitable material for consideration in various applications related to industry or research.

TABLE 2. Composition of cactus mucilage obtained by X-ray fluorescence spectrometry at a sample' moisture content of 96.43%

| Content of the chemical elements | Value [%] | Content of the oxides | Value [%] |
|---|---|---|---|
| Potassium (K) | 1.7810 | Potassium oxide ($K_2O$) | 2.6042 |
| Calcium (Ca) | 0.8190 | Magnesium oxide (MgO) | 0.6014 |
| Magnesium (Mg) | 0.5913 | Calcium oxide (CaO) | 0.3110 |
| Chlorine (Cl) | 0.2883 | Phosphorus pentoxide ($P_2O_5$) | 0.0372 |
| Phosphorus (P) | 0.0402 | | |
| Sulfur (S) | 0.0333 | Chlorine (Cl) | 0.0040 |
| Iron (Fe) | 0.0050 | Iron oxide ($Fe_2O_3$) | 0.0033 |
| Zinc (Zn) | 0.0034 | Sulfur trioxide ($SO_3$) | 0.0024 |
| Manganese (Mn) | 0.0031 | Manganese oxide (MnO) | 0.0017 |
| Copper (Cu) | 0.0019 | Zinc oxide (ZnO) | 0.0008 |

Source: own work.

Although Table 1 presents the elemental composition of Opuntia mucilage, it is important to note that this composition is not universal for all cactus species. While variations are generally small, differences may occur depending on the genus and species, environmental conditions, soil mineral content, plant maturity, and even the season. Therefore, the chemical profile reported here should be interpreted as specific to this particular sample, and it may differ slightly from the mucilage obtained from other specimens growing in different regions.

Table 3 shows that cactus mucilage has a high viscosity, indicating a thick, gelatinous appearance, typical of substances with water-retaining capacity. The density of these substances is quite similar to that of water, suggesting they do not significantly alter soil structure.

TABLE 3. Properties of cactus mucilage

| Property | Value |
|---|---|
| Viscosity | 1,087.9 cSt |
| Density | $0.9948 \text{ g·cm}^{-3}$ |
| Potential of hydrogen (pH) | 4.61 |

Source: own work.

However, they also improve material cohesion and water retention. The slightly acidic pH of the mucilage indicates a chemical environment that could favor certain biochemical reactions and even enhance formulation stability. Ultimately, these aspects give cactus mucilage significant potential for use in soil improvement, especially in infrastructure projects where improved material cohesion and water retention are sought (De la Cruz Vega, 2023).

## Undisturbed soil

The results of the particle-size analysis of the tested soil sample are presented in Table 4, enabling the determination of the particle-size distribution and the classification of the soil according to the established criteria – an essential step for evaluating soil behavior (Gutiérrez Rodríguez, 2023).

The results obtained from Table 4 show a granulometric analysis of the analyzed soil sample, indicating a composition of 14.08% gravel, 85.51% sand, and 0.42%

fine material, which allows it to be classified as a primarily sandy and clean soil due to its low fine-particle content. According to the USCS classification system, the soil is classified as well-graded sand (SW), given that it presents a continuous and wide distribution of particle sizes within the sandy range. With respect to AASHTO, since less than 35% of the sample passes the Sieve No 200 and it is mainly sand with some gravel, the soil corresponds to Group A-1-b.

TABLE 4. Granulometry of the soil sample

| Sieve | Mesh [mm] | Weight [g] | Soil retained [%] | Cumulative of soil retained [%] | Soil passing [%] |
|---|---|---|---|---|---|
| 3″ | 76.200 | 0 | 0 | 0 | 100 |
| 2″ | 50.800 | 0 | 0 | 0 | 100 |
| 1 1/2″ | 38.100 | 0 | 0 | 0 | 100 |
| 1″ | 25.400 | 52.308 | 1.74 | 1.74 | 98.26 |
| 3/4″ | 19.050 | 34.808 | 1.16 | 2.90 | 97.10 |
| 1/2″ | 12.700 | 90.288 | 3.01 | 5.91 | 94.09 |
| 3/8″ | 9.525 | 42.478 | 1.42 | 7.33 | 92.67 |
| 1/4″ | 6.350 | 109.378 | 3.65 | 10.98 | 89.02 |
| No 4 | 4.760 | 93.048 | 3.10 | 14.08 | 85.92 |
| No 8 | 2.380 | 494.968 | 16.50 | 30.58 | 69.42 |
| No 16 | 1.190 | 567.208 | 18.91 | 49.48 | 50.52 |
| No 30 | 0.595 | 537.688 | 17.92 | 67.41 | 32.59 |
| No 50 | 0.297 | 489.528 | 16.32 | 83.72 | 16.28 |
| No 100 | 0.150 | 376.848 | 12.56 | 96.29 | 3.71 |
| No 200 | 0.075 | 98.928 | 3.30 | 99.58 | 0.42 |
| Bottom | – | 12.518 | 0.42 | 100 | – |
| | Total | 2,999.994 | | | |

Source: own work.

During the analysis of the samples from Tanks 1, 2, and 3, the liquid limit was determined (Fig. 2). For this purpose, samples with different moisture contents were prepared, and the number of blows required to close the cut groove was recorded. After performing the corresponding calculations, a liquid limit value of 19.16 was obtained for the sample.
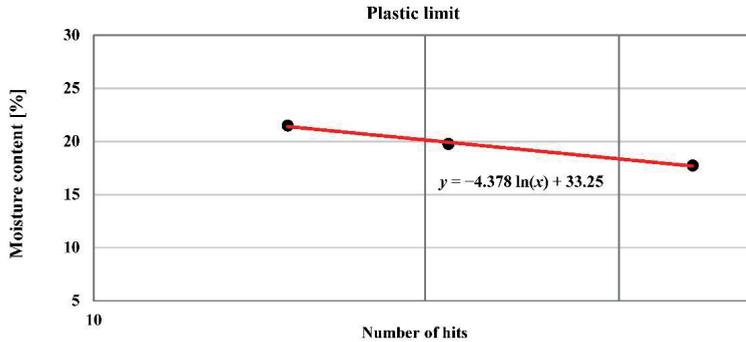
**Plastic limit**



FIGURE 2. Liquid limit of the soil sample
Source: own work.

## Standard Proctor test of soil with cactus mucilage dosages

The results of the tests are analyzed to identify patterns, trends, and significant variations in soil properties. Data are updated against certain standards, and useful recommendations are made based on the results obtained, which will determine applicable improvements in land use in the study area (Castro-Solis et al., 2024). The standard Proctor test was performed on undisturbed soil samples with different dosages of cactus mucilage, with the aim of determining the maximum dry density and optimal soil moisture content (Reyes, 2010). To this end, different doses of cactus mucilage were supplied to the soil (4%, 6%, 8% CM).

Dry density data obtained from the standard Proctor tests are presented in Figure 3. Among the samples tested, the soil with 6% cactus mucilage stands out for exhibiting the highest value. This dosage results in improved compactability and greater stability compared with the other dosages. These findings suggest that incorporating 6% mucilage enhances soil cohesion, thereby increasing its strength and resistance to applied loads.
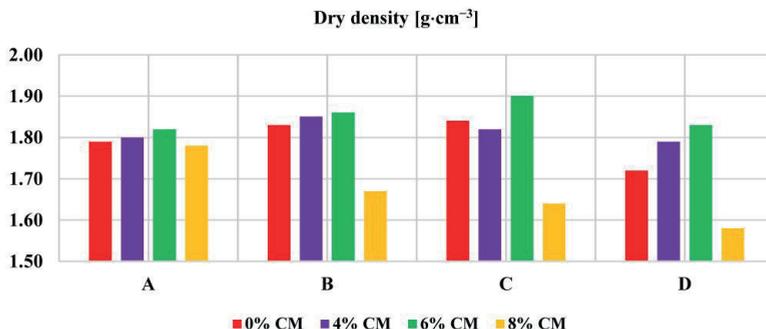
FIGURE 3. Comparative graph of dry density values of soil with cactus mucilage (CM)

Source: own work.

Figure 4 presents the test results showing that using 4% and 6% mucilage provided higher dry densities (1.85 and 1.90 g·cm$^{-3}$, respectively) compared to the original soil without mucilage (1.84 g·cm$^{-3}$). In this case, the 6% dosage provided the highest density, resulting in greater soil compaction and stability. Moisture content also increased, from 12.27% (undisturbed) to 19.11% (with 6% cactus mucilage). When the mucilage content was 8%, the dry density decreased, as extreme humidity impairs compaction processes due to the hygroscopic properties of the mucilage, leading to poor soil compaction.
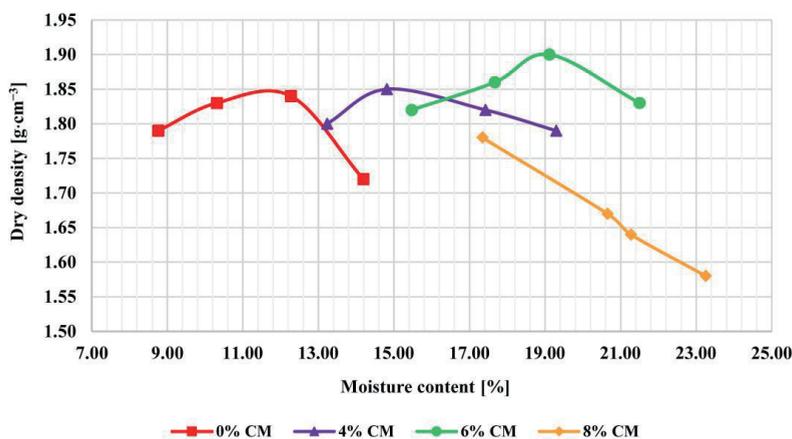


FIGURE 4. Comparative graph of dry density values of soil with cactus mucilage (CM)

Source: own work.

The 6% cactus mucilage dosage used in this research was the most effective, achieving a maximum dry density of 1.90 g·cm$^{-3}$ and an optimum moisture content of 19.11%. This represents a significant improvement in soil compaction compared to the undisturbed sample. These results partially coincide with Campos (2022), who, after employing higher concentrations of nopal mucilage (40%), reported a higher dry density of 2.168 g·cm$^{-3}$, but with a lower optimum moisture content of 8.3%. This is likely due to differences in soil type and the nature of the mucilage used. Huamán Roca and Reaño Quiespe (2022) did use high concentrations of San Pedro cactus mucilage, up to 90% concentration, but their results yielded a lower dry density of 1.45 g·cm$^{-3}$. This suggests that the type of cactus used, as well as the excess addition, may hinder the soil's densification capacity.

Building on the findings of this research, Aranda-Jiménez and Suárez--Dominguez (2014) demonstrate how small doses of mucilage, for example, 2.5%, can progressively increase soil dry density, reaching 1.91 g·cm$^{-3}$, thus confirming the effectiveness of more controlled dosages. Finally, Tanta (2022) concluded that low mucilage concentrations (up to 9%) do not significantly affect the dry density of 1,600 g·cm$^{-3}$ achieved in the study, although they did contribute to reducing plasticity. All these studies support the notion that a controlled dosage, such as the 6% used in this study, can improve soil mechanical properties without reaching the values that impair compaction due to high moisture content or saturation of the material.

The mucilage acts as a natural binder, joining the soil particles without producing any internal structural modification of the material. Its main function is to improve cohesion and compaction, which increases the stability of the soil without altering its fundamental physical composition. Additionally, once compacted, this improved soil can be covered with an asphalt layer, which serves as protection against moisture, erosion, and environmental changes, helping preserve the properties achieved during the stabilization process.

The results in Table 5 show that dry density varies noticeably with the amount of cactus mucilage added. The natural soil (0%) exhibits a mean dry density of 1.84 g·cm$^{-3}$ with very low variability, reflecting consistent measurements. A slight increase is observed at 4% mucilage, where the mean rises to 1.85 g·cm$^{-3}$, although variability increases moderately. The 6% dosage yields the highest dry density (1.90 g·cm$^{-3}$), supported by its confidence interval, which lies entirely above those intervals of the previous treatments, indicating a significant improvement in compaction. In contrast, the 8% dosage results in the lowest density (1.78 g·cm$^{-3}$), with a confidence interval clearly separated from the others, confirming that this higher dosage reduces the soil's compactability. Overall, the data indicate that 6% mucilage provides the most favorable compaction performance among the tested dosages.

TABLE 5. Statistical indicators (*SD*, *SEM*, *CI*)

| Cactus mucilage dosage [%] | Mean [g·cm$^{-3}$] | *SD* | *SEM* | 95% *CI* |
|---|---|---|---|---|
| 0 | 1.84 | 0.010 | 0.006 | 1.828–1.852 |
| 4 | 1.85 | 0.015 | 0.009 | 1.833–1.867 |
| 6 | 1.90 | 0.020 | 0.012 | 1.876–1.924 |
| 8 | 1.78 | 0.018 | 0.010 | 1.760–1.800 |

Source: own work.

The results of the Shapiro–Wilk test indicate that all mucilage dosages (0%, 4%, 6%, and 8%) exhibit *p*-values greater than 0.05, meaning none of the distributions deviate significantly from normality. Since normality is not rejected for any group, the dataset meets one of the key assumptions required for parametric analysis. Therefore, it is statistically appropriate to apply a one--way ANOVA to evaluate differences in dry density among the various mucilage treatments (Table 6).

TABLE 6. Shapiro–Wilk normality test results

| Content of cactus mucilage [%] | W statistic | *p* | Normal distribution? |
|---|---|---|---|
| 0 | 0.8925 | 0.3948 | yes |
| 4 | 0.8604 | 0.2616 | yes |
| 6 | 0.9281 | 0.5835 | yes |
| 8 | 0.9736 | 0.8636 | yes |

Source: own work.

The one-way ANOVA analysis shows a statistically significant effect of mucilage percentage on the soil's dry density ($F = 8.37$; $p = 0.0028$). Since the *p*-value is less than 0.05, the null hypothesis, asserting that all group means are equal, is rejected. Therefore, it is concluded that the different mucilage dosages produce real variations in dry density (Table 7).

TABLE 7. Analysis of variance (ANOVA)

| Source of variation | Sum of squares (*SS*) | Degrees of freedom (*df*) | Mean square (MS) | *F* | *p* |
|---|---|---|---|---|---|
| Between groups | 0.1183 | 3 | 0.03940 | 8.37 | 0.0028 |
| Within groups | 0.0565 | 12 | 0.00471 | – | – |
| Total | 0.1748 | 15 | – | – | – |

Source: own work.

This result confirms that mucilage is not merely a physical additive but significantly modifies the soil's compaction behavior. In practical terms, the 6% dosage is the most efficient, yielding the highest dry density, whereas the 8% dosage reduces compaction efficiency due to the excessive moisture contributed by the mucilage.

## Conclusions

Adding cactus mucilage to soil significantly improves it, especially in terms of compaction and the moisture required to achieve good compaction. The best results were obtained with about 6% mucilage; at that amount, the soil compacted well and had just the right moisture to remain strong. However, it is important to note that adding too much mucilage introduces excessive moisture, which reduces soil compaction.

For example, when 8% was used, there was too much moisture, and instead of improving the soil, it actually made it looser and less dense. Therefore, it is important to find the right balance – not too little, not too much. Another advantage of mucilage is that it helps distribute moisture evenly throughout the soil, resulting in more uniform compaction and fewer air pockets. This is key to ensuring the ground remains stable and can bear weight.

Reviewing other studies, it is clear that cactus mucilage can improve soil, but the results vary depending on soil type and the amount of mucilage used. Overall, 6% appear to provide optimal balance between strengthening the soil and controlling moisture. Since it is natural, it is a promising alternative to chemical stabilizers – not only for environmental benefits but also for cost savings.

### Acknowledgments

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## Summary

**Soil improvement with the addition of natural materials, such as cactus mucilage.**
In civil engineering, a frequent situation arises, when soils to be used in projects have little resistance or are very plastic to be used in projects, so they must be improved. The procedure of improving soils through natural stabilizers such as cactus mucilage is an ecological alternative. The objective of this work is to evaluate the properties of mucilage and the effect it has on the compaction properties of the soil from Luzuriaga Street, located in the Barranca District. Different dosages (4%, 6%, and 8%) of cactus mucilage (CM) were used on this SW (in accordance with soil sample in accordance with USCS) and A-1-b (according to AASHTO) soil sample, and the properties were evaluated by standard Proctor tests. The results of the cactus mucilage showed a humidity of 96.43% and potassium and calcium were identified as the main elements present, the viscosity was 1,087.9 cSt, the density was 0.9948 g·cm$^{-3}$ and its pH was 4.61. With respect to the properties of soil with CM they indicated that 6% mucilage is the one that results in a higher dry density of 1.90 g·cm$^{-3}$ and an optimal moisture content of 19.11%, which means an improvement in compaction in addition to stability. As a conclusion it was stated that the cactus mucilage modifies the structure of the soil by increasing the cohesion between the particles, resulting in a more uniform mixture. It is also indicated that a moderate dose such as 6% optimizes the properties of the soil.