ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

Northeast Geosciences Journal

v. 12, nº 1 (2026)

https://doi.org/10.21680/2447-3359.2026v12n1ID41382

Effects of treatment of zinc industrial waste with chemical binders

Efeito do tratamento químico de resíduo industrial de zinco com ligantes químicos

Tennison Freire de Souza Junior[1]; Alessander Cristopher Morales Kormann[2]; Sidnei Helder Cardoso Teixeira[3]; Paulo Henrique Nogueira Metzker[4]; Marcio Rogério Jorge[5]

1 Federal University of Paraná, PPGEC/DCC, Curitiba, Paraná, Brazil. Email: tennisongeotec@gmail.com
ORCID: https://orcid.org/0009-0007-7874-0593
2 Federal University of Paraná, PPGEC/DCC, Curitiba, Paraná, Brazil. Email: acmkormann@gmail.com
ORCID: https://orcid.org/0000-0002-4512-3763
3 Federal University of Paraná, PPGEC/DCC, Curitiba, Paraná, Brazil. Email: sidnteix@outlook.com
ORCID: https://orcid.org/0000-0002-3522-1706
4 NEXA Resources, Management, Três Marias/MG, Brazil. Email: phmetzker@hotmail.com
ORCID: https://orcid.org/ 0009-0008-8622-0675
5 NEXA Resources, Management, Três Marias/MG, Brazil. Email: Marcio.jorge0071@gmail.com
ORCID: https://orcid.org/ 0009-0002-1119-2274

Abstract: The generation of industrial mining waste is an inherent outcome of the beneficiation process, requiring sustainable and cost-effective management practices in compliance with current regulations. At present, such waste may be disposed of via dams, pits, geobags, or dry stacking, depending on the specific needs and operational strategies of mining enterprises. In the case of dry stacking, a primary challenge for mining companies is securing adequate areas for drying and disposal, underscoring the potential benefits of employing chemical binders to accelerate drying and reduce contaminant levels in the waste. This study investigates the use of chemical binders to decrease drying time and examines the chemical and geomechanical behavior of compacted filtered zinc industrial waste (CFZIW) and compacted improved zinc industrial waste (CIZIW) at different curing periods (7, 28, and 120 days) through laboratory testing. The results indicate that the application of chemical binders significantly reduced both the drying time and concentrations of hazardous contaminants in zinc mining waste. However, the incorporation of binders also led to alterations in the shear strength parameters, influenced by binder content, curing duration and pH levels.
Keywords: Industrial Mining Waste; Geomechanical Behavior; Chemical Binders.

Resumo: A geração de rejeitos industriais de mineração é um resultado inerente ao processo de beneficiamento, exigindo práticas de gestão sustentáveis e economicamente viáveis em conformidade com as normas vigentes. Atualmente, tais rejeitos podem ser dispostos em barragens, cavas, geobags ou empilhamento a seco, dependendo das necessidades específicas e estratégias operacionais das empresas mineradoras. No caso do empilhamento a seco, um dos principais desafios para as mineradoras é a disponibilidade de áreas adequadas para secagem e disposição, o que ressalta os potenciais benefícios do uso de aglutinantes químicos para acelerar a secagem e reduzir os níveis de contaminantes presentes nos rejeitos. Este estudo investiga o uso de aglutinantes químicos para reduzir o tempo de secagem e analisa o comportamento químico e geomecânico do rejeito industrial de zinco filtrado e compactado (CFZIW) e do rejeito industrial de zinco melhorado e compactado (CIZIW), em diferentes períodos de cura (7, 28 e 120 dias), por meio de ensaios laboratoriais. Os resultados indicam que a aplicação de aglutinantes químicos reduziu significativamente tanto o tempo de secagem quanto as concentrações de contaminantes perigosos nos rejeitos de mineração de zinco. Entretanto, a incorporação de aglutinantes também ocasionou alterações nos parâmetros de resistência ao cisalhamento, influenciadas pelo teor de aglutinante, tempo de cura e níveis de pH.
Palavras-chave: Residuo industrial de mineração; Comportamento geomecânico; Ligantes químicos.

Received: 06/09/2025; Accepted: 28/01/2026; Published: 02/02/2026.

1. Introduction

Tailings dams remain widely used in mining operations due to their historically established role as disposal facilities and to the operational simplicity associated with material deposition. However, following the failures of the Fundão (Mariana, MG) and Córrego do Feijão (Brumadinho, MG) dams, Brazilian mining companies have increasingly adopted disposal solutions based on safer, technically robust, and economically viable methods for managing tailings and industrial waste generated during extraction and beneficiation processes. In this context, among the alternatives evaluated, the disposal of tailings or industrial waste through filtered stacking—also known as dry stacking—has become a relevant and increasingly preferred option in the mining sector, particularly after the publication of NBR 13.028 (2025).

The limited practical experience with dry stacking in Brazil, combined with the lack of a comprehensive regulatory framework specifically governing this disposal method, has led to uncertainties regarding the long-term geomechanical behavior of these engineered geomaterials. At present, some of the main standards applicable to the disposal of contaminated filtered waste in the country include NBR 10.157 (ABNT, 1987), which establishes minimum requirements for the design, implementation, and operation of hazardous waste landfills aimed at protecting surface and groundwater resources, as well as ensuring the safety of facility operators and surrounding communities. In addition, CONAMA Resolution No. 313 (2002) establishes the National Inventory of Industrial Solid Waste and provides guidelines for the generation, characterization, storage, transportation, treatment, reuse, recycling, recovery, and final disposal of industrial solid waste.

The use of quicklime to accelerate the drying process of iron mining byproducts was investigated by Rissoli et al. (2024). In a complementary manner, recent studies have shown that chemical stabilization through the addition of quicklime and/or Portland cement represents a promising approach for optimizing the disposal of industrial waste and mining tailings (Consoli et al., 2022; Consoli et al., 2023; Mafessoli et al., 2023). In this context, the present study aims to evaluate the mechanical behavior of zinc industrial waste subjected to chemical stabilization using quicklime and Portland cement, in comparison with untreated filtered waste. As discussed by Han (2015), chemical agents—also referred to as binders—can be incorporated into soils and combined with existing geomaterials to produce hardened materials, referred to as improved geomaterials, which exhibit significant increases in strength and stiffness. These agents may include lime, Portland cement, silicate-based gels, and various chemical solutions.

The stabilization effect on zinc industrial waste was assessed through laboratory testing of specimens containing 5% quicklime and 10% Portland cement, prepared at different void ratios (1.5–2.2) and cured for 7, 28, and 120 days. The results showed that the addition of these binders significantly reduced the drying time, decreased the concentrations of contaminant constituents in the industrial waste, and improved the mechanical strength parameters, including effective cohesion (c') and effective friction angle (φ').

2. Background

The use of chemical binders in mining tailings represents a promising alternative for improving their geotechnical and environmental properties. Materials such as lime (hydrated or quicklime), Portland cement, blast furnace slag, and other industrial binders can promote chemical reactions capable of reducing plasticity, increasing shear strength, decreasing permeability, accelerating drying time, and mitigating the potential for liquefaction (Kramer, 1986; Consoli et al., 2022), as well as internal and surface erosion processes. In addition, industrial tailings or waste, even after filtration, often exhibit moisture contents higher than the optimum moisture content for compaction, which requires extensive drying areas to achieve suitable compaction conditions. One effective alternative for reducing drying time is the incorporation of quicklime into the material (Rissoli et al., 2023).

Han (2015) further emphasized that, in addition to binder hydration, ion exchange reactions, and the formation of pozzolanic products, the chemical stabilization of soils with these agents involves reaction processes responsible for the generation of specific hydration products. Portland cement is composed of several compounds capable of chemically reacting with water, with calcium silicate hydrate (C–S–H) being the primary product formed from the hydration of the main constituents of ordinary Portland cement (C_3S, C_2S, C_3A, and C_4AF). During this process, calcium hydroxide ($Ca(OH)_2$) is also released, which promotes pozzolanic reactions similar to those observed in lime stabilization. The progressive formation of hydration products over time results in soil stiffening (loss of workability), setting (solidification), and hardening (strength gain).

During the zinc beneficiation process, jarosite—a sulfate-group mineral byproduct with the chemical formula $KFe_3(SO_4)_2(OH)_6$—is generated and classified as industrial waste. According to Seyer et al. (2001), jarosite precipitates formed during the leaching of zinc ferrites can be combined with predetermined proportions of Portland cement, lime, and water to produce a material known as Jarofix, which exhibits long-term chemical, physical, and environmental stability. The literature reports successful applications of Jarofix in pavement construction (Pappu et al., 2010; Sinha et al., 2012, 2018, 2019, 2022). In addition, mining companies in countries such as India, Canada, and Spain have adopted the disposal of zinc industrial waste using the Jarofix technology.

3. Methodology

3.1 Material

The materials used in this study included CP III Portland cement, in accordance with NBR 16697 (2018), industrial quicklime complying with NBR 6473 (2003), and potable water supplied by the local distribution system. The industrial waste investigated originates from a zinc production facility located in the interior of the state of Minas Gerais, Brazil. This waste, referred to as tertiary slime, consists of a mixture of three byproducts: (a) flotation tailings, with a solids content of approximately 3%; (b) underflow material with a pH of about 9 and a solids content of approximately 8%; and (c) neutralization sludge, which, after filtration, forms a belt cake with a solids content of approximately 40%.

As shown in Figure 1, the zinc industrial waste (ZIW) is predominantly composed of silt (40–60%), sand (20–40%), and a residual gravel fraction of approximately 10%, according to ASTM D7928 (2021). Based on international soil classification systems, the material was classified as MH (high-compressibility silt) under the Unified Soil Classification System (USCS), in accordance with ASTM D2487-17 (2020). Despite the significant silt fraction, the material was classified as A-7-5 according to the Highway Research Board (HRB) system, following ASTM D3282 (2024).

Atterberg limit tests performed on the zinc industrial waste samples yielded liquid limit (LL) values ranging from 59% to 62% and plasticity index (PI) values between 11% and 13%, in accordance with ASTM D4318 (2017). The specific gravity of solids ranged from 25.96 kN/m^3 to 26.43 kN/m^3, as determined following ASTM D854 (2023). The chemical composition of the tertiary slime was predominantly composed of $CaSO_4$ (47.3%), SiO_2 (27.4%), Fe_2O_3 (10.1%), $Mg_2(OH)_2SO_4$ (5.8%), and $NH_4Fe_3(SO_4)_2(OH)_6$ (3.5%), with other minor constituents present in proportions below 6%.

Compaction tests were conducted at standard Proctor energy in accordance with ASTM D698-12 (2021) for both chemically improved zinc industrial waste (CIZIW) and compacted filtered zinc industrial waste (CFZIW). The optimum moisture content (OMC) of CIZIW ranged from 57.5% to 63.4%, whereas that of CFZIW varied between 53.2% and 56.0%. As illustrated in Figure 2, the incorporation of chemical binders (CP III Portland cement and quicklime) shifted the compaction curves to the left, resulting in lower maximum dry unit weights and higher optimum moisture contents. This behavior is attributed to the fine-grained and hydrophilic nature of the chemical binders.

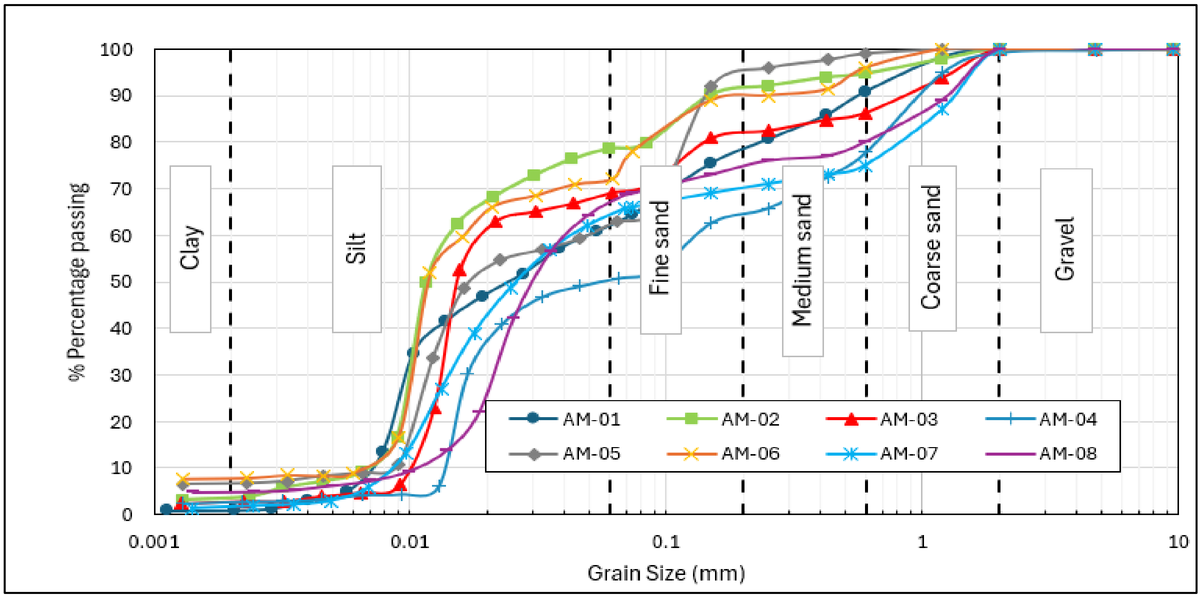


Figure 1 – Grain size distribution curves of zinc industrial waste (ZIW).
Source: Authors (2025).

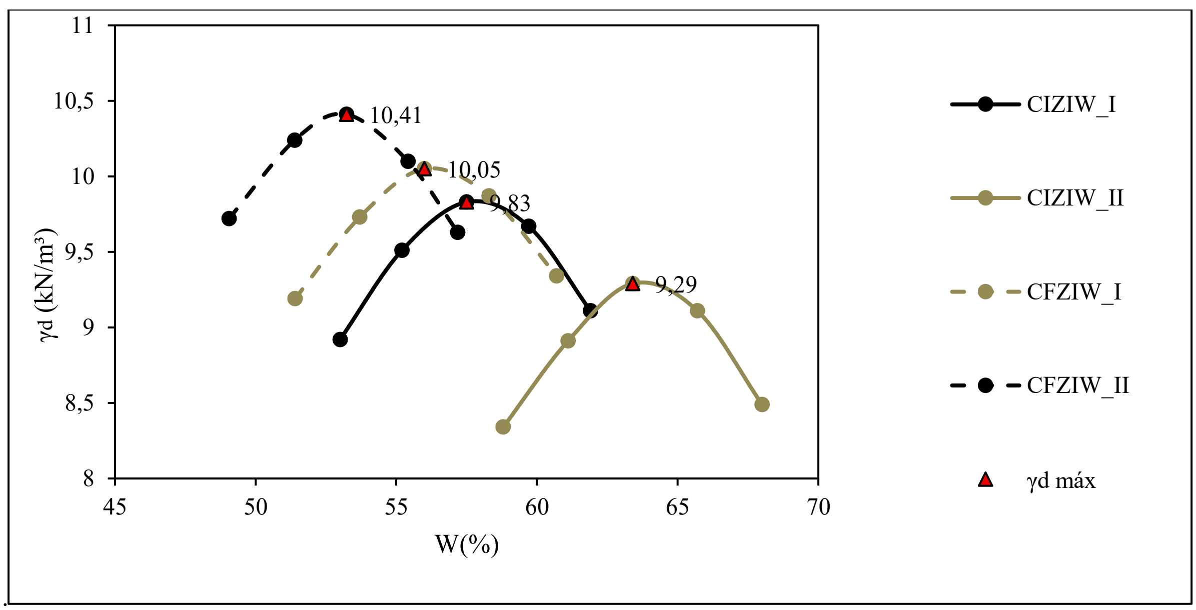


Figure 2 – Normal Proctor Compaction Curves of CIZIW and CFZIW.
Source: Authors (2025).

3.2 Methods

3.2.1 Executive Procedure for Experimental Landfills

This study aimed to investigate the geomechanical and chemical behavior of compacted filtered zinc industrial waste (CFZIW) and compacted improved zinc industrial waste (CIZIW) under different compaction efforts, resulting in distinct void ratios and a total of four analysis scenarios. The proportions of Portland cement and quicklime were defined based on an adaptation of the well-established Jarofix dosage proposed by Sinha et al. (2018), adjusted to achieve a target pH of 12.

In total, six experimental embankments (ELs) were constructed, varying according to the optimum moisture content range shown in Figure 2, void ratios, treatment type, and curing periods of 7, 28, and 120 days, as summarized in Table 1.

Table 1 – Matrix of experimental landfills.

EL	ID	e_{ave}	During period (days)	H_L (m)	W_c (%)	Material
EL_01	EL_01_120d	2.2	120	0.200	56.650	CIZIW
EL_02	EL_02_120d	1.9	12	0.200	60.830	CIZIW
EL_03	EL_03_7d	1.5	7	0.200	56.680	CIZIW
	EL_03_28d	1.5	28	0.200	56.680	CIZIW
	EL_03_120d	1.5	120	0.200	56.680	CIZIW
EL_04	EL_04_0d	1.5	0	0.200	51.690	CFZIW
EL_05	EL_05_0d	1.8	0	0.200	55.200	CFZIW
EL_06	EL_06_0d	1.7	0	0.200	55.350	CFZIW

Legend: EL = experimental landfill; e_{ave} = average void index of waste; HL = compaction layer thickness and Wc = water content.

Source: Authors (2025).

The geomaterial used in this study was obtained from a zinc beneficiation plant, where the industrial waste was dewatered using a filter press and subsequently stockpiled in a designated yard. This material is referred to as filtered zinc industrial waste (FZIW). The chemically improved zinc industrial waste (CIZIW) was produced through a treatment process similar to the Jarofix method described by Seyer et al. (2001). In this process, FZIW was initially mixed with lime milk (a suspension of water and quicklime) and homogenized using industrial mixers. Subsequently, Portland cement was sprayed onto the pretreated FZIW, and the mixture was homogenized again using industrial mixers installed on conveyor belts in a dedicated treatment area.

After filtration, the moisture content of the material produced at the beneficiation plant was higher than the target moisture content required for compaction, making moisture reduction necessary prior to disposal. Therefore, before placement and compaction of both CIZIW and FZIW, the materials were temporarily stockpiled in a designated area beneath an inflatable tent and monitored daily until suitable compaction conditions were achieved. The inflatable tent was maintained by high-capacity ventilation systems and was designed to control moisture conditions and prevent additional wetting of the materials due to rainfall.

Both materials were collected using a hydraulic excavator and transported to the experimental embankment construction area by dump trucks. The construction of the experimental embankments followed conventional earthwork practices, employing hydraulic excavators, water trucks, motor graders, crawler tractors equipped with leveling attachments, and tamper-type compactors. The inflatable tent consisted of a large-span structure supported by high-capacity ventilation and exhaust systems, designed to control the moisture conditions of both CFZIW and CIZIW and to prevent moisture increases caused by precipitation. Figure 3 illustrates the execution of the layers in the experimental embankments.

(a) *(b)*

Figure 3 – Construction of experimental landfills using earthmoving equipment: (a) layer spreading; (b) layer compaction.
Source: Authors (2025).

Upon completion of the construction of the experimental embankments (4.00 m × 10.00 m), a waiting period of 24 hours was observed prior to the collection of disturbed and undisturbed samples. In the central region of each experimental embankment, excavations were carried out to extract undisturbed blocks measuring 30 cm × 30 cm × 30 cm, as well as disturbed samples collected in 25 kg bags from the compacted layers of filtered and treated zinc industrial waste. The undisturbed samples were carefully trimmed, wrapped with smooth PVC film, covered with white cotton fabric, and placed inside wooden boxes to ensure protection during transportation and storage. Subsequently, the samples were stored in a curing chamber maintained at a temperature of 23 °C ± 2 °C and a minimum relative humidity of 95%, in order to provide adequate curing conditions for the development of the study, in accordance with ASTM C511 (2021).

3.2.2 Chemical Analyses - Leaching and Solubilization

The characterization of the industrial waste was performed through tests on undisturbed samples, leachate extracts, and solubilized extracts, and the classification was conducted in accordance with NBR 10004 (ABNT, 2004), based on the data presented in Table 2. Representative samples were collected following the procedures established in NBR 10007 (ABNT, 2004) to ensure the reliability of the leaching and solubilization test results. The environmental and public health risk classification of compacted improved zinc industrial waste (CIZIW) and compacted filtered zinc industrial waste (CFZIW) was also carried out in accordance with NBR 10004 (ABNT, 2004). The determination of water-soluble substances, such as heavy metals, in CIZIW and CFZIW was performed according to the procedures outlined in NBR 10005 (ABNT, 2004). In addition, the potential for contaminant release under acidic conditions—unlike the leaching test, which is conducted under neutral conditions—was assessed following NBR 10006 (ABNT, 2004).

3.2.3 Drying time

The drying time evaluation consisted of determining the period required for the materials to reach the target moisture contents, W (%), presented in Table 2. For this purpose, the moisture contents of compacted improved zinc industrial waste (CIZIW) and compacted filtered zinc industrial waste (CFZIW) were monitored using moisture content tests conducted in accordance with ASTM D2216-19 (ASTM, 2019) at a controlled temperature of 50 °C. Owing to the high concentrations of sulfates and ettringite present in the material, temperatures exceeding 50 °C could induce degradation processes (Alonso and Fernández, 2004).

3.2.4 Shear strength analyses – CIU triaxial tests

The CIU (Consolidated Undrained) triaxial tests were conducted in accordance with ASTM D4767-11 (ASTM, 2020). Cylindrical specimens were trimmed from undisturbed blocks to standard dimensions of 50 mm × 100 mm (H/D = 2.0).

Following trimming, the specimens were placed in the triaxial apparatus and subjected to back-pressure saturation at 500 kPa until a minimum B-value of 0.95 was achieved. The testing conditions adopted for the CIU triaxial tests performed on undisturbed samples obtained from the experimental embankments are summarized in Table 2.

The curing time of the CIZIW samples was defined as the period between the construction of the experimental embankments and the initiation of the CIU triaxial tests. This procedure was adopted to avoid curing under confining stress, as highlighted by Rotta et al. (2003).

Table 2 – Test conditions for CIU triaxial tests on experimental landfills.

EL	e_{ave}	W_t (%)	p'0 (kPa)
EL_01_120d	2.2	53.75	100, 400, 700 and 1000
EL_02_120d	1.9	56.17	100, 400, 700 and 1000
EL_03_7d	1.5	48.64	100, 400, 700 and 1000
EL_03_28d	1.5	49.53	100, 400, 700 and 1000
EL_03_120d	1.5	49.00	100, 400, 700 and 1000
EL_04_0d	1.5	44.54	100, 400, 700 and 1000
EL_05_0d	1.8	46.91	100, 400, 700 and 1000
EL_06_0d*	1.7	63.80	250, 500, 750 and 1000

Source: Authors (2025).

4. Results and Discussions

4.1 Chemical analysis of industrial waste - Leachates and solubilized samples

The leaching test was performed in accordance with NBR 10005 (ABNT, 2004), in which a 100 g sample was placed in contact with 2000 mL of Solution 1 for 18 ± 2 h at a temperature of 23 ± 2 °C. This test evaluates the transfer potential of organic and inorganic substances present in solid waste through dissolution in the extracting medium.

According to NBR 10006 (ABNT, 2004), solubilization is defined as the process by which a substance—typically in the solid state—dissolves in a solvent to form a homogeneous solution. This process involves interactions between solute and solvent particles, allowing the solute to disperse uniformly within the solvent and resulting in a single-phase mixture. The solubilization test was performed by placing a 250 g sample in contact with 1000 mL of deionized water for a period of 7 days at a temperature of 23 ± 2 °C.

Tables 3 to 8 present the results for substances whose concentrations in the solubilization and leaching tests exceeded the maximum permitted values (MPV) established by Brazilian regulations. The initial analysis of the compacted filtered zinc industrial waste indicated that the concentrations of aluminum, arsenic, cadmium, lead, manganese, and sulfates exceeded the MPV. Notably, sulfate concentrations in samples EL_04, EL_05, and EL_06 substantially surpassed the limits established by NBR 10006 (ABNT, 2004), reaching values between 3905.9 mg/L and 6574.3 mg/L. The pH values of these samples ranged from 6.18 to 7.23, indicating conditions from slightly acidic to slightly alkaline, as shown in

Table *3*.

According to NBR 10005 (ABNT, 2004), leachates are liquids generated by the percolation or passage of water (or other liquids) through industrial waste. During this process, chemical compounds are extracted by a solvent—whether acidic, basic, or neutral—that exhibits affinity for the constituents being removed. As shown in Table 3, cadmium and lead concentrations in the experimental embankments EL_04, EL_05, and EL_06 exceeded the maximum permitted values (MPV) by approximately 20 times.

Table 3 – Chemical analysis of solubilization parameters for CFZIW — EL_04, EL_05, and EL_06.

Parameters	**MPV (mg/L)**	**CFZIW**		
		EL_04 (pH=7.23)	**EL_05 (pH=6.18)**	**EL_06 (pH=6.55)**
Aluminum	0.200	0.272	0.319	0.326
Arsenic	0.010	0.024	0.019	0.015
Cadmium	0.005	0.279	0.368	0.347
Lead	0.010	0.021	-	0.009
Manganese	0.100	8.233	14.516	12.904
Sulfate	250.000	6574.300	3905.900	4257.600

Source: Authors (2025).

Table 4 – Chemical analysis of leaching parameters for CFZIW — EL_04, EL_05, and EL_06

Parameters	**MPV (mg/L)**	**CFZIW**		
		EL_04 (pH=5.72)	**EL_05 (pH=5.41)**	**EL_06 (pH=5.38)**
Cadmium	0.500	4.049	4.356	4.781
Lead	1.000	15.106	22.367	26.668

Source: Authors (2025).

When comparing EL_01 and EL_02 with EL_04, EL_05, and EL_06, it is evident that compacted improved zinc industrial waste (CIZIW) exhibited lower solubilized concentrations of cadmium, lead, and manganese, reducing these values to below the maximum permitted value (MPV) thresholds. Sulfate concentrations decreased by more than 50%; however, they remained above the MPV. In addition, as shown in Table 4, a marked increase in pH was observed, reaching values of 7.87 and 8.87, which imparted an alkaline character to the zinc industrial waste.

Alkalinity promotes the chemical stability of hydrated phases such as C–S–H and $Ca(OH)_2$, reducing the likelihood of their dissolution while preserving mechanical integrity and structural durability. In addition, alkaline conditions facilitate chemical neutralization and enhance the immobilization of heavy metals. With respect to the leached constituents (see Table 6), only cadmium exceeded the maximum permitted value (MPV) under slightly alkaline conditions (pH just above 7), suggesting increased contaminant retention associated with the solubilization process. The slight increase in aluminum concentration may be attributed to the presence of C_3A in the Portland cement clinker composition.

Table 5 – Chemical analysis of solubilization parameters for CIZIW — EL_01 and EL_02

Parameters	**MPV (mg/L)**	**CIZIW - 120 days**	
		EL_01 (pH = 7.87)	**EL_02 (pH =8.87)**
Aluminum	0.200	0.302	0.414
Arsenic	0.010	0.0670	0.073
Nitrate	10.000	34.170	19.450
Sulfate	250.000	703.000	1379.700

Source: Authors (2025).

Table 6 – Chemical analysis of the leaching parameters of CIZIW – EL_01 and EL_02

Parameters	**MPV (mg/L)**	**CIZIW - 120 days**	
		EL_01 (pH = 7.02)	**EL_02 (pH =7.11)**
Cadmium	0.500	-	0.726

Source: Authors (2025).

It is noteworthy that, although Portland cement was incorporated primarily to enhance mechanical strength, the curing time analysis revealed an increase in sulfate concentrations with extended curing durations (see Table 7). This behavior may indicate some degree of sample heterogeneity or the formation of ettringite under later-stage alkaline conditions (pH > 7).

Tables 7 and 8 indicate that, over the curing period, no significant changes occurred in the solubilization and leaching parameters of the improved zinc industrial waste. When the EL_03 samples at different curing times are compared with samples EL_01 and EL_02, a marked reduction in the solubilized concentrations of cadmium, manganese, and sulfates relative to the maximum permitted values (MPV) is again observed, likely as a result of contaminant neutralization associated with increased alkalinity. In addition, the presence of residual components such as sodium and nitrate was detected in the improved zinc industrial waste, probably due to the incorporation of Portland cement.

Table 7 – Chemical analysis of the solubilization parameters of CFZIW – EL_03.

Parameters	MPV (mg/L)	EL_03 - CIZIW		
		7 days (pH = 8.18)	28 days (pH =7.13)	120 days (pH =8.19)
Aluminum	0.200	0.4507	0.352	0.943
Arsenic	0.010	0.044	0.101	0.122
Cadmium	0.005	-	-	-
Lead	0.010	-	-	0.034
Manganese	0.100	-	-	0.192
Nitrate	10.000	19.760	20.460	-
Sodium	200.000	-	-	209.660
Sulfate	250.000	1525.800	1696.700	1944.200

Source: Authors (2025).

Table 8 – Chemical analysis of the leaching parameters of CFZIW – EL_03.

Parameters	MPV (mg/L)	EL_03 - CIZIW		
		7 days (pH =7.26)	28 days (pH = 7.1)	120 days (pH =6.73)
Cadmium	0.500	0.762	1.224	1.536
Lead	1.000	-	1.246	1.939

Source: Authors (2025).

Based on current standards, the studies conducted on filtered industrial waste and on waste treated with lime and Portland cement revealed that the leachate and solubilized extracts contained levels of cadmium, lead, and sulfates exceeding the established limits, thereby classifying the material as Class I — Hazardous Waste, according to NBR 10.004 (ABNT, 2004). Although the addition of quicklime interacted with free contaminants and consequently reduced their concentrations over the curing period due to an encapsulation effect, the 5% dosage was insufficient to bring these levels down to safe disposal thresholds.

4.2 Drying time of CIZIW and CFZIW

Figure 4 illustrates the total drying time of the materials comprising compacted improved zinc industrial waste (CIZIW) and compacted filtered zinc industrial waste (CFZIW). Under the exposure and climatic conditions prevailing during the study, the CIZIW materials reached the target moisture content (Wc) in a shorter time than the CFZIW materials. Excluding sample EL_01, which exhibited an atypically short drying time compared with the other samples, the incorporation of chemical binders generally resulted in an approximate 40% reduction in the drying time of zinc industrial waste.

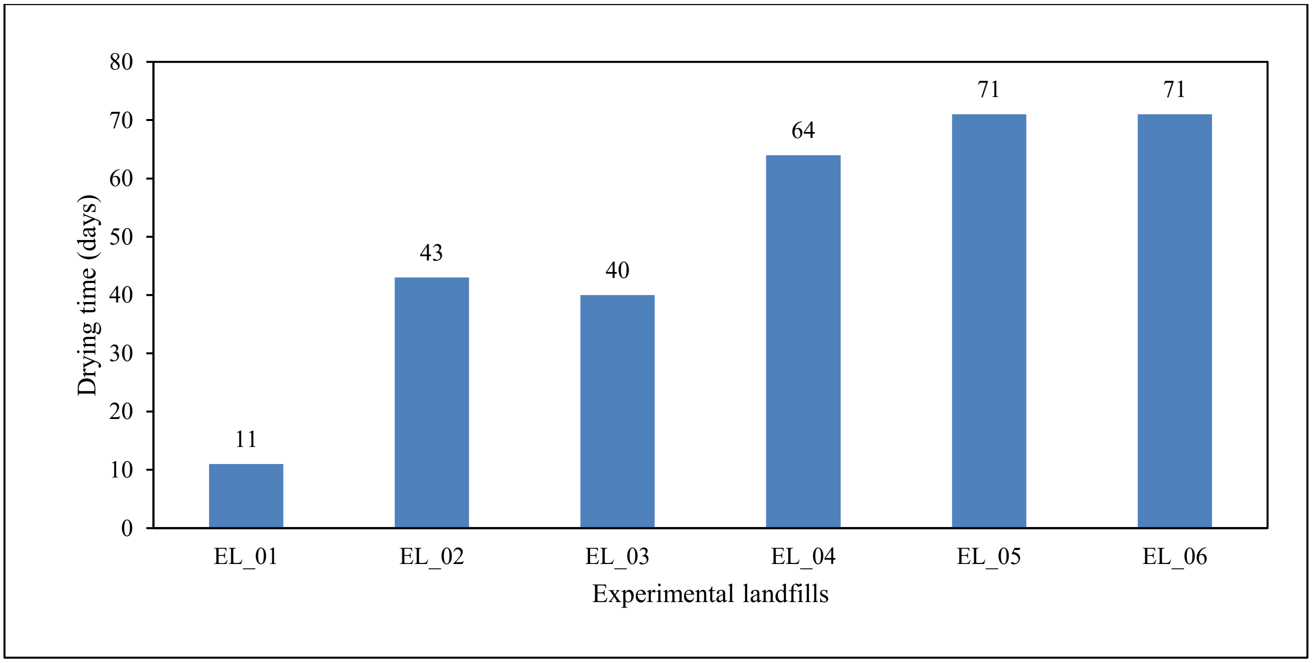
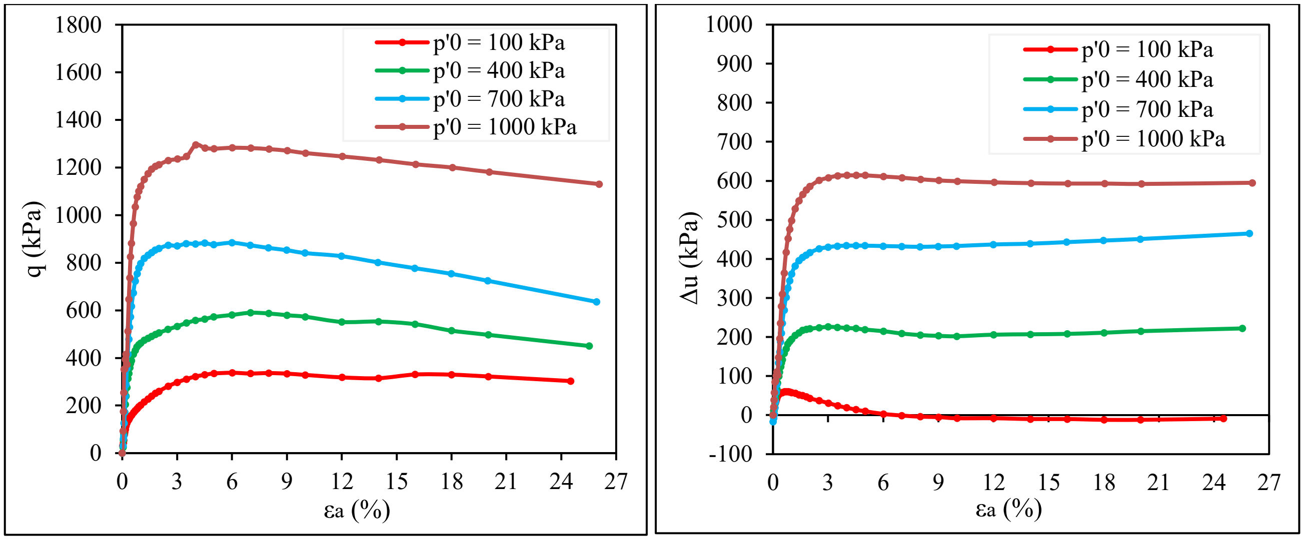


Figure 4 – Evaluation of the drying time of CIZIW and CFZIW.
Source: Authors (2025).

The chemical binders absorbed and hydrated upon contact with the excess water present in the post-filtration zinc industrial waste, while simultaneously promoting water evaporation through the exothermic reactions associated with the hydration of Portland cement and quicklime, as described by Ingles and Metcalf (1973). Although this approach may increase the disposal costs of zinc industrial waste, the results demonstrate that the use of chemical binders is effective in accelerating the drying process.

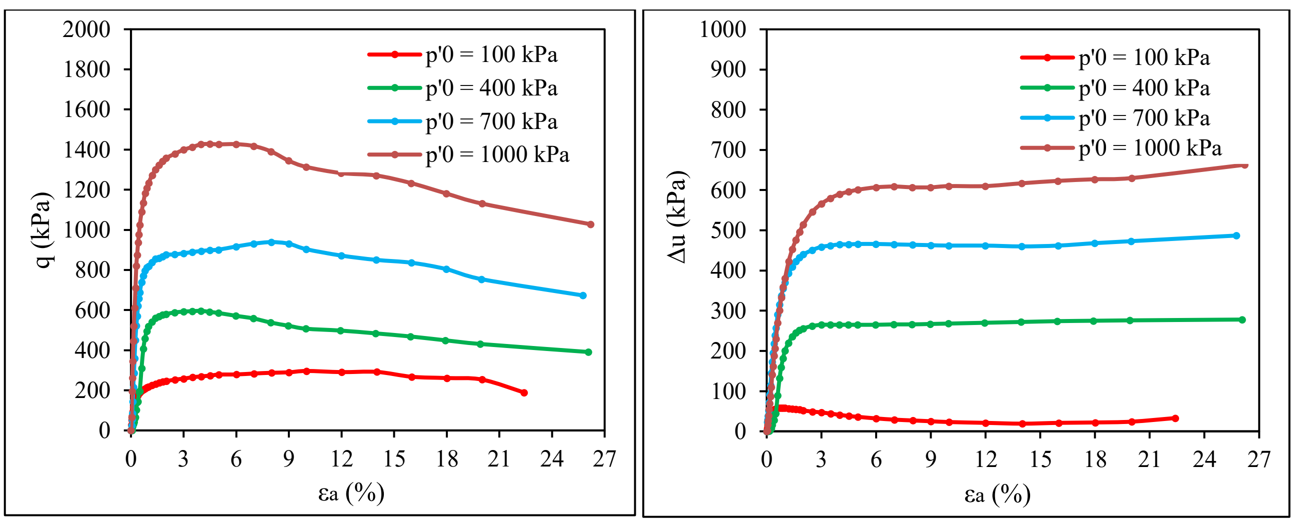
4.3 Shear Strength Analysis — CIU Triaxial Tests

In this section, Figures 6 to 13 present the results of the CIU triaxial tests (see Table 1) in the form of deviatoric stress versus axial strain and excess pore pressure versus axial strain plots. It can be observed that, except for some cases at an initial effective confining pressure of p'_0 = 100 kPa, both the filtered and the chemically improved zinc industrial waste exhibited predominantly contractive behavior ($\Delta u > 0$). The residual amount of chemical binders, combined with insufficient compaction, was not sufficient to induce dilative behavior in the samples. This behavior is likely associated with a loss of interparticle bonding resulting from the hydration of Portland cement.



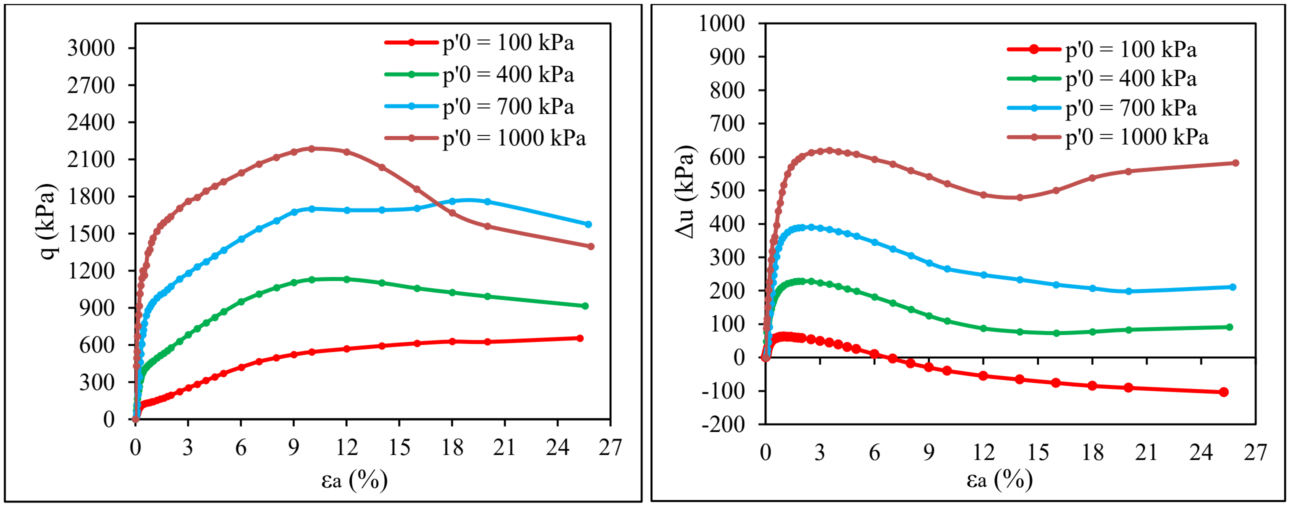
(a) *(b)*

Figure 5 – CIU triaxial tests - EL_01: (a) deviatoric stress vs. axial strain; (b) excess pore pressure vs. axial strain. Source: Authors (2025).



(a) *(b)*

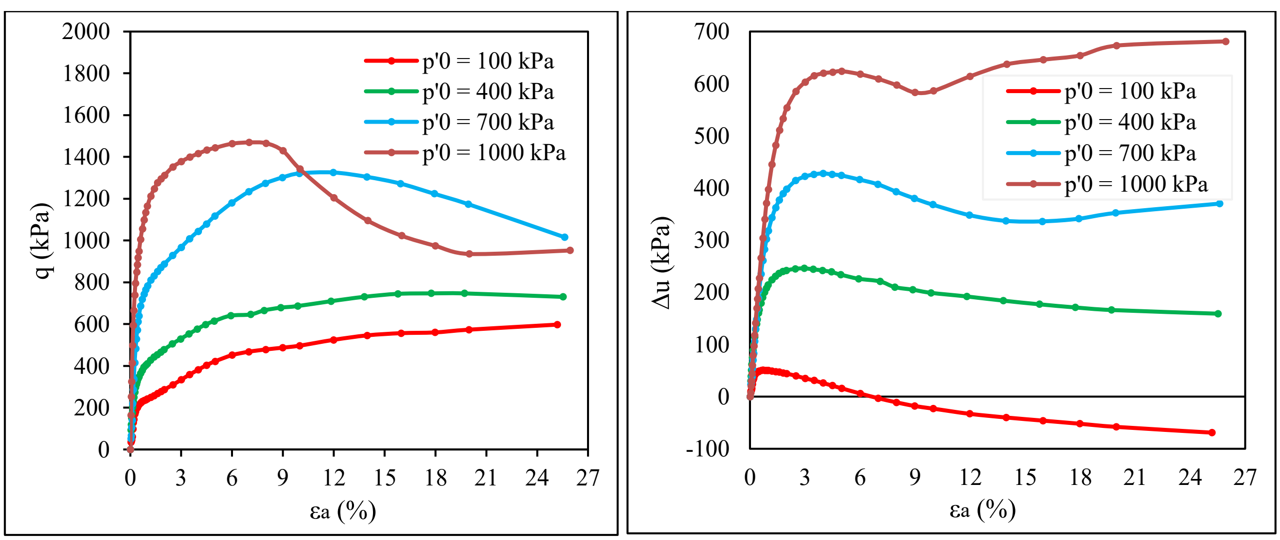
Figure 6 – CIU triaxial tests - EL_02: (a) deviatoric stress vs. axial strain; (b) excess pore pressure vs. axial strain. Source: Authors (2025).



(a) *(b)*

Figure 7 – CIU triaxial tests - EL_03_7d: (a) deviatoric stress vs. axial strain; (b) excess pore pressure vs. axial strain. Source: Authors (2025).

It is also observed that, in general, the CIU triaxial tests showed an increase in sample stiffness with increasing confining stress, regardless of the presence of chemical binders. Owing to the low degree of cementation of the materials, the applied confining stresses were likely insufficient to break the chemical bonds in the case of compacted improved zinc industrial waste (CIZIW). Consequently, the increase in confining stress resulted in higher shear strength and greater stiffness for both CIZIW and compacted filtered zinc industrial waste (CFZIW) samples.



(a) *(b)*

Figure 8 – CIU triaxial tests - EL_03_28d: (a) deviatoric stress vs. axial strain; (b) excess pore pressure vs. axial strain. Source: Authors (2025).

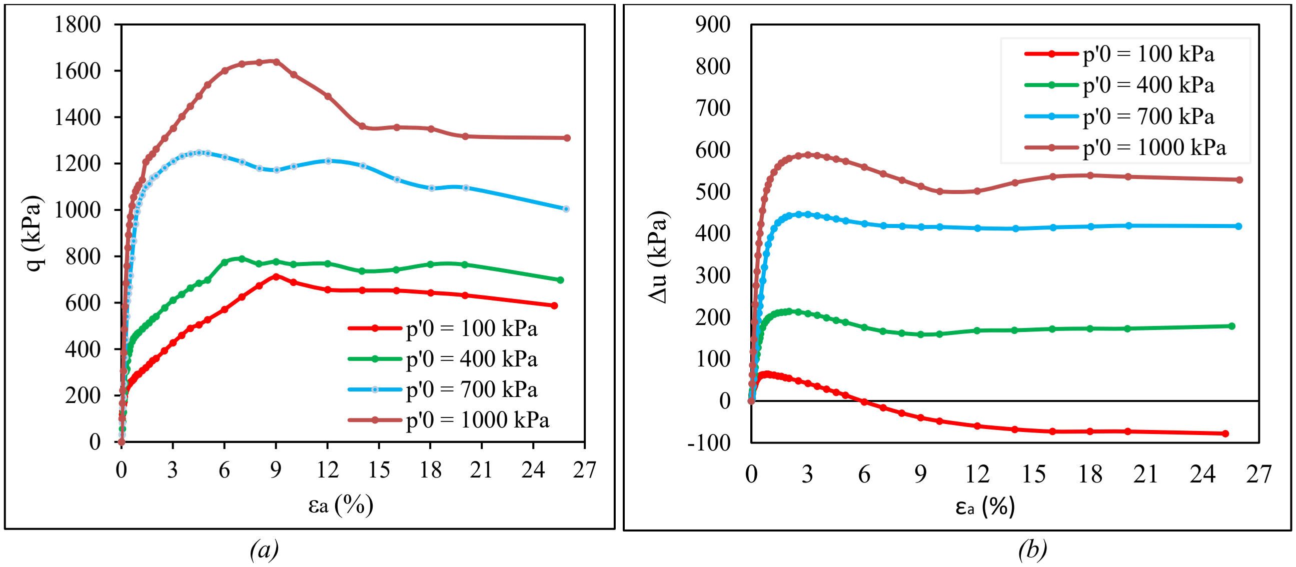


Figure 9 – CIU triaxial tests - EL_03_120d: (a) deviatoric stress vs. axial strain; (b) excess pore pressure vs. axial strain.

Source: Authors (2025).

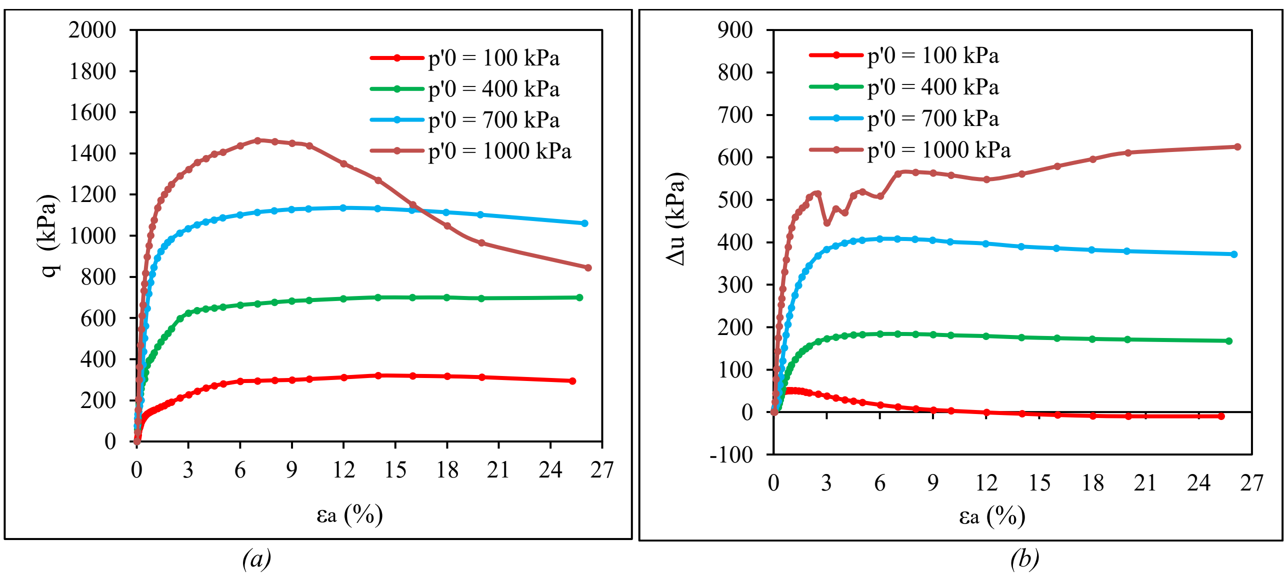
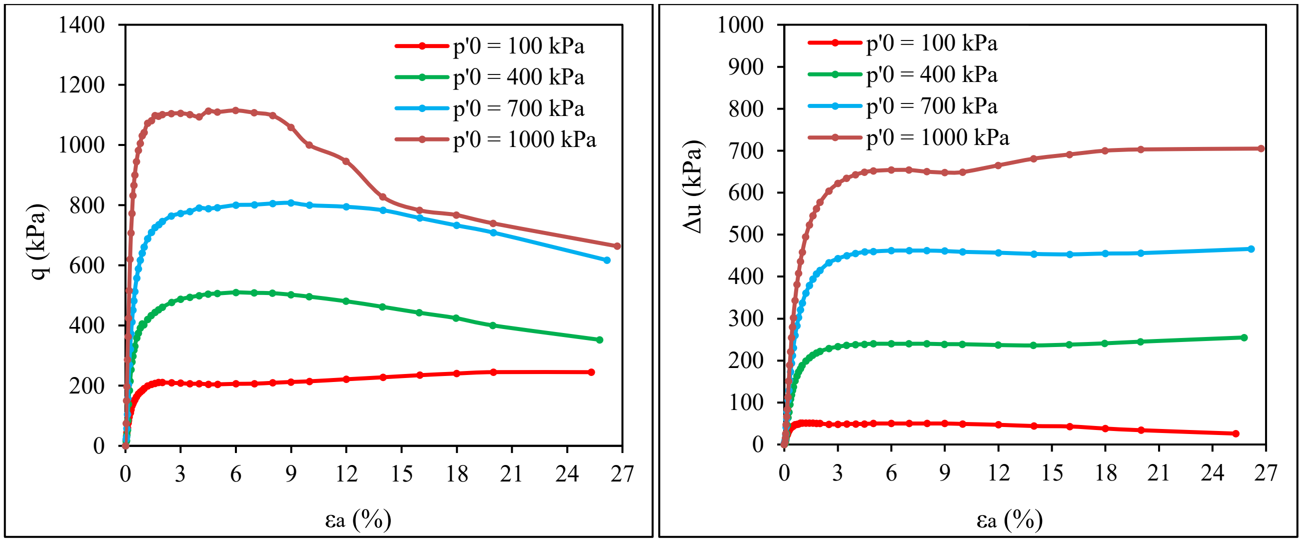


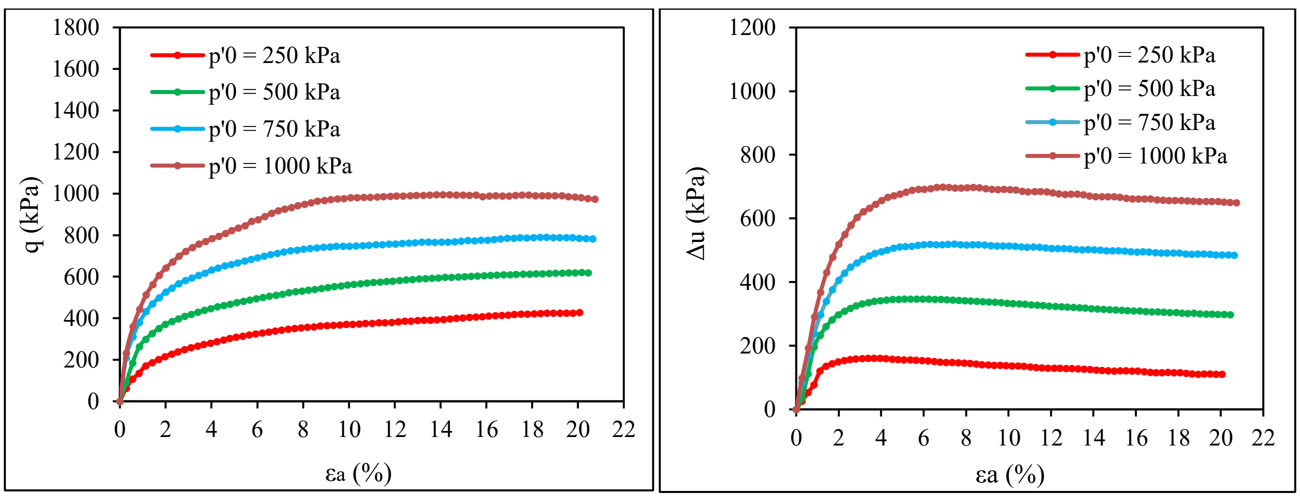
Figure 10 – CIU triaxial tests - EL_04_0d: (a) deviatoric stress vs. axial strain; (b) excess pore pressure vs. axial strain.

Source: Authors (2025).



(a) *(b)*

Figure 11 – CIU triaxial tests - EL_05_0d: (a) deviatoric stress vs. axial strain; (b) excess pore pressure vs. axial strain. Source: Authors (2025).



(a) *(b)*

Figure 12 – CIU triaxial tests - EL_06_0d: (a) deviatoric stress vs. axial strain; (b) excess pore pressure vs. axial strain. Source: Authors (2025).

Figure 13 illustrates the behavior of compacted improved zinc industrial waste (CIZIW) under different average void ratio conditions after 120 days of curing. As shown, the shear strength parameters increased with decreasing void ratio, with the effective friction angle rising from 38.79° to 41.51° as the void ratio decreased from 2.2 to 1.5. This reduction in void ratio led to a decrease in air volume and a corresponding increase in intergranular contact, thereby enhancing shear resistance (Lambe and Whitman, 1969; Ingles and Metcalf, 1973).

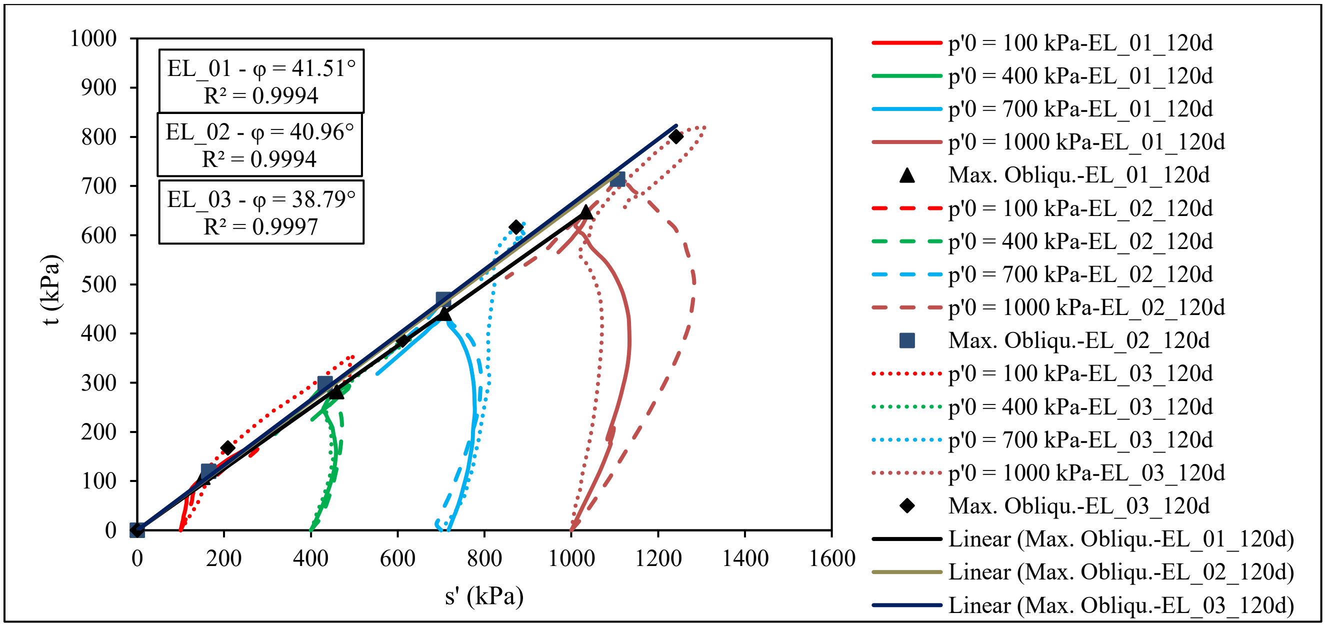


Figure 13 – Comparison of stress path graphs for different void ratios in CIZIW.
Source: Authors (2025).

A similar behavior was observed for compacted filtered zinc industrial waste (CFZIW), as shown in Figure 14, which presents the stress path plots for different void ratios. The effective friction angle of CFZIW varied within a relatively narrow range (approximately 1.2°) as a function of the void ratio. It is also noteworthy that the shear strength parameters of samples EL_05 and EL_06 exhibited a high degree of repeatability, even under different initial effective confining pressures (p'_0), which suggests a certain level of homogeneity among the analyzed samples.

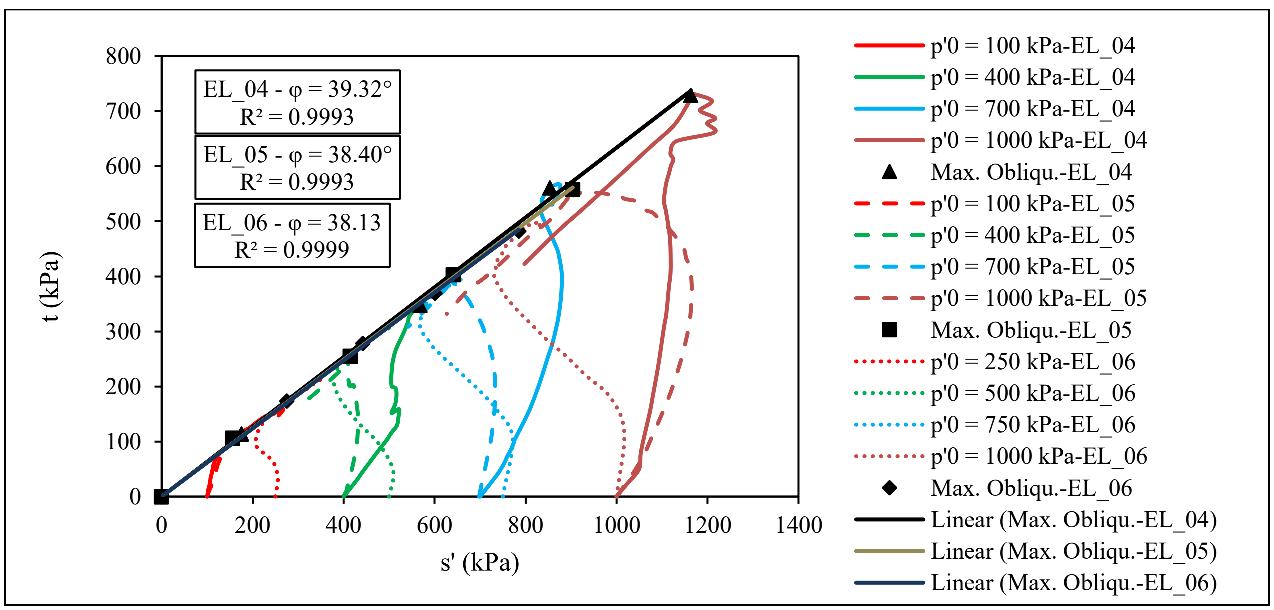


Figure 14 – Comparison of stress path graphs for different void ratios in CFZIW.
Source: Authors (2025).

Figure 15 illustrates the effect of curing time on the mechanical behavior of compacted improved zinc industrial waste (CIZIW). In theory, extended curing periods promote increases in mechanical strength due to the formation of stable hydrated compounds associated with the chemical binders, as reported by Ingles and Metcalf (1975), Carvalho et al. (2023), Mafessoli et al. (2023), and Consoli et al. (2022).

However, the shear strength parameters were observed to decrease with increasing curing time, suggesting the possibility of chemical degradation associated with the sulfate concentration in the material. According to Dermatas (1995), the detrimental effects of sulfate ions on the strength of cement- or lime-stabilized soils had already been demonstrated by Mehta et al. (1955) and Sherwood (1962). These studies reported losses in strength and material disintegration when cement-stabilized soils were immersed in sulfate solutions or when sulfate-rich soils stabilized with Portland cement were submerged in water.

When comparing sulfate attack in soil–cement systems with that in concrete, Gordon (1962), as cited by Dermatas (1995), suggested that differences in reaction kinetics may be associated with the density of the soil–cement matrix. The lower density of soil–cement allows sulfate solutions or water to diffuse more readily than in concrete. As discussed in Section 4.1, even after chemical improvement, sulfate concentrations in sample EL_03 remained elevated, ranging from approximately 1600 mg/L to 2000 mg/L.

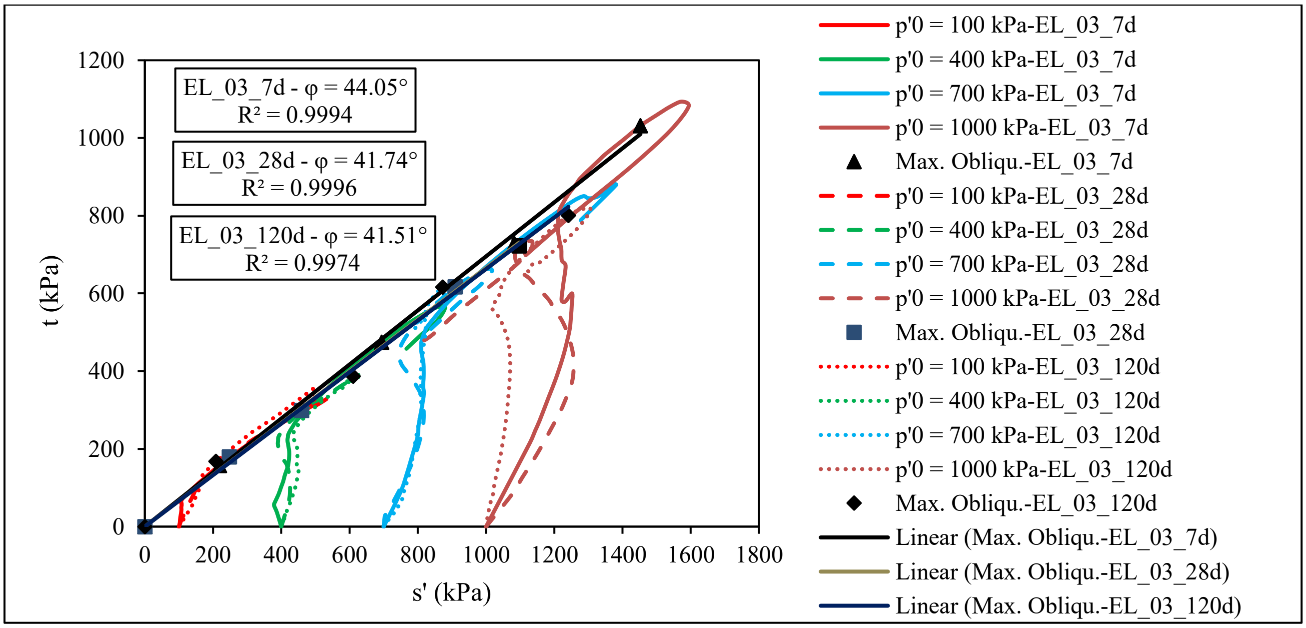


Figure 15 – Comparison of stress path graphs for different Curing time in CIZIW.
Source: Authors (2025).

5. Final Considerations

This study aimed to analyze the behavior of compacted improved zinc industrial waste (CIZIW) and compacted filtered zinc industrial waste (CFZIW), comparing the effects of chemical binder incorporation (CP III Portland cement and quicklime), void ratio, and curing time. Based on the experimental program conducted using samples collected from experimental embankments, the following conclusions can be drawn:

The incorporation of chemical binders reduced the drying time of zinc industrial waste. This behavior is attributed to the hydration of both quicklime and Portland cement, which convert free water into bound water through the formation of stable compounds. In addition, the exothermic hydration reactions of these binders increase the temperature, thereby promoting the evaporation of part of the free water. Overall, the use of chemical binders resulted in an approximately 40% reduction in the drying time of zinc industrial waste.

The adoption of inflatable tents as a strategy for moisture protection and material control during rainy periods proved to be effective. However, these structures were observed to maintain elevated relative air humidity, which partially hindered the evaporative drying of the material. Consequently, the use of this approach requires careful evaluation when applied to waste disposal and/or mining tailings management processes;

The chemical binders effectively reduced the concentrations of certain contaminants, including cadmium, lead, and manganese, to levels below the maximum permitted values (MPV). This reduction is likely attributable to an encapsulation effect resulting from the combined action of quicklime and Portland cement, as well as to the increase in pH, which created an alkaline environment (pH > 7);

Although the chemical modifications did not alter the hazard classification of the zinc industrial waste under NBR 10.004 (ABNT, 2004), they significantly reduced the concentrations of hazardous contaminants, which is beneficial for minimizing the contamination potential of industrial waste disposal structures;

The CIU triaxial tests showed that both compacted improved zinc industrial waste (CIZIW) and compacted filtered zinc industrial waste (CFZIW) samples exhibited volumetric behavior characterized by a contractive tendency, as indicated by the generation of excess positive pore pressure. This behavior may be associated with the high fines content of the material, which was not fully cemented and relied primarily on intergranular friction. In addition, the stiffness of both materials increased with increasing confining stress (p'_0);

The compacted improved zinc industrial waste (CIZIW) exhibited higher shear strength than the compacted filtered zinc industrial waste (CFZIW). Although the incorporation of chemical binders contributed to faster drying and increased the fines content of the mixture, it also likely promoted the formation of stable hydrated compounds under residual conditions after compaction. The CFZIW exhibited effective friction angles ranging between 38° and 39°, whereas the CIZIW displayed effective friction angles between 38.8° and 44.1°, depending on the void ratio, curing time, and pH.

Acknowledgements

The authors express their gratitude to CNPq (National Council for Scientific and Technological Development) and CAPES (Coordination for the Improvement of Higher Education Personnel) for supporting research in Brazil.

References

ABNT. NBR 6473: Cal virgem e cal hidratada. Rio de Janeiro, 2003.
ABNT. NBR 10004: Resíduos Sólidos – Classificação. Rio de Janeiro, 2004.
ABNT. NBR 10005: Lixiviação de resíduos – Procedimento. Rio de Janeiro, 2004.
ABNT. NBR 10006: Solubilização de resíduos – Procedimento. Rio de Janeiro, 2004.
ABNT. NBR 10007: Amostragem de resíduos sólidos – Procedimento. Rio de Janeiro, 2004.
ABNT. NBR 10157: Aterros de resíduos perigosos – Critérios para projeto, construção e operação. Rio de Janeiro, 1987.

ABNT. NBR 13028: Elaboração e apresentação de projeto de barragens para disposição de rejeitos, contenção de sedimentos e reservação de água – Requisitos. Rio de Janeiro, 2025
ABNT. NBR 16697: Cimento Portland – Requisitos. Rio de Janeiro, 2018.

ALONSO, C.; FERNANDEZ, L. Dehydration and rehydration processes of cement paste exposed to high temperature environments. *Journal of Materials Science*, v. 39, p. 3015-3024, 2004.

ASTM. C511: Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes. West Conshohocken, 2021.
ASTM. D698-12: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³)). West Conshohocken, 2021.
ASTM. D854: Standard Test Methods for Specific Gravity of Soil Solids by the Water Displacement Method. West Conshohocken, 2014.
ASTM. D2216-19: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. West Conshohocken, 2019.
ASTM. D2487-18: Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). West Conshohocken, 2020.
ASTM. D3282: Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes. West Conshohocken, 2024.

ASTM. D4318-17e1: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. West Conshohocken, 2017.

ASTM. D4767-11: Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils. West Conshohocken, 2020.

CARVALHO, J. V. de A. et al. Evaluation of Strength Parameters for Application in Cemented Iron Ore Tailings Stacks. *Soils and Rocks*, v. 53, p. 775-788, 2023.

CHEN, T. T.; DUTRIZAC, J. E. A mineralogical study of jarofix products for the stabilization of jarosite for disposal. *Journal of The Minerals, Metals & Materials Society*, p. 917–933, 2000.

CONAMA. Resolução nº 313: Dispõe sobre o Inventário Nacional de Resíduos Sólidos Industriais. Brasília, 2002.

CONSOLI, N. C. et al. Behaviour of compacted filtered iron ore tailings–Portland cement blends: New Brazilian trend for tailings disposal by stacking. *Applied Sciences*, v. 12, p. 1-18, 2022.

CONSOLI, N. C.; TOMASI, L. F.; MARQUES, S. F. V. Cement-enhancing mechanical behavior of tailings behind upstream tailings dam for safe decommissioning. *Journal of Materials in Civil Engineering*, v. 35, n. 5, 2023.

CRAIG, R. F. Craig's Soil Mechanics. 7. ed. London; New York: Spon Press, 2004. 447 p.

DERMATAS, D. Ettringite-Induced Swelling in Soils: State-of-the-Art. *Applied Mechanics Reviews*, v. 48, n. 10, p. 659–673, 1995.

HAN, J. Principles and Practice of Ground Improvement. New York: John Wiley and Sons, 2015. 418 p.

INGLES, O. G.; METCALF, J. B. Soil Stabilization: Principle and Practice. New York: John Wiley and Sons, 1973. 373 p.

KRAMER, S. L. Geotechnical Earthquake Engineering. Upper Saddle River: Prentice Hall, 1996. 672 p.

LAMBE, W. T.; WITHMANN, R. V. Soil Mechanics. New York: John Wiley and Sons, 1969. 548 p.

MAFESSOLI, M. et al. Response of Artificially Cemented Iron Ore Tailings for Dry Stacking Disposal over a Wide Range of Stresses. *Indian Geotechnical Journal*, v. 53, p. 904–915, 2023.

MEHTA, S. R.; CHADDA, L. R.; KAPUR, R. N. Role of detrimental salts in soil stabilization with and without cement: Effect of sodium sulphate. *Indian Concrete Journal*, v. 33, n. 7, p. 336-337, 1955.

PAPPU, A.; MOHINI, S.; SHYAM, R. A. Recycling hazardous jarosite waste using coal combustion residues. *Materials Characterization*, v. 61, n. 12, p. 1342–1355, 2010.

RISSOLI, A. L. C. et al. Dry Stacking of Filtered Iron Ore Tailings: Comparing On-Field Performance of Two Drying Methods. *Geotechnical and Geological Engineering*, v. 42, p. 2937–2948, 2023.

ROTTA, G. V. et al. Isotropic yielding in an artificially cemented soil cured under stress. *Géotechnique*, v. 53, n. 5, p. 493-501, 2003.

SEYER, S.; CHEN, T. T.; DUTRIZAC, J. E. Jarofix: addressing iron disposal in the zinc industry. *Journal of Mineralogy*, v. 53, n. 12, p. 32–35, 2001.

SHERWOOD, P. T. Effect of sulfates on cement-and lime-stabilized soils. *Highway Research Board Bulletin*, n. 353, 1962.

SINHA, A. K.; HAVANAGI, V. G.; MATHUR, S. Design, construction and evaluation of jarofix embankment and sub grade layers. *International Journal of Environment Engineering Research*, v. 1, n. 3, p. 97–103, 2012.

SINHA, A. K.; HAVANAGI, V. G.; SHAHU, J. T. Characterisation of jarofix for use in geotechnical projects. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering*, v. 171, n. 5, p. 439–450, 2018.

SINHA, A. K.; HAVANAGI, V. G.; SHAHU, J. T. Stabilised jarofix waste material for road construction. *International Journal of Pavement Engineering*, s/v, s/n, p. 1-14, 2019.

SINHA, A. K.; HAVANAGI, V. G.; SHAHU, J. T. Construction and performance of jarofix waste material embankment. *Proceedings of the Institution of Civil Engineers – Construction Materials*, v. 175, n. 2, p. 49–64, 2022.

USBR. U.S. Department of Interior Bureau of Reclamation. Design Standards No. 13 – Embankment Dams - Chapter 4: Static Stability Analysis. Washington, DC, 2011. 159 p.