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Effects of Soil Sulfate Exposure on Surface Concrete Elements in Coastal Residential Buildings

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ABSTRACT

This study investigates the effects of soil sulfate exposure on surface concrete elements in resi-dential buildings in Parish on October 18, Canton of Portoviejo, Manabí, addressing a significant gap in local knowledge. From May to October 2023, 20 soil samples were collected and Geo-graphic Information Systems (GIS) were used for exposure mapping. Tests were performed ac-cording to the ASTM D2487 and ASTM C1580 standards to classify soil types and measure sulfate concentrations, following the Ecuadorian Construction Standard (NEC-SE-HM-2015) and ACI 318-19 guidelines. The findings revealed a predominance of clay soils (7 CH and 10 CL) and silt soils (2 MH and 1 ML), with moderate to very severe sulfate concentrations. These concentra-tions were associated with visible damage to the concrete structures, including efflorescence and surface erosion. This study provides a detailed classification map of sulfate exposure and its ef-fects on concrete, offering crucial insights for future construction and repair projects in the re-gion. The results highlight the importance of selecting appropriate materials and employing suitable construction techniques to mitigate sulfate-induced damage in concrete.

KEYWORDS: soil, sulfate exposure, concrete durability, GIS, Portoviejo, Manabí.

1. Introduction

The progress and development of a region are measured not only by economic growth but also by the quality and durability of its infrastructure. The Parish of October 18 in the Canton of Portoviejo, Manabí, Ecuador, has experienced significant urban development in recent decades. As the population grows and housing demand increases, concrete has become the primary construction material owing to its robustness and versatility [1]. However, the durability of concrete is threatened by exposure to sulfates present in the soil, which is a critical issue that has not been sufficiently explored in this region.

International research has shown that the interaction of concrete with sulfates can trigger harmful chemical reactions, affecting its integrity and lifespan. These reactions can cause expansion, cracking, and eventual deterioration of the material, compromising the stability of the structures [2,3]. The ACI Committee 201 has highlighted that concrete-sulfate reactions are particularly damaging in environments with high sulfate concentrations [4]. Oshiro et al. have noted that the porous nature of concrete can amplify these effects, making it crucial to understand these interactions to improve concrete performance in aggressive environments [5]. Additionally, studies emphasize the importance of enhancing concrete durability through strategic design and material selection to mitigate these risks in sulfate-rich settings [6]. Although these challenges are widely recognized globally, in Portoviejo, there is a general lack of awareness and specific regulations to address this issue [7]. The absence of local studies on the effects of sulfates on concrete highlights the urgent need for detailed research in this area.

This study aims to evaluate the influence of sulfates on surface concrete structures in the Parish on October 18. It seeks to establish a correlation between sulfate concentrations in the soil and the observed deterioration in concrete structures. To achieve this, a non-experimental quantitative approach has been adopted, collecting and analyzing soil samples to determine their sulfate content following the internationally recognized standards ASTM D2487-17 [8] and ASTM C1580-20 [9]. The results will be classified according to the Unified Soil Classification System and compared with the sulfate exposure standards established by NEC-SE-HM-2015 [10] and ACI 318-19 [11].

The primary purpose of this study is to provide a solid scientific basis for the development of effective strategies for mitigating and preventing sulfate damage in concrete structures. The research by Calvo et al., demonstrates that inadequate design to resist sulfates can lead to premature damage and high repair costs [12]. Concrete structures not designed to resist sulfate exposure can suffer premature damage, leading to high repair costs and significant structural risk [13]. Additionally, municipal entities must be equipped with adequate information and tools to regulate construction in areas with high sulfate concentrations [14]. Das highlights the necessity of geotechnical understanding in construction practices, essential for mitigating risks associated with sulfate-rich soils [15]. This study aims not only to fill a knowledge gap in the region, but also to influence local policies and regulations, promoting safer and more durable construction practices. Enhancing our knowledge in this field can lead to more innovative and effective construction solutions. The geospatial techniques in soil analysis described by Vega-Blancas et al., provide essential insights for mapping and assessing sulfate exposure, crucial for implementing preventive strategies [16]. The findings of this study have the potential to set a precedent for future studies in the field of geotechnical engineering and construction, emphasizing the importance of applied research and its impact on the daily lives of communities.

2. Materials and Methods

2.1. Research Approach

This project investigated how sulfate concentration in the soil affected the surface condition of concrete in residences in the Parish of October 18. It adopted a non-experimental quantitative approach, measuring sulfate concentrations and evaluating their correlation with concrete deterioration. Systematic random sampling techniques were used to select representative samples, and tests were conducted following national and international standards, in addition to the visual inspection of concrete damage. The research focused on observing and analyzing existing data, seeking patterns, and connections between sulfate concentration and concrete integrity without directly intervening under natural conditions [17].

2.2. Population and Sample

The study population included the entire surface area of Parish on "October 18". Systematic random sampling was employed to select boreholes or test pits at regular intervals to ensure an adequate representation of the entire parish [18]. According to Sampieri [19], systematic sampling involves selecting n elements from a population N based on an interval K, where K = N/n (Fig.1).

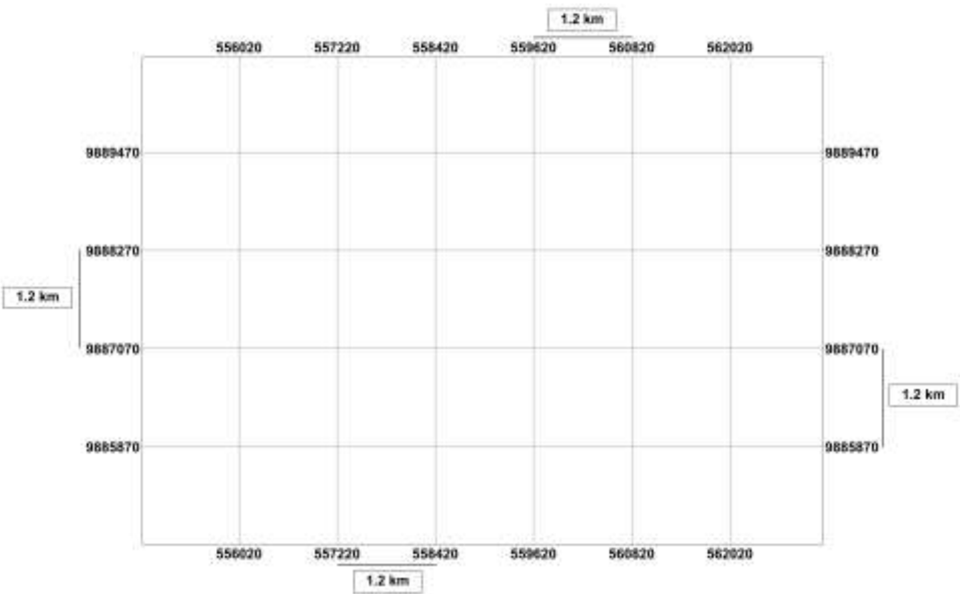

Figure 1. Grid mesh overlay on the study area.

For the geospatial analysis of the 1 537.86 ha (equivalent to 15.38 km²) area of the Parish of October 18 in Portoviejo, ArcGIS was used to establish its boundaries. A set of 20 samples was selected. With an initial population of N = 15.38 km² and n = 20 samples, an interval K = 0.78 km² was derived. However, because of the parish's geographical irregularity, and to ensure representative coverage without omitting specific areas, a recalculation with N = 28.8 km² was performed, resulting in a recalculated interval of K = 1.44 km^2. This translates into a systematic distance of 1.2 km (Fig. 2).

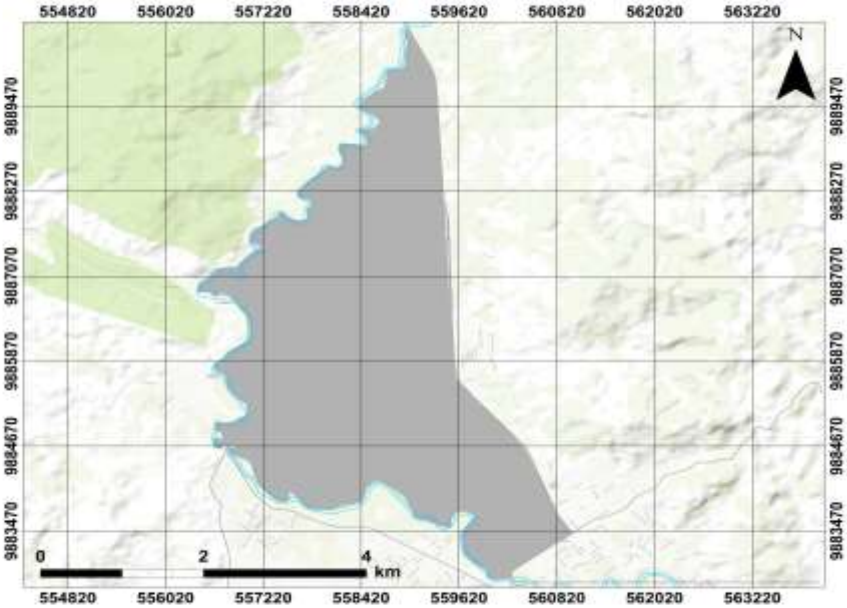

Figure 2. 1.2 km x 1.2 km grid overlay on the Parish of October 18.

2.3. Soil Sampling and Laboratory Tests

Meticulously planned exploratory expeditions were conducted in Parish on October 18. For sample extraction, tools such as shovels and hole diggers were used, following the specifications and recommendations of ASTM D420 [20]. To ensure sample integrity, it is essential to remove vegetation cover before drilling. Each sampling point was expected to be drilled to a depth of 1.5 meters, and at least 5 000 g of soil samples were collected in situ with a balance for laboratory testing.

2.4. Geotechnical Documentation and Cataloging of Samples

Once extracted, all samples underwent a detailed geotechnical registration process and were labeled according to a standardized laboratory protocol. These labels provide crucial data such as a unique geotechnical code, precise georeferenced coordinates of the sampling point, a technical description of the soil based on in situ observations, the presence and depth of the water table, and any other relevant geotechnical observations regarding the specific conditions of the sampling site.

2.5. Evaluation and Categorization of Sulfate Damage

2.5.1. Visible Damage Manifestations

Sulfate damage in concrete causes various symptoms, depending on the intensity and duration of exposure. An early indicator is efflorescence, with whitish crystals on the surface caused by the evaporation of soluble salts [2]. Additionally, the expansion caused by ettringite formation can lead to the appearance of cracks, delamination, and bulging on the concrete surface. In the advanced stages, mass loss and the formation of voids or cavities within the concrete can occur (Fig.3).

(a) (b)

Figure 3. (a) Corrosion of reinforcing steel in a perimeter column near borehole P-10 due to very severe sulfate conditions in the soil. (b) Cracking and steel corrosion in another column of the same perimeter wall.

2.5.2. Technical Evaluation of Damage

The technical evaluation of sulfate damage requires a systematic and multidisciplinary approach. Although visible manifestations provide important clues about the extent of damage, laboratory tests are essential for a comprehensive understanding. Tests following the specifications of ASTM C1580-20 and ASTM D2487-17 allow the measurement of sulfate concentration in the soil and the classification of soil types, respectively [8,9]. Additionally, compression strength tests can be conducted to determine the loss of structural strength in concrete, and petrographic tests can be performed to analyze microstructural alterations.

2.5.3. Categorization According to Standards

Various standards offer criteria for categorizing the risks and damage of sulfates in concrete. The Ecuadorian NEC-15 standard, shown in Table 1, establishes risk categories based on sulfate concentrations in the soil, ranging from low to very severe risks. These categories serve as guidelines for selecting appropriate materials and construction techniques [10]. Internationally, standards like ACI 318-19, detailed in Table 2, provide guidelines on concrete strength and precautions in areas where sulfate is present [11].

Table 1. Categories and exposure classes for sulfate chemical attack according to NEC standard.

Categorías	Severidad	Clase	Condición Sulfatos solubles en agua (SO_4) en el suelo, % en masa	Sulfato (SO_4) disuelto en agua, ppm
S Sulfato	No aplicable	S0	$SO_4 < 0.1$	$SO_4 < 150$
	Moderada	S1	$SO_4 < 0.1$	$150 \leq SO_4 < 1\,500$ agua marina
	Severa	S2	$0.2 \leq SO_4 \leq 2.0$	$1\,500 \leq SO_4 < 10\,000$
	Muy severa	S2	$SO_4 > 2.0$	$SO_4 > 10\,000$

Table 2. Categories and exposure classes for sulfate chemical attack according to ACI standard.

Category	Exposure class	Condition Water-soluble sulfate (SO_4^{2-}) in soil, %	Dissolved sulfate (SO_4^{2-}) in water, ppm
Sulfate (S)	S0 (not applicable)	$SO_4^{2-} < 0.1$	$SO_4^{2-} < 150$
	S1 (moderate)	$SO_4^{2-} < 0.1$	$150 \leq SO_4^{2-} < 1\,500$ or seawater
	S2 (severe)	$0.2 \leq SO_4^{2-} \leq 2.0$	$1\,500 \leq SO_4^{2-} < 10\,000$
	S3 (very severe)	$SO_4^{2-} > 2.0$	$SO_4^{2-} > 10\,000$

2.6. Sample Analysis and Interpretation Method

2.6.1. Determination of Sulfates in Soil Samples

The investigation of sulfate concentration in the soil samples followed a detailed protocol based on the ASTM C1580-20 standard [8]. The steps carried out were as follows: 500 g of each collected sample was taken. The material was dried at 110 ± 5 °C for 24 h in a laboratory oven. If necessary, the drying time could be extended to 36 h. Once dried, the material was ground and sieved using a 0.5 mm opening sieve. Dry and sieved samples (10 g) were weighed using an analytical balance with a readability of d = 0.1 mg. Distilled water (40 mL) diluted with 3 % nitric acid (HNO_3) was then added. The mixture was stirred for approximately 1 h at 25 °C. The mixture was left to rest for 30 min to decant the denser particles. The mixture was filtered using a glass funnel and folded filter paper to simulate an Erlenmeyer flask. Two 10 mL glass flasks were used to filter the solution and subsequently measure the sulfate concentration using a spectrophotometer. The spectrophotometer was turned on and calibrated to operate at 450 nm with a light path length of 4–5 cm. A barium chloride ($BaCl_2$)-based reagent was added to one of the samples, stirred, and stirred for 5 ± 0.5 min. To initialize the measurement equipment, one of the flasks without the reagent was placed in the corresponding cell of the spectrophotometer. Finally, the barium chloride solution was placed in a spectrophotometer to measure the turbidity generated by barium sulfate ($BaSO_4$) particles, and the corresponding readings were recorded. A calibration curve was used to determine sulfate concentration based on the measured absorbance. The average concentration was reported as the percentage of sulfate by the mass of the sample. If desired, it can be converted to mg SO_4 per kg of soil by multiplying the percentage of sulfate by 10 000.

2.6.1. Categorization of Soil Samples According to the Unified Soil Classification System

Accurate classification of fine soils is essential because of their unique characteristics and behaviors [9]. The steps to categorize fine soils are as follows: A representative sample of the fine soil to be categorized is taken. Through visual and tactile inspection, initial characteristics, such as color, texture, and the presence of organic or inorganic particles, were determined. Granulometric analysis was performed to determine the percentage of particles smaller than 0.075 mm (silt and clay). Atterberg limit tests were conducted to determine the Liquid Limit (LL), which is the moisture at which the soil transitions from a liquid state to a plastic state, and the Plastic Limit (PL), which is the moisture at which the soil transitions from a plastic state to a semi-solid state. From these values, the Plasticity Index (PI), which is the difference between the LL and PL, was calculated. Based on the results of the Atterberg limit tests and granulometric analysis, a designation is assigned to the soil. For example, it can be classified as low-plasticity clay (CL) or high-plasticity clay (CH). If the soil exhibits organic characteristics, designations such as organic silt (OL) or organic clay (OH) can be used. All results and observations will be documented meticulously. Finally, a detailed report was generated indicating the USCS classification of the fine soil, along with all relevant notes and characteristics observed during the process.

3. Results

This section provides a concise description of the experimental results, their interpretation, and conclusions that can be drawn from them.

3.1. Geotechnical Campaign

Table 3 presents a detailed breakdown of the geospatial coordinates corresponding to each sampling point obtained during the geotechnical campaign. These coordinates are essential because they provide the exact location of each sample, which is crucial for subsequent laboratory analyses.

Table 3. UTM coordinates of soil samples, Parish of October 18

Borehole	UTM - 17 M	
	East	North
P 1	559096	9889788
P 2	558846	9888726
P 3	558068	9888317
P 4	557810	9887519
P 5	557163	9887266
P 6	559154	9887801
P 7	557060	9886741
P 8	557683	9886715
P 9	559345	9886791
P 10	557175	9885610
P 11	559113	9885286
P 12	557579	9885774
P 13	557051	9884517
P 14	558118	9884394
P 15	558859	9884087
P 16	559690	9883229
P 17	559990	9883968
P 18	559923	9884703
P 19	560889	9883585
P 20	560922	9883416

Figure 4 shows the georeferenced points that mark the exact locations where geotechnical interventions were carried out up to depths of 1.5 meters. This map, prepared with the advanced capabilities of ArcGIS, provides a detailed visual perspective of the surveyed areas and establishes a solid foundation for rigorous analysis and interpretation of the collected data.

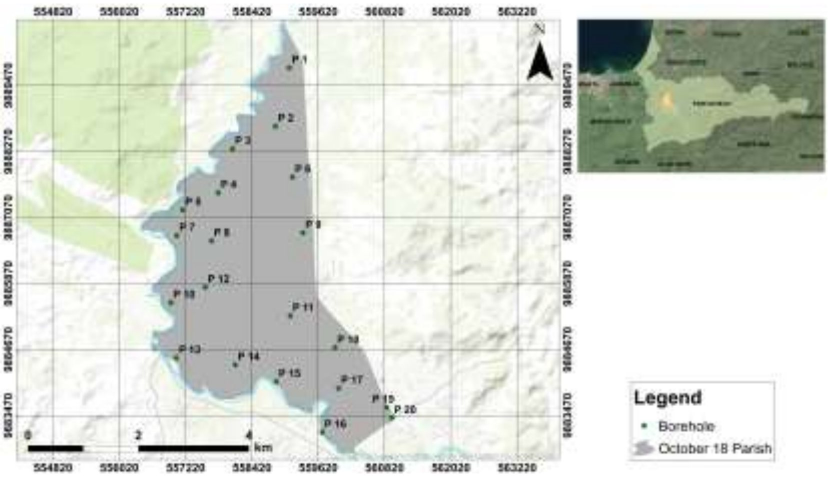

Figure 4. Boreholes conducted in the Parish of October 18.

Table 4 provides a comprehensive and accurate view of the soil characteristics, detailing the number of boreholes, groundwater table depths, geographic coordinates, sulfate concentration, as well as the class, category, and pathology identified during the field exploration. It is important to highlight that a high groundwater table can directly influence construction and design decisions. The locations P2, P6, and P18, where the groundwater table was detected at 0.7 m, 1.0 m, and 1.5 m respectively, are key for anticipating potential challenges or necessary adaptations in construction projects in the area.

Table 4. Geotechnical campaign matrix, Parish of October 18, Canton Portoviejo

WT (m)	East	North	Sulfate Concentration mg/Kg (ppm)	Category	Pathology
X	559096	9889788	13 700	Very Severe	No pathology (new homes)
0.7	558846	9888726	5 740	Severe	No pathology (new homes)
X	558068	9888317	3 090	Severe	No pathology (new homes)
X	557810	9887519	13 460	Very Severe	No pathology (new homes)
X	557163	9887266	1 680	Severe	No pathology (new homes)
1.0	559154	9887801	1 150	Moderate	Surface concrete erosion
X	557060	9886741	5 850	Severe	Efflorescence and surface concre
X	557683	9886715	3 180	Severe	No pathology (new homes)
X	559345	9886791	4 320	Severe	No pathology (new homes)
X	557175	9885610	17 430	Very Severe	Reinforcement corrosion
X	559113	9885286	3 850	Severe	Efflorescence in concrete
X	557579	9885774	8 790	Severe	No pathology (new homes)
X	557051	9884517	3 300	Severe	No pathology (new homes)
X	558118	9884394	3 470	Severe	No pathology (new homes)
X	558859	9884087	2 630	Severe	No pathology (new homes)
X	559690	9883229	340	Moderate	No pathology (new homes)
X	559990	9883968	590	Moderate	Concrete cracks
1.5	559923	9884703	3 600	Severe	Reinforcement corrosion
X	560889	9883585	520	Moderate	No pathology (homes demolis earthquake)
X	560922	9883416	410	Moderate	No pathology (homes demolis earthquake)

3.2. Geotechnical Soil Analysis in the Parish of October 18

Table 5 shows a detailed study of the geotechnical properties of the soil based on the USCS system and supported by the "ASTM D2487-17" standard. This evaluation was carried out at 20 specific points on October 18, Parish, in the Canton of Portoviejo, revealing essential characteristics for anticipating soil behavior under different conditions and loads.

Table 5. Classification Analysis according to the USCS system, Parish 18 de Octubre, Portoviejo Canton

Borehole	Depth (m)	WT (m)	W (%)	Sieve No. 4 % Passing	Sieve No. 10 % Passing	Sieve No. 40 % Passing	Sieve No. 200 % Passing	LL	PL	PI	USCS System
P 1	1.5	X	45	100	100	100	99	78	29	49	CH
P 2	1.5	0.7	60	100	100	100	100	60	33	27	MH
P 3	1.5	X	44	100	100	100	100	85	36	49	CH
P 4	1.5	X	55	100	100	100	100	73	35	38	MH
P 5	1.5	X	35	100	100	100	99	44	26	18	CL
P 6	1.5	1.0	51	100	100	100	99	52	26	26	CH
P 7	1.5	X	39	100	100	100	99	43	24	19	CL
P 8	1.5	X	53	100	100	100	99	48	27	21	CL
P 9	1.5	X	41	100	100	100	96	38	24	14	CL
P 10	1.5	X	41	100	100	100	98	44	27	17	ML
P 11	1.5	X	52	100	100	100	99	57	29	28	CH
P 12	1.5	X	50	100	100	99	96	67	25	42	CH
P 13	1.5	X	42	100	100	100	99	41	24	17	CL
P 14	1.5	X	45	100	100	100	97	40	25	15	CL
P 15	1.5	X	37	100	100	99	92	43	23	20	CL
P 16	1.5	X	36	100	100	100	68	33	23	10	CL
P 17	1.5	X	54	100	100	100	98	83	34	49	CH
P 18	1.5	1.5	52	100	100	100	99	49	26	23	CL
P 19	1.5	X	48	100	100	99	98	42	24	18	CL
P 20	1.5	X	49	100	100	100	99	57	25	32	CH

High-compressibility clays (CH): Seven samples were identified under this category. These soils, characterized by their cohesion and water retention capacity, can present challenges in construction, especially in areas prone to moisture variations.

Low-compressibility clay (CL): Ten samples were categorized. Although they share certain characteristics with high-compressibility clays, their response to changes in moisture and load tends to be more moderate, but still requires adequate planning when building on them.

High- and low-compressibility silts (MH and ML): Three samples were classified into these categories. These soils have less cohesion than clay, but their properties can vary considerably with changes in moisture.

Inorganic high-compressibility silts (MH and ML): Three samples were classified under these categories. These soils have less cohesion than clays, but their properties can vary considerably with changes in moisture.

Fig 5 shows a geotechnical zoning map of the Parish on October 18 according to the USCS (ASTM D2487-17) standards, highlighting different soil types and their distribution across the area.

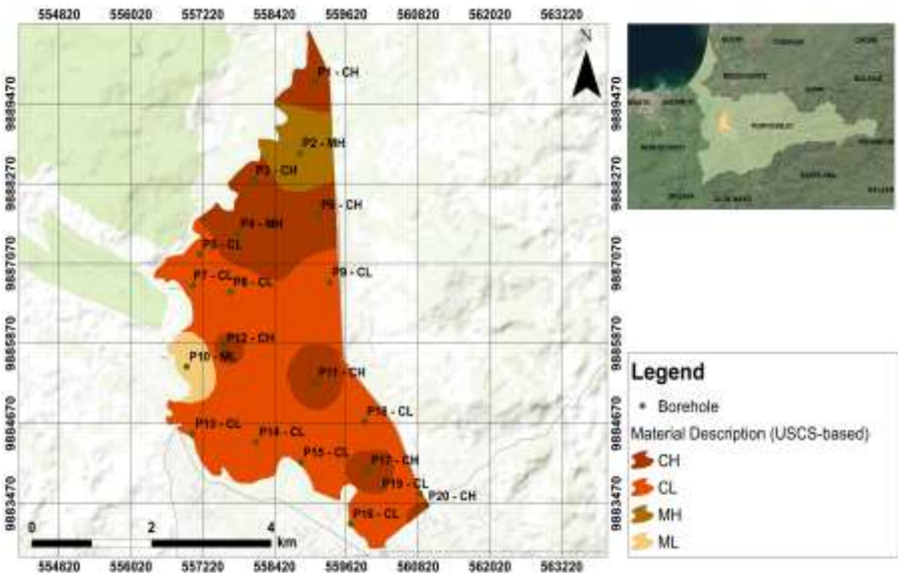

Figure 5. Geotechnical zoning map of the Parish of October 18 according to USCS (ASTM D2487-17)

3.3. Sulfate Concentration

Determining the sulfate concentration in soil is critical for understanding the geotechnical and structural implications of a terrain, especially when it comes to concrete structures. The methodology stipulated in the "ASTM C1580-20" standard was used for this analysis.

Table 6. Sulfate Exposure Analysis, Parish 18 de Octubre, Portoviejo Canton

Borehole	East	North	Sulfate Concentration mg/Kg (ppm)	Water-soluble Sulfates (SO_4) in Soil, % by mass	WT	Category	Class
P 1	559096	9889788	13 700	1.4	X	Very Severe	S3
P 2	558846	9888726	5 740	0.6	0.7 m	Severe	S2
P 3	558068	9888317	3 090	0.3	X	Severe	S2
P 4	557810	9887519	13 460	1.3	X	Very Severe	S3
P 5	557163	9887266	1 680	0.2	X	Severe	S2
P 6	559154	9887801	1 150	0.1	1.0 m	Moderate	S1
P 7	557060	9886741	5 850	0.6	X	Severe	S2
P 8	557683	9886715	3 180	0.3	X	Severe	S2
P 9	559345	9886791	4 320	0.4	X	Severe	S2
P 10	557175	9885610	17 430	1.7	X	Very Severe	S3
P 11	559113	9885286	3 850	0.4	X	Severe	S2
P 12	557579	9885774	8 790	0.9	X	Severe	S2
P 13	557051	9884517	3 300	0.3	X	Severe	S2
P 14	558118	9884394	3 470	0.3	X	Severe	S2
P 15	558859	9884087	2 630	0.3	X	Severe	S2
P 16	559690	9883229	340	0	X	Moderate	S1
P 17	559990	9883968	590	0.1	X	Moderate	S1
P 18	559923	9884703	3 600	0.4	1.5 m	Severe	S2
P 19	560889	9883585	520	0.1	X	Moderate	S1
P 20	560922	9883416	410	0	X	Moderate	S1

From an exhaustive analysis of 20 samples, as detailed in Table 6, sulfate exposure was classified into three distinct categories, according to the guidelines of the NEC 2015 standard:

Moderate (Class S1): Includes samples from boreholes P6, P16, P17, P19, and P20, with water-soluble sulfate concentrations ranging between 150 and 1 500 ppm. Despite being considered moderate, it is essential to implement protection strategies for the concrete structures in these areas.

Severe (Class S2): This category encompasses most samples, such as P2, P3, P5, P7, P8, P9, P11, P12, P13, P14, P15, and P18, with concentrations varying between 1 500 and 10 000 ppm. These areas require rigorous care and detailed planning when using concrete because of the high presence of sulfates.

Very Severe (Class S3): Samples P1, P4, and P10 fall within this segment, exhibiting sulfate (SO_4) levels higher than 10 000 ppm. Therefore, it is crucial to adopt advanced and specialized construction techniques when working with concrete.

Fig 6 shows the sulfate exposure classification map in Parish on October 18, according to NEC 2015 and ACI 318-19 standards.

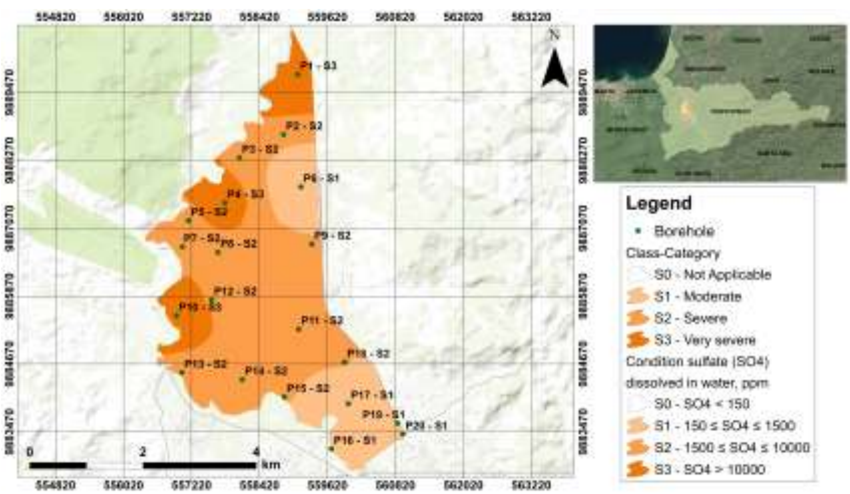

Figure 6. Sulfate exposure classification map in the Parish of October 18 according to NEC 2015 and ACI 318-19 standards

Table 7. Descriptive statistical parameters of sulfate concentration in the soil

Statistical Parameter	Sulfate Concentration SO_4 mg/kg (ppm)
Mean	4 855
Median	3 385
Minimum	340
Maximum	17 430
Range	17 090
Standard Deviation (SD)	4 848.66
Coefficient of Variation (CV %)	99.87
Skewness	1.5

Kurtosis	1.52

After reviewing the descriptive statistical parameters of sulfate concentration in the soil, presented in Table 7, and analyzing the geotechnical data of the soils of Parish on October 18 according to the USCS classification and sulfate concentration, as detailed in Table 8, certain relationships and trends can be identified. The mean is 4 855.0 mg/kg, indicating the average sulfate concentration in the sample. The median of 3 385.0 mg/kg, which is lower than the mean, suggesting that more than half of the observations had concentrations below the average, indicating an asymmetric distribution. The minimum recorded value was 340 mg/kg and the maximum was 17 430 mg/kg, demonstrating a significant difference in concentrations within the sample. The high standard deviation of 4 848.66 mg/kg indicates considerable variability in sulfate concentrations among the different samples. This means that not all values are close to the average, but are quite dispersed. The range of 17 090 mg/kg reinforces the idea of wide dispersion in the sample values. The coefficient of variation, which is 99.87 %, reflects high variability relative to the mean. This indicates that the data dispersion is proportionally large compared with the average concentration level. A skewness of 1.50 indicates an asymmetric distribution with a skew towards lower values, meaning there is a higher concentration of lower sulfate concentration values. A kurtosis of 1.52 indicates that the distribution is more peaked than a normal distribution, implying a higher tendency to have extreme values in the sample. This aligns with the extremely high values observed in the data. This research shows that all analyzed soils are of a fine granular nature, highlighting that they are 100 % plastic. A key point is that no trend was established between the classification and sulfate concentrations. This particularity lies in the fact that the USCS classification evaluates the soil mainly by its particle size and plasticity without incorporating factors such as sulfate concentrations.

Table 8. Sulfate Exposure Analysis related to the SUCS soil classification system, Parish 18 de Octubre, Portoviejo Canton

Borehole	Sulfate Concentration mg/kg (ppm)	USCS System	Severity	Class
P 1	13 700	CH	Very Severe	S3
P 2	5 740	MH	Severe	S2
P 3	3 090	CH	Severe	S2
P 4	13 460	MH	Very Severe	S3
P 5	1 680	CL	Severe	S2
P 6	1 150	CH	Moderate	S1
P 7	5 850	CL	Severe	S2
P 8	3 180	CL	Severe	S2
P 9	4 320	CL	Severe	S2
P 10	17 430	ML	Very Severe	S3
P 11	3 850	CH	Severe	S2
P 12	8 790	CH	Severe	S2
P 13	3 300	CL	Severe	S2
P 14	3 470	CL	Severe	S2
P 15	2 630	CL	Severe	S2
P 16	340	CL	Moderate	S1
P 17	590	CH	Moderate	S1
P 18	3 600	CL	Severe	S2
P 19	520	CL	Moderate	S1

P 20	410	CH	Moderate	S1

Figure 7 shows the sulfate concentration according to soil type in the Parish of October 18, while Figure 8 illustrates the linear trend between the percentage passing through sieve 200 and the concentration of SO_4 in ppm.

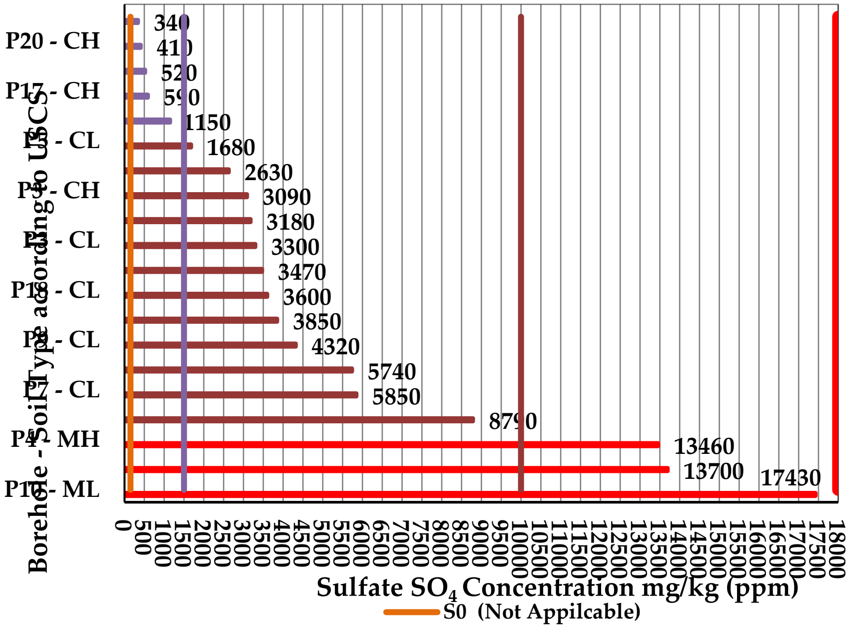

Figure 7. Sulfate concentration according to soil type, Parish of October 18

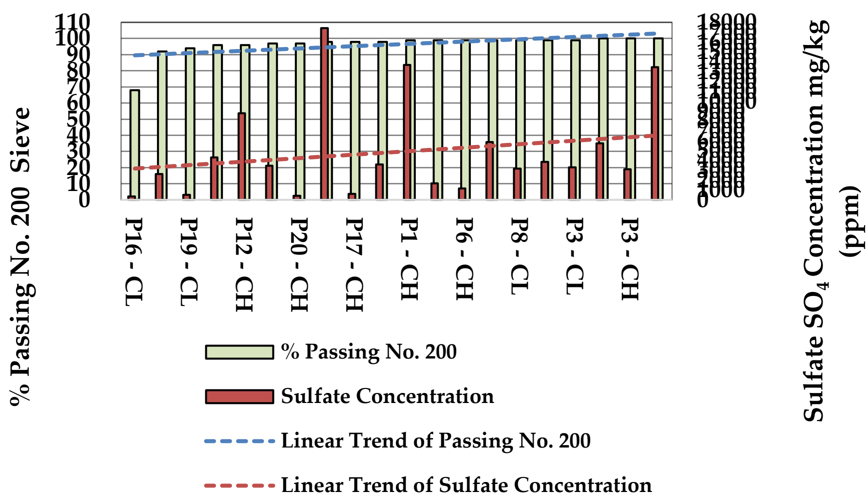

Figure 8. Linear trend between the % passing through sieve 200 and the concentration of SO_4 in ppm

4. Discussion

From a geotechnical and chemical perspective, the Parish of October 18 exhibited a complex interaction between soil classification according to the USCS and sulfate concentration. According to research conducted by Liu et al. [21], soil classification is essential for understanding soil behavior, particularly in geotechnical situations. Clays, whether of high compressibility (CH) or low compressibility (CL), as found in most boreholes, show notable variations in sulfate concentration. This suggests that, beyond geotechnical classification, there are local factors that affect soil chemistry. a study by Zhao et al. [22] indicated that local environmental factors, such as human intervention and geological characteristics, significantly influence soil chemistry. This influence is particularly evident in boreholes near the Portoviejo River and oxidation pond (Fig.9). These aquatic areas, with their changing dynamics, especially during the rainy season, can alter soil saturation and, therefore, the mobility and concentration of sulfates. The analysis by Castro et al. [23] on variations in sulfate quantities in groundwater, especially those linked to local factors such as agricultural practices and the introduction of fertilizers, supports the idea of the influence of water bodies and other factors on soil chemistry.

These clayey soils, especially those near bodies of water, can experience significant changes in their mechanical and chemical properties. The ability of clays to retain water can amplify the effects of sulfates, endangering the integrity of concrete structures. Ramírez et al. [24] highlighted how various circumstances, such as the presence of impurities such as sulfates in the ground, can influence the strength and performance of concrete constructions.

Additionally, the detection of groundwater levels near the surface at certain points such as P2, P6, and P18 adds another layer of complexity to the analysis. These groundwater levels may indicate a higher susceptibility to infiltration and movement of dissolved substances. Consequently, concrete structures in these areas are more vulnerable to chemical attacks, especially sulfates. Guo et al. [25], pointed out that certain environmental conditions, including the presence of high groundwater levels, can influence the properties of concrete under sulfate attack. In addition, Castro et al. [23], examined the effects of sulfates on concrete, highlighting that this interaction can lead to cracking and the eventual failure of concrete.

Within the parish, heterogeneity was identified in sulfate concentrations, ranging from "Very Severe" (S3) to "Moderate" (S1) classifications. From a geotechnical perspective, it is critical to recognize that sulfates, by reacting with concrete, have the ability to induce expansion, generate cracks, and compromise the structural integrity. In particular, areas adjacent to the river and oxidation pond, such as P10, P12, P13, and P14, show high sulfate concentrations, reflecting the possible contribution of these aquatic environments to the chemical dynamics of the soil. This phenomenon of sulfate-concrete interaction, with its consequent adverse effects, has been corroborated in specialized studies, as evidenced in the work of Guo et al. [25].

Zoning based on USCS classification and sulfate concentration is fundamental for urban planning (Fig.9). According to Carvajal et al. [26], it is crucial to consider the specific geotechnical characteristics of a region when planning and designing structures. Areas categorized as "Very Severe" (S3) required specialized construction strategies to ensure concrete durability. Given the differences in sulfate concentrations, it is important to adopt a specific structural design and rigorously select materials, considering the geotechnical conditions of the site. This methodology in material choice and design to ensure concrete resistance to sulfates is supported by the findings of Tahwia et al. [27].

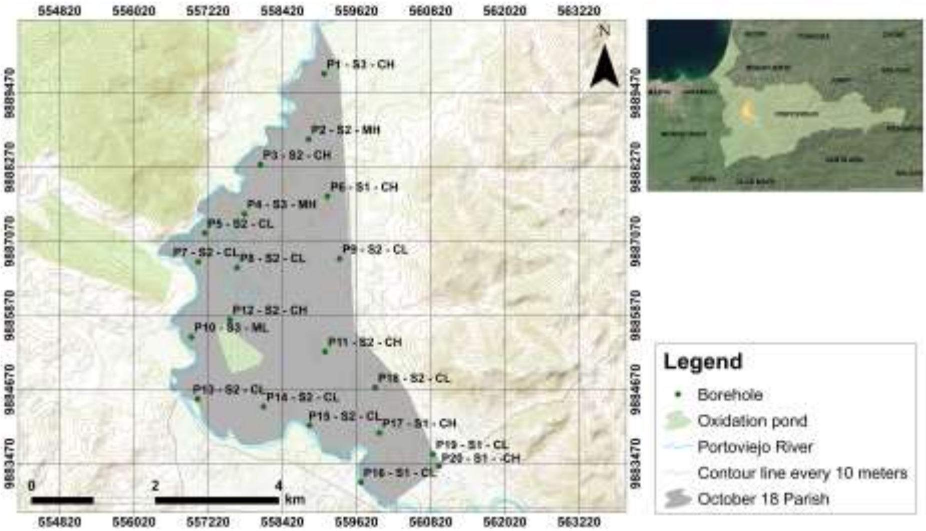

Figure 9. Zoning Map of USCS Classification and Sulfate Concentration

Based on the results of the present investigation, it is essential to conduct additional studies to explore the relationship between soil, river water, and oxidation ponds. By doing so, we can deepen our technical understanding of how proximity to these water bodies can alter sulfate concentrations in the soil. This variability, in turn, has the potential to influence the properties and behavior of concrete, which is a critical aspect in geotechnical engineering.

5. Conclusions

Several soil types were identified according to the Unified Soil Classification System (USCS), consisting primarily of seven high-compressibility clays (CH), ten low-compressibility clays (CL), two high-plasticity silts (MH), and one low-plasticity silt (ML). This information, represented in a zoning map (Fig.9), is fundamental for guiding future construction projects, considering the geological influence and predominance of Holocene fluvial deposits in the canton [28]. The presence of soils with a high Plasticity Index, susceptibility to volume changes and stability under different loads, and the significant concentration of sulfates pose important challenges in the field of construction. These geological and chemical conditions highlight the need to consider factors such as soil compressibility, expansion potential, and chemical characteristics when planning and designing structures in Portoviejo.

The analysis of sulfate levels (SO4) in this study was divided into three categories: moderate (S1) in five boreholes, severe (S2) in 12 samples, and Very Severe (S3) in three of the 20 total samples. The presence of sulfates is linked to factors such as proximity to the Portoviejo River, agricultural activities, proximity to the oxidation pond treating the canton's wastewater, groundwater levels less than 1.5 meters deep at points P-2, P-6, and P-18, and the water retention capacity of clay soils.

The study results clearly demonstrate how sulfates negatively affect concrete. The sulfate exposure classification map (Fig.6), with a depth range of up to 1.5 meters, facilitates the selection of appropriate materials for construction and urban planning in the Parish of October 18. This map is an essential tool for selecting cement types that prevent chemical deterioration and ensure the durability of future construction.

(a) (b)

Figure 10. (a) Erosion of concrete and masonry elements on the front facade of the residential building near borehole P6. (b) Surface erosion on the column and beam observed at borehole P6, with a groundwater table at 1.0 m depth.

Additionally, the study identified various concrete pathologies associated with different sulfate exposure levels. In boreholes P-6 and P-7, surface concrete erosion was observed (Fig.10), classified as Moderate-S1 and Severe-S2, respectively, demonstrating a detrimental chemical reaction between soil sulfates and concrete components. Choosing sulfate-resistant MS and HS cement types in these areas could have mitigated this type of deterioration. The corrosion of steel reinforcements in boreholes P-10 Very Severe-S3 and P-18 Severe-S2 (Fig.11), with high sulfate concentrations, highlights the need for using HS cement and pozzolans or slags, highly resistant to sulfates, in zones of severe and very severe exposure. This measure is vital to prevent corrosion and extend the structures' service life.

(a) (b)

Figure 11. (a) Reinforcement corrosion in borehole P-18, with a groundwater table at 1.5 m depth. (b) Deteriorated concrete column with exposed and corroded steel reinforcement due to severe sulfate conditions, observed at borehole P-18.

The efflorescence observed in the concrete of borehole P-11, with Severe-S2 sulfate exposure (Fig.12), indicates sulfate migration through the concrete. In these circumstances, selecting HS cements that minimize sulfate mobility, and therefore, efflorescence formation, is essential. Finally, the cracks detected in borehole P-17 in the Moderate-S1 exposure zone (Fig.13) may have resulted from concrete expansion due to sulfate product formation. In these cases, using MS cements designed to resist sulfates can be an effective strategy to reduce the risk of cracking.

(a) (b)

Figure 12. (a) Perimeter wall of the residential building, affected by severe sulfate levels and showing efflorescence, near borehole P-11. (b) Shallow foundation affected by severe sulfate conditions in the area of borehole P-11, showing signs of efflorescence.

(a) (b)

Figure 13. (a) Soil sample extraction at 1.5 m depth for laboratory tests at borehole P-17. (b) Cracks in the concrete at borehole P-17, caused by moderate sulfate conditions.

The correlation between sulfate concentrations and the observed concrete damage (surface erosion, efflorescence, and reinforcement corrosion) demonstrates that exposure to high sulfate concentrations is directly related to greater deterioration of surface concrete elements. This observation validates the hypothesis, showing the absence of low sulfate levels (Low-S0 category) in all boreholes. Therefore, sulfate exposure in the soil significantly impacts the durability and integrity of concrete structures in Parish on October 18, being higher in areas with high sulfate concentrations.

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