

# Stabilization of dispersive soils in the Bolivian Amazon using magnesium chloride hexahydrate (bischofite)

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**ABSTRACT:** Dispersive soils are widely found across different regions, and their tendency to deflocculate in the presence of water can lead to severe problems and failures in civil engineering projects. Detecting, characterizing, and stabilizing these soils is therefore essential to ensure long-term infrastructure performance. Traditional stabilizers such as lime and cement are effective but often associated with high environmental impact and elevated construction costs. This study investigates the stabilization of dispersive soils identified in a highway construction project in the Bolivian Amazon using magnesium chloride hexahydrate (bischofite). Physical and chemical characterization tests were performed, followed by an analysis to determine the optimal dosage of bischofite required to mitigate soil dispersion. The results show that a 20% bischofite-in-water solution applied at 5% of the soil's dry mass significantly improves soil behavior, reducing its dispersivity classification. These findings demonstrate that bischofite may offer a cost-effective and environmentally sustainable alternative for stabilizing dispersive soils. This is particularly relevant for Bolivia, given its position as one of the world's largest holders of lithium reserves, and the fact that bischofite is a low-cost byproduct of lithium carbonate production.

**KEYWORDS:** Soil stabilization, dispersive soil, bischofite.

## 1 INTRODUCTION

Dispersive soils represent a problematic material for road infrastructure construction due to their physicochemical properties in the presence of water. These properties make them highly susceptible to erosion, which can compromise the integrity and durability of built infrastructure. The dispersive nature of these soils is associated with a predominant presence of exchangeable sodium ( $\text{Na}^+$ ) in the soil compared to other ions like potassium ( $\text{K}^+$ ), calcium ( $\text{Ca}^{2+}$ ), or magnesium ( $\text{Mg}^{2+}$ ) (Consoli, Samaniego and Villalba, 2016). When a soil has a high sodium content, the water film and electric double layer surrounding the particles become thicker, intensifying the repulsive forces between particles. As a result, the soil becomes more susceptible to dispersion (Fan and Kong, 2013; Li et al., 2024). This mechanism is further exacerbated in soils with a high pH.

The properties of dispersive soils can be modified using chemical agents such as calcium hydroxide (hydrated lime), calcium sulfate (gypsum), and aluminum sulfate. These agents increase the electrolyte concentration in the pore solution and the levels of exchangeable calcium, thereby reducing the dispersive properties of the soil (Consoli et al., 2016). Other stabilization alternatives include the use of fly ash (Indraratna, Nulalaya and Kuganenthira, 1991) and cement (Vakili et al., 2021). However, the use of these agents presents significant drawbacks, such as high production costs and environmental pollution from carbon dioxide ( $\text{CO}_2$ ) emissions, as well as the potential groundwater contamination (Ren et al., 2023; Fan et al., 2025).

In recent years, several alternative stabilizers have been investigated to improve the behavior of dispersive soils. These efforts have focused on reducing the environmental impact while maintaining or enhancing stabilization effectiveness. These alternatives include the use of industrial byproducts or waste materials such as silica fume, glass powder, and plaster of Paris kiln dust (PKD) (Türköz, Umu and Öztürk, 2021; Miguel et al., 2022; Fatima et al., 2023). An additional promising alternative, and the subject of the present study, is the application of bischofite, or magnesium chloride hexahydrate ( $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ ). Bischofite is a natural mineral found in subterranean brine deposits in salt flats and is

characterized by its high concentration of magnesium. Specifically in civil engineering, bischofite is used as a chemical stabilizer for unpaved roads. Its properties, including hygroscopicity and the ability to lower the freezing point of water, enhance moisture control, increase the shear strength, and durability against freeze-thaw cycles (Thenoux and Vera, 2002).

The effectiveness of bischofite in stabilizing dispersive soils is attributed to its primary component, magnesium chloride. This compound acts through cation exchange, where the divalent magnesium ( $\text{Mg}^{2+}$ ) cations displace the monovalent sodium ( $\text{Na}^+$ ) cations from the soil structure. This process reduces the thickness of the diffuse electric double layer, increasing the flocculation and, consequently, mitigating the soil's dispersive properties. Moreover, magnesium chloride can increase the surface tension of water, which leads to an increase in soil cohesion and strength (Soltani-Jigheh et al., 2024). The efficacy of this mechanism has been demonstrated in laboratory studies. For example, Turkoz et al. (2014) assessed the soil's dispersion potential using the pinhole and crumb tests with different percentages of magnesium chloride addition. This study reported that the additive not only reduced dispersivity but also modified other physical properties of the soil, such as the plasticity index and swelling.

In this context, the main objective of this study is to evaluate the effectiveness of bischofite in improving the dispersive properties of a local soil from the Bolivian Amazon. This was achieved through an experimental program that included the characterization of the materials and the evaluation of the dispersivity of both a highly dispersive soil and its treated blends with different bischofite contents. This assessment was performed using the Crumb test, Pinhole test, and double hydrometer test. Additionally, the samples were analyzed for soluble salts, ionic composition in the pore solution, cation exchange capacity (CEC), and exchangeable sodium percentage (ESP).

The use of bischofite is particularly relevant in Bolivia, which holds one of the world's largest lithium and magnesium brine reserves: the Uyuni Salt Flat. The large-scale availability of this natural resource positions bischofite as an accessible and economically available solution for stabilizing local soils.

## 2 MATERIALS AND METHODS

### 2.1 Dispersive soil

The soil analyzed in this research was obtained from the embankments along the Rurrenabaque – Riberalta highway in the department of Beni, northern Bolivia. This highway traverses the basins of the Beni and Mamoré rivers, which form part of the Amazon River basin. The samples were collected in a disturbed state and were taken to the laboratory for their physical and chemical characterization.

Based on the Unified Soil Classification System (USCS), the material is classified as high-plasticity inorganic clay (CH). The results of the characterization, including the Atterberg limits (ASTM D 4318), compaction properties (ASTM D 698), and particle size distribution (ASTM D 422), are summarized in Table 1.

Table 1. Physical properties of the soil.

Parameter		Value
Atterberg limits		
Liquid limit	(%)	50.80
Plastic limit	(%)	26.50
Plasticity index	(%)	24.30
Compaction properties		
Max. dry density	(g/cm <sup>3</sup> )	1.741
Optimum moisture content	(%)	18.50
Grain size		
Sand	(%)	8.13
Fines	(%)	91.87

Figure 1 presents the results of the X-ray diffraction (XRD) analysis, which identified the mineral phases present in the undisturbed soil sample. The diffraction peaks revealed characteristic minerals such as quartz (46-1045) and illite (26-911), which are common in this type of clay. Previous research has demonstrated that soils with these characteristics present significant geotechnical risks (Scheuermann Filho et al., 2021).

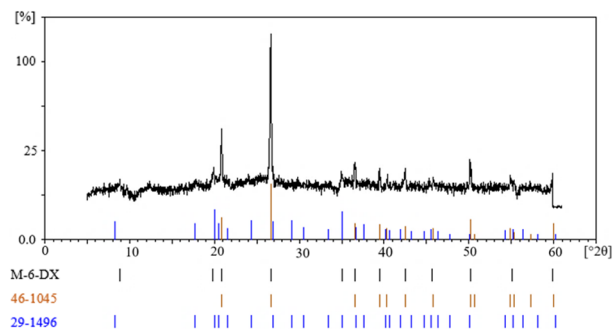


Figure 1. X-ray diffraction (XRD) analysis of soil.

### 2.2 Magnesium chloride hexahydrate (bischofite)

Solid magnesium chloride hexahydrate was acquired from YLB (Yacimientos de Litio Bolivianos) and subjected to mineralogical characterization tests. As shown in Table 2, this analysis was performed to identify the main components of the bischofite. This mineralogical characterization confirms the product's purity and its potential for reaction in highly dispersive soils.

Table 2. Physicochemical properties of bischofite

Component/Property		Value
Concentration	(%)	82.0 - 96.0
Sodium (Na)	(%)	0.50 - 3.1
Chlorides (Cl)	(%)	28.5 - 40.0
Potassium (K)	(%)	0.05 - 1.20
Magnesium (Mg)	(%)	9.50 - 11.60
Lithium (Li)	(%)	0.15 - 1.01
Moisture	(%)	1.10 - 2.00
Solubility	(g/cm <sup>3</sup> )	90.0
pH in saturated solution	(-)	4.5 - 7.0
Density	(g/cm <sup>3</sup> )	1.20 - 1.25

### 2.3 Specimen preparation

To prepare the stabilizing solutions, different concentrations of bischofite dissolved in water were used to evaluate their performance at various proportions. Three solutions were prepared based on mass percentages: 5% bischofite and 95% water, 20% bischofite and 80% water, and 40% bischofite and 60% water. Low and high stabilizer concentrations were selected to analyze their effect on the soil and the degree of improvement achieved at different dosages.

The soil mixtures were prepared by incorporating the bischofite solutions directly into the soil, using an amount of solution equivalent to 5% of the soil's dry mass. The remaining water required to reach the optimum moisture content was then added.

### 2.4 Performance and dispersivity tests

To evaluate the performance of the bischofite solutions, a series of physical and chemical tests were conducted on both untreated soil samples and on samples treated with different bischofite solution concentrations. The physical tests included the Atterberg limits (ASTM D4318), as well as the Crumb test (ASTM D6572), Pinhole test (ASTM D4647), and double hydrometer test (ASTM D4221). In addition, the chemical analyses for soluble salts and Cation Exchange Capacity (CEC) were performed to identify and quantify the cations of calcium, magnesium, sodium, and potassium. The salinity tests were carried out according to the criteria of the USDA and NOM-021-REC/NAT-2000, while the methodology used for CEC determination was the EPA SW-846 Method 9080.

## 3 RESULTS

### 3.1 Atterberg limits test

The results of the consistency limits are presented in Figure 2. Incorporating 5% of bischofite produced only a slight reduction in the liquid limit (LL) and plastic limit (PL), with values of 50.1% and 26.0% respectively. Consequently, the plasticity index (PI) decreased only to 24.1%, indicating that the soil does not exhibit a significant improvement in its plastic structure at low bischofite concentrations, which can be attributed to the limited interaction between magnesium and the clay particles.

Increasing the bischofite concentration to 20% led to a noticeable decrease in LL, PL, and PI. At 40% concentration, this trend became even more pronounced with LL, PL, and PI reducing to 46.7%, 24.9%, and 21.8% respectively. This considerable reduction can be attributed to the effect of magnesium chloride, which causes a reduction in the thickness of the clay's diffuse double layer. This, in turn, decreases the clay's capacity to retain free water, thereby reducing its plasticity. Similar reductions in plasticity indices have been reported by Yeganeh Rikhtehgar and Teymür (2024).

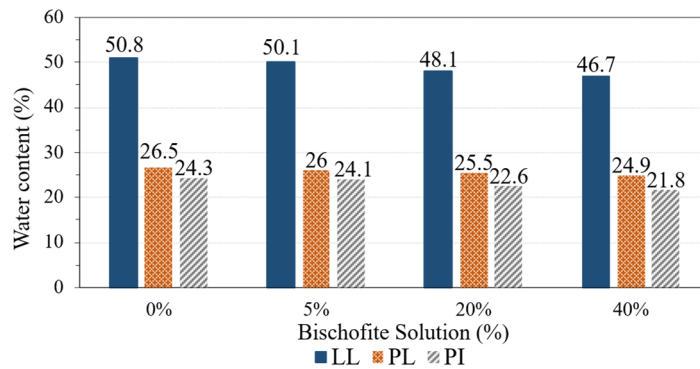


Figure 2. Consistency limits results for different bischofite concentrations.

### 3.2 Crumb tests

The Crumb test results, shown in Table 3, classified the natural or untreated soil as dispersive (Grade 4). The clear influence of water on the 15 mm soil cubes was evident, as the disintegration and water turbidity were observed after the first hour, suggesting a weak internal structure of the soil and a dispersive behavior. Conversely, the bischofite-treated samples exhibited a different behavior. All concentrations (5%, 20%, and 40%) classified the soil as non-dispersive (Grade 1), as immersion in water did not cause a significant loss of clay cohesion even after 6 hours. As a result, the water in the containers remained clear. This significant difference between the behavior of the samples is attributed to the stabilizing effect of magnesium ions, which induce flocculation and reduce the electrical double layer, thereby considerably limiting the dispersivity of the soil.

### 3.3 Pinhole test

The Pinhole test conducted on the natural soil indicated a moderately to slightly dispersive behavior (ND3), as depicted in Figure 3. The test began with an initial head of 50 mm, for which the flow rate was 0.16 ml/s. The flow rate gradually increased, reaching 2.7 ml/s when the head was raised to 180 mm. The final diameter of the pinhole was 3.50 mm. Water turbidity also changed from completely clear to very dark by the end of the test, with some suspended particles. These results confirm the dispersive nature of the natural soil.

For the 5% bischofite concentration, the soil was still classified as slightly dispersive (ND3), as shown in Figure 3.

The initial flow rate under a 50 mm head was 0.14 ml/s. This flow rate increased progressively, reaching a maximum of 2.50 ml/s at a head of 380 mm with a final pinhole diameter of 3.00 mm. Although turbidity was less intense and persistent than in the natural soil, more particles were entrained.

The soil treated with the 20% bischofite concentration was classified as non-dispersive (ND1) as observed in Figure 3. The initial flow rate was 0.34 ml/s under a head of 50 mm. The flow rate increased moderately as the head was progressively raised to 180 mm, 380 mm, and 1020 mm, reaching a maximum of 2.13 ml/s. For this case, the final pinhole diameter was 1.00 mm and turbidity changed from completely clear at the beginning of the test to dark by the end of it, with several particles entrained. This result reflects a notable improvement in the soil's internal cohesion and erosion resistance, demonstrating a significant stabilizing effect.

Finally, the results of the test performed on the soil treated with 40% bischofite concentration classified the sample as non-dispersive (ND1). The flow rate began at 0.29 ml/s under a head of 50 mm and increased gradually, reaching a maximum of 2.94 ml/s under a 1020 mm head. The final pinhole diameter was 1.50 mm and throughout the test, turbidity remained completely clear, and no entrained particles were observed. These results indicate that this concentration and dosage maintains a high resistance to dispersion. However, the final flow rate was higher than that of the 20% treatment, suggesting that excessive bischofite concentration may produce adverse effects.

Table 3. Crumb test results at different immersion times (ASTM D6572).

Registration time	Sample			
	Natural soil (Grade 4)	5% Concentration (Grade 1)	20% Concentration (Grade 1)	40% Concentration (Grade 1)
2 minutes				
1 hour				
6 hours				

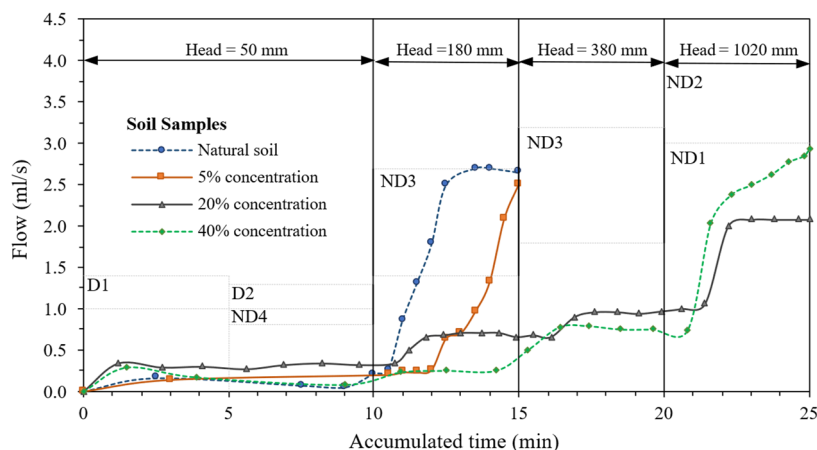


Figure 3. Pinhole tests results for different soil samples.

### 3.4 Double hydrometer test

A summary of the results of the double hydrometer test are presented in Table 4. These indicate that the natural soil exhibits highly dispersive behavior since the fines percentage of 99.51% with a dispersant and 72.90% without a dispersant, result in a dispersion index of 73.26%. This value exceeds the 35% threshold, which is the minimum reference value suggested by Djoković et al. (2018). Values over 35% are typically associated with soils exhibiting high instability in the presence of water.

Table 4. Double hydrometer test results for Soil dispersivity identification

Bischofite content	% Fines with dispersant	% Fines without dispersant	Disp. index (%)	Classification
0%	99.51	72.9	73.26	Dispersive
5%	97.35	69.66	71.56	Dispersive
20%	58.12	27.53	47.37	Dispersive
40%	95.64	7.5	7.84	Non-dispersive

For the 5% bischofite treatment, fines percentages of 97.35% (with dispersant) and 69.66% (without) were obtained, resulting in a dispersion index of 71.56%. Although this value represents a slight decrease compared to the natural soil, it remains above the standard limit and the soil is still classified as dispersive. The 20% concentration showed a clearer improvement, with fines contents of 58.12% and 27.53% and a dispersion index of 47.37%; however, the soil continued to be classified as dispersive.

Finally, the 40% bischofite treatment provided the necessary evidence to classify the soil as non-dispersive. The fines percentages were 95.64% (with dispersant) and 7.5% (without), resulting in a dispersion index of just 7.84%.

### 3.5 Soluble salts and ion composition in solution

The results of these analyses (Table 5) indicate that the concentration of soluble cations was influenced by the addition of bischofite. The soluble Na content was highest in the natural soil (12.39 mEq/L) and decreased to 7.39 mEq/L with a 40% bischofite concentration. This effect is attributed to the dilution of sodium due to the considerable increase of calcium and magnesium in the liquid phase, particularly in the 40% treatment where calcium concentration reached 40 mEq/L.

The Sodium Adsorption Ratio (SAR) of the solution decreased as the bischofite content increased, from 12.39 in the natural soil to 1.25 in the 40% treatment. This confirms that even though the sodium concentration remains considerable,

the proportional increase of Ca and Mg significantly reduces the risk of soil dispersion caused by Na. This reduction in SAR is also reflected in the %Na, which indicates an improvement in the chemical quality of the soil solution.

The CROSS index decreased from 14.92 to 1.39 as the bischofite concentration increased from 0% to 40%, suggesting a more favorable ionic balance in the soil solution at high bischofite doses. This behavior has been observed in previous studies, which have demonstrated that the predominance of Ca and Mg cations, with their flocculation potential, can stabilize the soil structure (Rengasamy and Marchuk, 2011).

Table 5. Results of soluble cations, SAR, %Na, and CROSS for different bischofite concentrations.

Bischofite content	Ca (mEq/L)	Mg (mEq/L)	Na (mEq/L)	K (mEq/L)	SAR	% Na	CROSS
0%	0.50	1.50	12.39	0.16	12.39	85.15	14.92
5%	1.14	2.45	11.34	0.15	8.46	75.20	10.00
20%	6.00	7.50	4.70	0.13	1.81	25.64	2.08
40%	40.00	30.00	7.39	0.13	1.25	9.53	1.39

Figure 4 depicts a clear inverse relationship between the percentage of sodium in the solution and the total concentration of soluble cations (TDS). As the bischofite dose applied to the soil increases, the soil's dispersivity tends to decrease. According to Gallegos Fonseca et al. (2014), this type of graph provides reliable results for identifying soil dispersivity. Therefore, it can be concluded that these findings support the effectiveness of bischofite treatment in improving the chemical stability of the soil at 20% and 40% stabilizer concentrations.

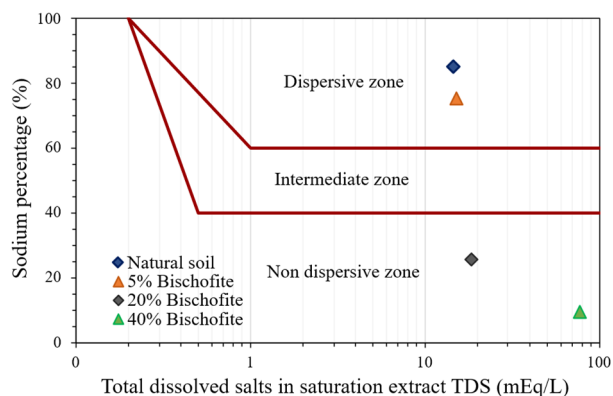


Figure 4. Soil dispersivity classification based on sodium percentage and total dissolved salts (TDS) concentration.

### 3.6 Cation Exchange Capacity (CEC) and Exchangeable Sodium (ESP)

The results, presented in Table 6, show that the Cation Exchange Capacity (CEC) progressively increased with the bischofite content in the soil. It increased from 15.39 mEq/100g in the natural soil to 43.35 mEq/100g in the 40% bischofite treatment. This increase is attributed to the incorporation of cation-rich salts, particularly Mg and Na, which reflects that the availability of exchange sites increases with higher bischofite content in the stabilizing solutions.

The Exchangeable Sodium Percentage (ESP) also showed an increase with bischofite concentration, reaching a maximum value of 13.34% for the treated soil with 20% of bischofite. However, in the 40% bischofite treatment, the ESP was 9.02%, which could be related to the different cation proportions. The high Mg concentration (30 mEq/100g) likely partially displaced sodium from the exchange sites, leading to this effect.

The ESP, calculated from the SAR values, showed a significant decrease with increasing bischofite content, from 14.54% in the untreated soil to 0.58% with 40% bischofite. This behavior is explained by the fact that the SAR (shown in Table 5) decreased drastically. Despite the increase in sodium, the considerable elevation of calcium and magnesium in the solution reduced the availability of sodium for adsorption. This information is used for classifying the soil based on the percentage of exchangeable sodium. According to Singh et al. (2018), a soil is no longer classified as dispersive when its ESP value is less than 7%. Therefore, the soil samples stabilized with 20% and 40% bischofite concentration are not considered dispersive.

Table 6. Summary of chemical test results for dispersivity assessment.

Bischofite content	Ca*	Mg *	Na *	K *	CEC *	ESP (%)	ESP ec. SAR (%)
0%	6.98	6.94	0.71	0.76	15.39	4.61	14.54
5%	7.86	6.63	1.52	1.05	17.06	8.91	10.09
20%	10.00	5.00	2.61	1.96	19.57	13.34	1.39
40%	7.50	30.00	3.91	1.94	43.35	9.02	0.58

\* Values presented in mEq/100g

## 4 CONCLUSIONS

The natural soil (0% bischofite) exhibited highly dispersive behavior with a dispersion index of 73.26% in the double hydrometer test, an ND3 classification in the Pinhole test, and a Grade 4 in the Crumb Test. The high sodium content (85.15%) and a TDS of 14.55 mEq/L demonstrate the elevated susceptibility to internal erosion in the soluble salts test. Furthermore, its high ESP of 14.54% and low CEC of 15.39 mEq/100g confirm the erosive potential of this clay. To improve the dispersivity properties of this clay, the use of bischofite at different concentrations (5%, 20%, and 40%) was evaluated. For this purpose, bischofite solutions were prepared in water, and the dose of this solution mixed with the soil was 5% of the dry weight of the samples.

The 5% bischofite treatment showed slight reductions in the plasticity limits and the dispersion index (71.56%). However, it did not achieve significant changes in the dispersivity classification according to the Pinhole test, remaining at ND3. The Crumb Test, on the other hand, showed some visual improvement in cohesion (Grade 1). The reduction of %Na and ESP in the chemical tests was limited. Consequently, the overall results indicate that this concentration is insufficient to relevantly modify the dispersive behavior.

Treating the soil with 20% bischofite produced substantial improvements, reducing the dispersion index to 47.37% and successfully classifying the soil as non-dispersive (ND1) in both the Pinhole and Crumb tests. In addition, a decrease in %Na to 25.64% and an increase in TDS (18.33 mEq/L) were recorded, which classifies this mixture as non-dispersive. The ESP of 1.39% also places the soil below the dispersivity thresholds defined in the literature.

The application of 40% bischofite achieved the best performance in the double hydrometer test, with a dispersion index of just 7.84%, and it maintained the ND1 classification in both the Pinhole and Crumb tests. Chemically, it presented the highest TDS (77.52 mEq/L) and the lowest %Na and ESP, at 9.53% and 0.58%, respectively. Despite this, the improvement compared to the 20% treatment was not proportional across all parameters.

Bischofite has proven to be an effective stabilizer for highly dispersive soils, especially at concentrations approaching 20%, where the dispersive behavior is mitigated from both a physical and chemical standpoint. Although 40% offers superior improvements, 20% represents a balance between performance and material optimization, making it the most recommended option for practical applications.

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