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Original Research Article

Stabilization strategy of normal and chrome tanning effluent mixed subsoil: a novelty to enhance the soil characteristics

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Abstract: Soil stabilisation is a unique method to effectively and accurately find a solution to the issues caused by loose subsoil. This research investigates the problems of uncontrolled industrial effluent disposal, mainly from tannery enterprises, which presents severe environmental problems in emerging nations due to soil properties changing and large regions being unfit for cultivation and human habitation. The study uses Atterberg's limits, sieve analysis, and direct shear testing to examine the effects of untreated tannery effluents on soil parameters. The findings show that the soil's shear strength, moisture content, and flexibility have all significantly decreased. Lime and waste stone powder were added to lessen these impacts, and this improved soil stability was shown by an increase in the values of all the variables. For efficient soil remediation, the study suggests using waste stone powder and lime in the following proportions: 0%, 3%, 6%, and 9%. Combining lime stabilisation methods with industrial by-products like slag and fly ash opens up new possibilities for enhancing the geotechnical characteristics of polluted soils. This study emphasises how important it is to use customised geotechnical design techniques to handle soil contamination issues in infrastructure and foundation projects, especially in areas where the leather industry predominates.

Keywords: Cohesive soil, Stabilization, Chrome tanning effluent, Stone powder, Lime, Shear strength, Plastic limit, Liquid limit, Soil stabilisation, Loose subsoil.

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1. Introduction

Pakistan is a global leader in the manufacture of leather goods. Pakistan is home to a large number of tannery enterprises (Sikander *et al.*, 2021). Due to the chemical reactions, the waste released by these companies, including poisonous substances and heavy metals, is changing the composition and form of the nearby land water sources (Khatun *et al.*, 2024). Tannery wastewater has poisoned thousands of hectares of land and several priceless water sources (Pavithra, 2019). When soils come into contact with these effluents, their characteristics are altered, which might impact the soil's engineering behaviour (Irfan *et al.*, 2018). Numerous research has been conducted recently to look at how the chemistry of the pore water affects the properties of soil strength. However, tannery effluent has a different effect on soil, and the engineering behaviour of soil must vary based on the chemical makeup of the structure supporting it. Out of all industrial wastes, tanning effluents are the most polluting. They contribute significantly to the pollution caused by chromium. For example, the tannery industries in India alone release between 2000 and 3000 tons of chromium into the environment each year; the aqueous effluent has chromium concentrations ranging from 2000 to 5000 mg/l, compared to the suggested permitted discharge limits of 2 mg/l.

Additionally, the stability of slopes, foundations, and piles can be impacted when the soil around them becomes contaminated (Sibi & Karthigeyan, 2018). In the era of the Industrial Revolution, a geotechnical engineer's responsibilities became more complex as traditional geotechnical principles and theories needed to consider the behaviours of contaminated soils. To ensure accurate design of underground foundations and structures, design methodologies must be modified to account for the effects of contaminants on soil properties. The term "lime stabilization" describes the process of stabilizing soil by the addition of limestone products, such as calcium hydroxide ($Ca(OH)_2$) and oxide (CaO) (Saldanha *et al.*, 2021). In Europe, quicklime is the most often used lime product for stabilizing lime. The well-known industrial by-products are fly ash, slag, rice husk, and waste stone powder. To enhance the geotechnical characteristics of the impacted soil and the qualities of pozzolanic stabilized materials, ash has been collected and combined with cement and lime.

Because chromium is hazardous to both people and animals and may linger in the environment for a long time, it is a particularly worrying contaminant. The ecosystem may suffer significantly if untreated chrome tanning wastewater is dumped into bodies of water. It can harm agricultural land, taint drinking water, and kill fish and other aquatic life. Developing cost-effective and efficient solutions for treating chrome tanning wastewater has garnered more attention recently. Numerous therapy approaches have been suggested, such as chemical, biological, and physical processes (Zhang & Chen, 2020).

Using mixed cohesive subsoil is one possible method of treating chrome tanning wastewater (MCS). MCS is a naturally occurring substance comprising a blend of clay, silt, and sand particles. It has been demonstrated to successfully eliminate various contaminants from wastewater, such as organic debris, sulphides, and chromium (Tyagi *et al.*, 2024). This study aims to find out how well MCS treats chrome tanning wastewater. The following goals will be the main focus of the study. To describe the MCS samples and the chrome tanning effluent. To assess, using MCS, how various operational parameters affect the number of contaminants removed from chrome tanning effluent to create a chrome tanning effluent treatment system design using MCS (Proshad *et al.*, 2024) [9]. The results of this investigation will offer essential details on MCS's capability for treating chrome tanning wastewater. This may create a more economical and environmentally friendly method for treating this dangerous effluent.

Global soil contamination with chromium has resulted chiefly from the widespread practice of land-based tannery waste disposal, which was predicated on the idea that the major species in the tannery waste would be the thermodynamically stable Cr (III) species. However, recent findings of dangerously high concentrations of Cr (VI) in groundwater and surface water in several parts of the world raise serious concerns about how Cr-containing wastes are now disposed of. Even though Cr (III) is thermodynamically stable, the oxidation of Cr (III) to Cr (VI) in the soil environment can be accelerated by the presence of some naturally occurring minerals, mainly MnO_2 oxides. Because Cr (VI) is bioavailable at high pH levels and is consequently highly mobile, this aspect is of public concern as it increases the danger of groundwater pollution. Due to their lack of access to a shared treatment facility, many small-scale tanneries nationwide dispose-off their waste in open fields or landfills (Zhang *et al.*, 2022).

The effluent from the post-tanning section cannot be entirely cleansed using cleaner methods to minimize chromium in wastewater, such as the high exhaustion process or direct or indirect chromium recycling (China *et al.*, 2020; Ullah *et al.*, 2021). Combinations of metallic cat ions, such as titanium, magnesium, aluminium, and zirconium, were tested instead of chromium to overcome this difficulty. However, the current results are not entirely satisfactory for all types of leather. In some types of leather, synthetic organic tanning chemicals, either by themselves or in conjunction with a metallic cat ion, may be used instead of chromium, given that worker and environmental health and safety laws are followed. The leather business is vital to the worldwide industrial landscape, serving various industries, including luxury goods, fashion, automotive, and upholstery. Our everyday lives are adorned by its items, which range from chic accessories to cozy house and car seats. The artistry and cultural legacy highlight the industry's importance it upholds in addition to its economic influence. The chrome tanning technique, which is well regarded for its capacity to endow leather goods with exceptional durability and appealing qualities, is at the core of creating premium leather. However, chrome tanning poses an environmental problem for which creative solutions and attention are needed: chrome tanning effluent (Sinha, 2021).

The relationship between industrial operations and the environment has long been discussed and researched, especially in areas with thriving industries. The leather industry is one such sector that is essential to the economies of both India and Pakistan. Pakistan is the world's top producer of leather goods, and India has many tannery enterprises that contribute substantially to this booming industry. The tanneries' effluent discharge has significant and far-reaching repercussions for the environment, especially for poisoning naturally occurring clay soil. Nevertheless, the industry's prosperity comes at a cost. Heavy metals and other harmful materials found in tannery effluent seep into nearby water and land sources, where they initiate a complex series of reactions that ripple through the soil structure. The soil's composition and characteristics are altered due to this effluent's penetration into the ground (Raimi *et al.*, 2022). Therefore, these modifications can potentially upset the soil's engineering behaviour, affecting the impacted regions' biological balance and the nearby buildings' stability.

This study aims to explore the complexities of tannery effluent pollution in the setting of naturally occurring clay soil. It explores the elements—lime, waste stone powder, and chrome tanning effluent—that propel these changes, illuminating their distinct functions and relationships. Through an investigation of the chemical processes and the ensuing engineering consequences, the research seeks to clarify the significant impact of these components on soil characteristics. There are several ramifications, including adjustments to slope stability, compressibility, permeability, and load-bearing capacity. These changes bring severe environmental problems and difficulties for infrastructure development and building. The devastation of priceless water supplies and hundreds of hectares of land is a clear reminder of how vital it is to comprehend and solve this problem. This research aims to close the gap between environmental science and engineering in quest of complete solutions. It highlights how crucial it is to do thorough soil testing, design remediation plans for each site, and implement strict regulatory measures to reduce effluent leakage. It also emphasizes how important it is to take into account the distinct chemical makeup of the effluent and how it interacts with the local soil conditions, as a one-size-fits-all strategy is unlikely to result in mitigation and restoration that is both successful and sustainable (Ullah *et al.*, 2024; Chaurasia & Kumar, 2022; Kalsoom & Batool, 2020).

We hope that this investigation into the effects of tannery effluent on natural clay soil will add to the increasing body of knowledge that seeks to reconcile environmental protection with industrial advancement. By using various waste products as stabilizers, we may enhance soil characteristics, and by doing so, we can pave the road for prospering enterprises and our priceless natural environment to coexist sustainably (Edirisinghe, 2022; Piyadasa & Bandara, 2021; Singh *et al.*, 2022; Khan *et al.*, 2018; Khan *et al.*, 2021). Physical techniques, including excavation and soil washing, have been used to get rid of polluted soil (Azhar *et al.*, 2022). The goal of chemical techniques is to neutralize and stabilize chromium, which includes using amendments such as lime and organic materials (Cui *et al.*, 2023).

Using plants to clean up contaminated soil is known as phytoremediation, and it has gained popularity as a sustainable method. Research showed how some plant species may build up and stabilize chromium in the soil (Shah & Daverey, 2020).

The goals of the research are as follows.

- To investigate the properties of virgin clay soil and clay that has been tainted by tannery waste.
- We are measuring the contaminated soil's fundamental index characteristics.
- A direct shear test will determine the contaminated soils shear strength.
- Waste stone powder and industrial by-products like lime can strengthen the polluted soil.

2. Materials and method

2.1. Soil sample collection

The most prevalent bedding and subgrade soil in Karak City's coastline region, Khyber Pakhtunkhwa, Pakistan, is highly plastic clayey. To prevent the uninvited entrance of waste, debris, or organic soil, soil samples were gathered from the Karak shoreline region close to the natural gas field area at depths ranging from 0.5 to 1 meter.

2.2. Soil sample preparation

The soil was then ground into a fine powder and dried in an oven at (110 and 105) °C for a whole day. All of the lumps were then broken into little pieces. The experiment was conducted in a lab setting using various sieves in a sieve shaker. After the shaking step was completed, all samples were prepared using the soil. The amount of soil on each sieve was measured to extract and eliminate stones from the main soil mass structure. Four samples were produced and sealed in thick plastic bags to ensure no oil evaporation or soil particle moisture absorption.

2.3. Experimental tests

Several lab experiments were conducted to assess the geotechnical characteristics of oil-contaminated samples (OCS).

- Sieve analysis (ASTM D6913M-17)
- Atterberg limits (ASTM D4318)
- Direct Shear (ASTM D3080/D3080M)

This investigation used the highly malleable clayey soil sample employed in two separate states—the normal state and the state polluted with industrial effluent containing chromium tannins. Lime and stone powder were added in this study at a ratio of 0% to 9% with a 3% interval to improve the changes in the soil's qualities.

3. Results and discussion

3.1. Sieve analysis

The results of sieve analysis experiments with graphical representations of the standard and contaminated clayey samples are shown below. The usual soil sample showed a gradation structure characteristic of clayey soils, with a considerable number of small particles making it through the finer sieves. While the contaminated soil sample showed a discernible shift in its particle distribution, this pattern of distribution is consistent with the predicted features of clay, which is defined by a high percentage of tiny particles (silts and clays), leading to limited permeability and a high capacity for water retention.

Table-1: Sieve analysis of normal clay sample (Total sample = 500gm)

S. No.	Opening (mm)	Mass retained oneach sieve (gram)	Cumulative mass retained above each sieve (gram)	Percent finer (%)
4	4.75	57.16	0	11.432
10	2	171.73	171.73	34.346
16	1.19	58.98	230.71	11.796
20	0.85	40.72	271.43	8,144
30	0.595	41.05	312.48	8.21
40	0.425	31.76	344.24	6.342
60	0.250	28.55	372.79	5.71
80	0.185	13.39	386.18	2.678
100	0.150	6.03	392.21	1.206
200	0.075	18.01	410.22	3.602
Pan		29.42	310	5.884

The cohesiveness and structure of the soil appeared to be impacted by the presence of industrial effluent, namely chromium tannins. Perhaps as a result of chemical interactions between the tannins and soil particles, the tiny particles appeared more aggregated. In comparison to regular soil, this could have led to a little increase in the number of coarser particles being retained on the higher sieves.

Figure 1: Sieve analysis was done on a typical clayey sample

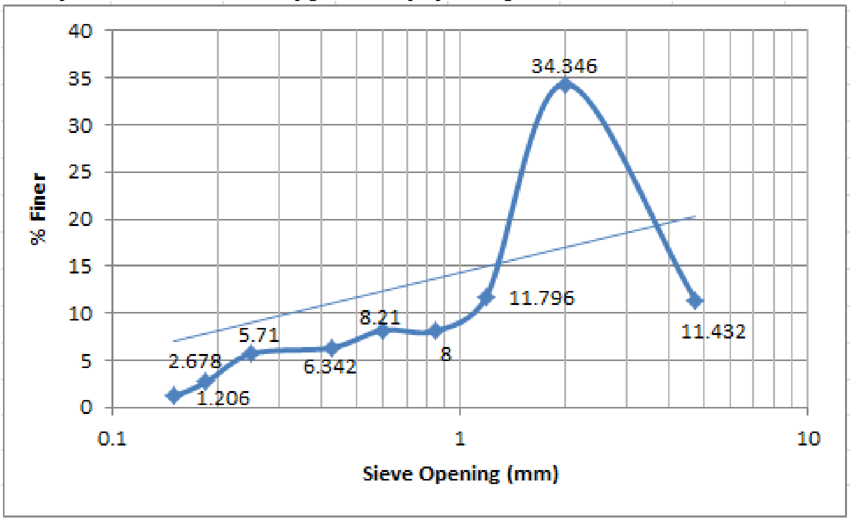
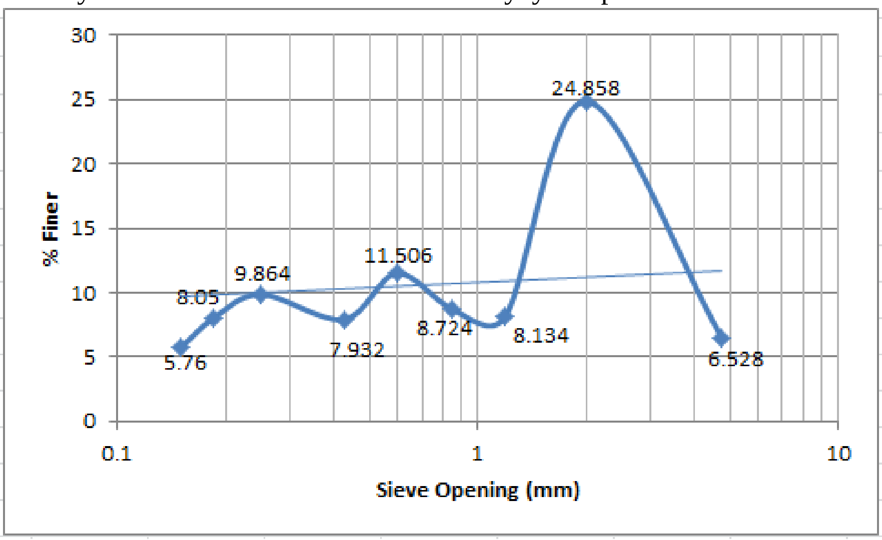


Table-2: Sieve analysis of contaminated clay sample (Total sample = 500gm)

S. No.	Opening (mm)	Mass retained on each sieve (gram)	Cumulative mass retained above each sieve (gram)	Percent finer (%)
4	4.75	32.64	0	6.528
10	2	124.29	124.29	24.858
16	1.19	40.67	164.96	8.134
20	0.85	43.62	208.58	8.724
30	0.595	57.53	266.05	11.506
40	0.425	39.66	305.71	7.932
60	0.250	49.32	355.03	9.864
80	0.185	40.25	395.28	8.05
100	0.150	28.80	424.08	5.76
200	0.075	32.38	456.46	6.476
Pan		4.77	461.23	0.954

Figure 2: Sieve analysis was done on a contaminated clayey sample



3.2. Atterberg limits

The results of the liquid limit and plastic limit in tables from and graphical representation are as given below. The liquid limit and plastic limit results were performed on the standard and contaminated clayey soil samples. In this investigation, unpolluted and contaminated with industrial effluent, including chromium tannins, clayey soil samples had their Atterberg limits (LL, PL, and PI) established.

Table-3: Values of the liquid limit of standard and contaminated clayey soil with 0% to 9% stone powder and lime additive

Normal clayey soil sample		
S. No.	Percent Additive (%)	Liquid Limit (PL)
1	0	68.55
2	3	51.85
3	6	24.6
4	9	25.5
Contaminated clayey soil sample		
S. No.	Percent Additive (%)	Liquid Limit (%)
1	0	43
2	3	55
3	6	46.5
4	9	21.32

The impact of gradually increasing the amounts of stone powder and lime (0%, 3%, 6%, and 9%) was assessed to determine how these stabilizers affect the plasticity of the soil. Tests revealed that both lime and stone powder favourably affected the flexibility properties of both typical and chromium-polluted soils. Because of its chemical interaction with soil particles, lime had a more noticeable effect than stone powder, which mainly served as a filler to improve the structure of the soil. The negative impacts of chromium pollution were effectively mitigated, and the combination of lime and stone powder improved soil stability and workability. The soil quality steadily improved as stabilizers were added one at a time.

Figure 3: Liquid limit of average clayey soil

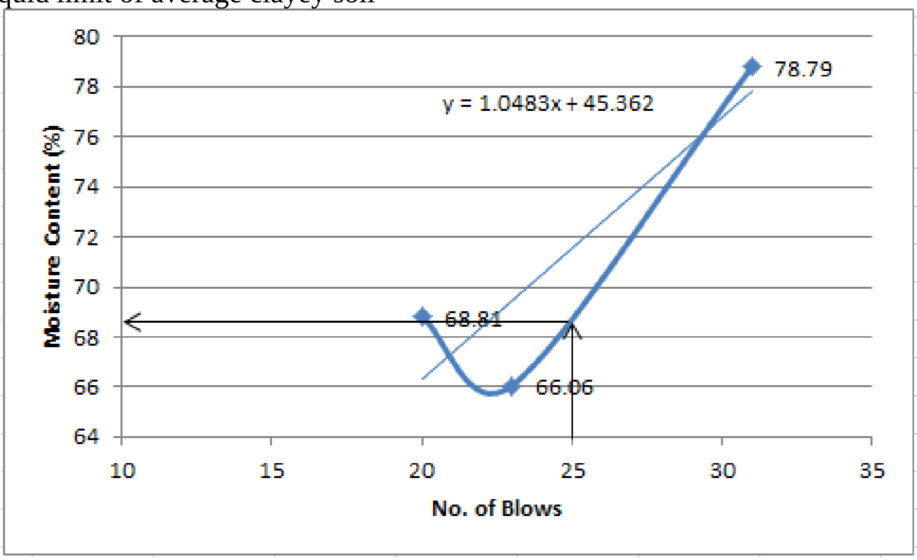


Figure 4: Liquid Limit of clay soil with 3% stone powder and lime

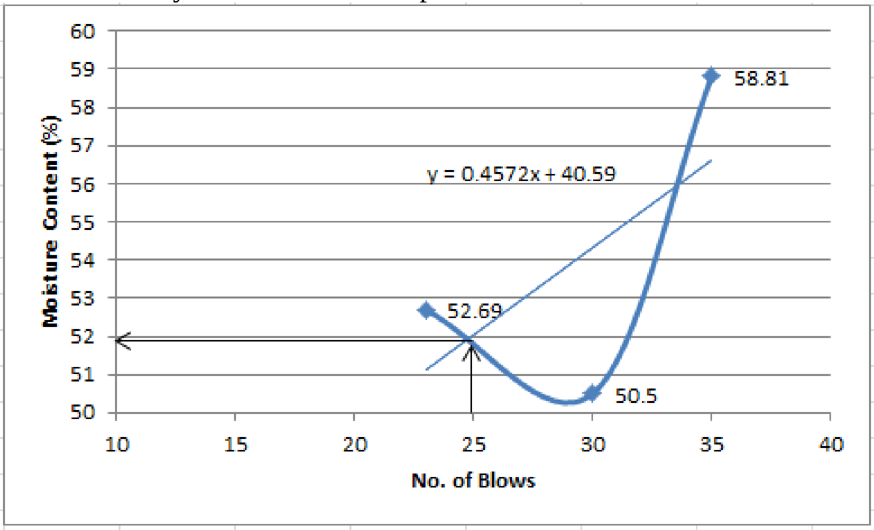


Figure 5: Liquid limit clay soil with 6% stone powder and lime

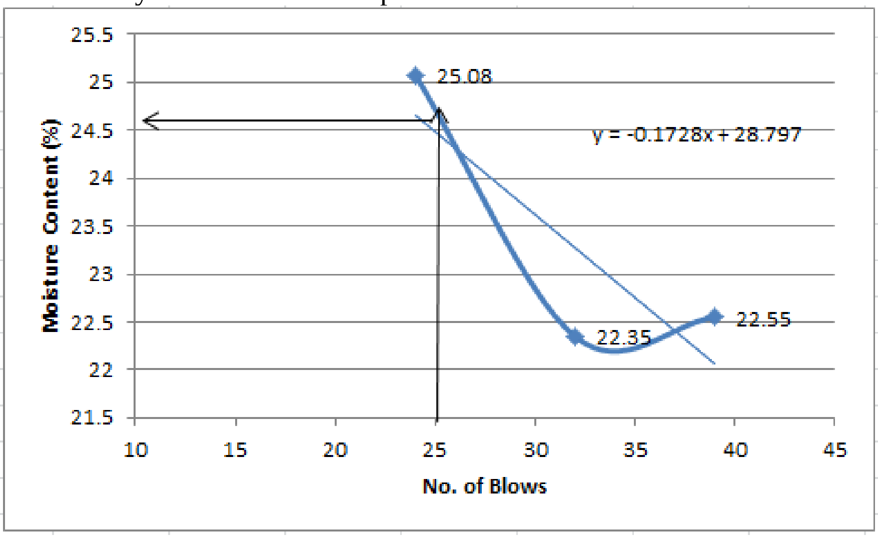


Figure 6: Liquid limit of clay soil with 9% stone powder and lime

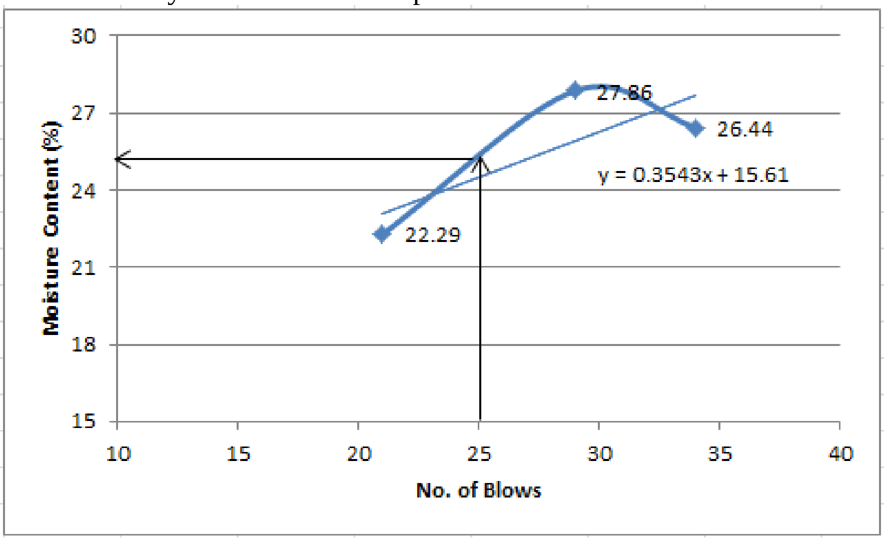


Figure 7: Liquid Limit of contaminated clay soil

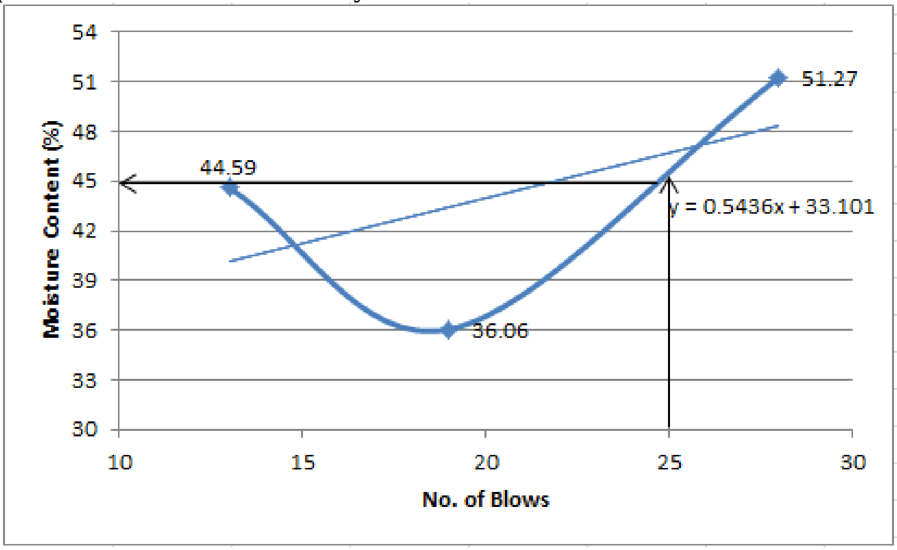


Figure 8: Liquid limit of contaminated clay soil with 3% stone powder and lime

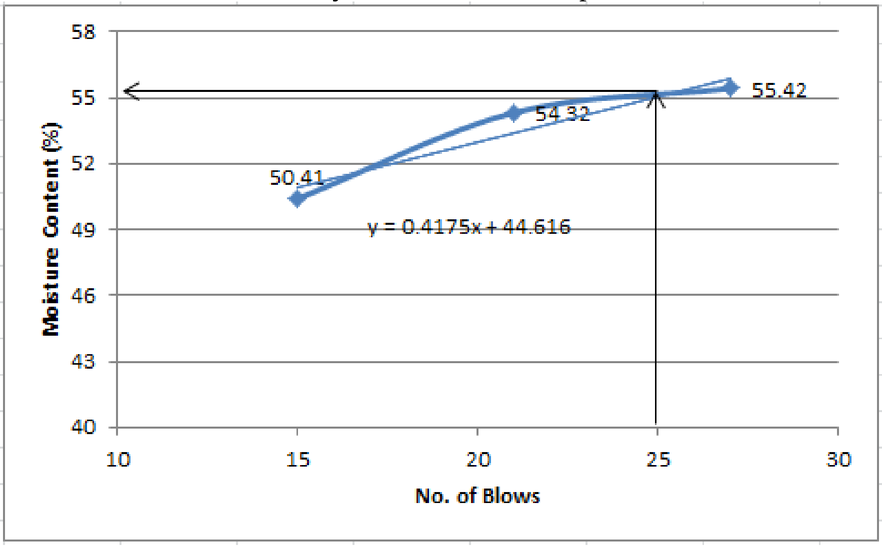


Figure 9: Liquid limit of contaminated clay soil with 6% stone powder and lime

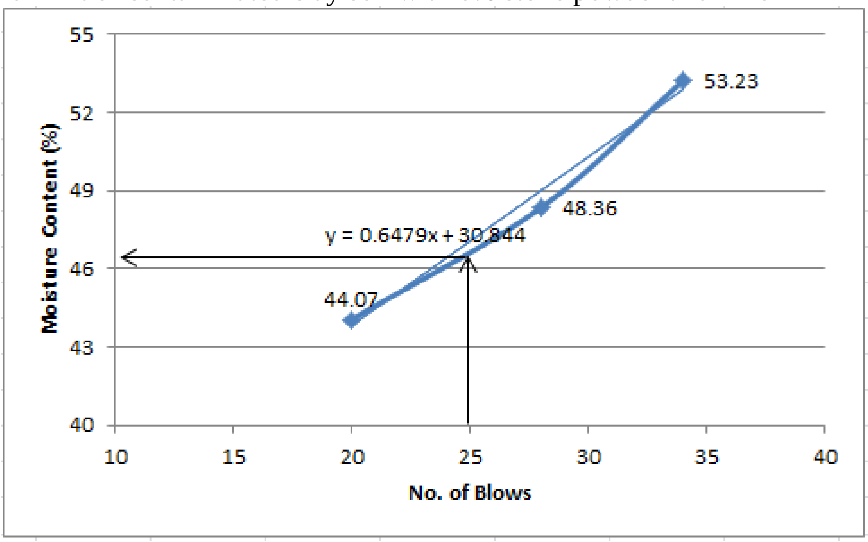


Figure 10: Liquid limit of contaminated clay soil with 9% stone powder and lime plastic limit

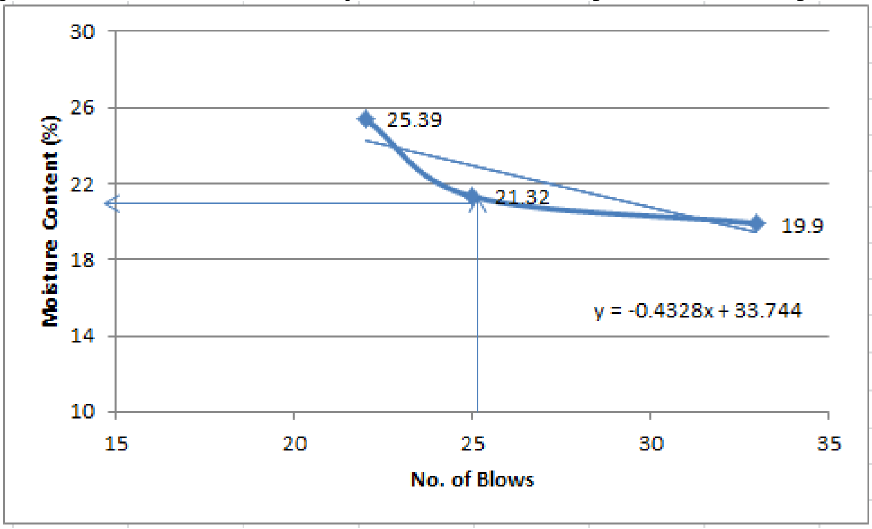


Table-4: Values of the plastic limit and Plasticity Index (PI) of standard and contaminated clayey soil with 0% to 9% stone powder and lime additive

S. No.	Percent Additive (%)	Plastic Limit (PL)	Plasticity Index (PI)
Normal clayey soil sample			
1	0	44	24.55
2	3	20	31.85
3	6	18	6.6
4	9	19	6.5
Contaminated clayey soil sample			
S. No.	Percent Additive (%)	Plastic Limit (%)	Plasticity Index (PI)
1	0	19	24
2	3	22	33
3	6	20	26.5
4	9	18	3.32

3.3. Direct Shear Test (DST)

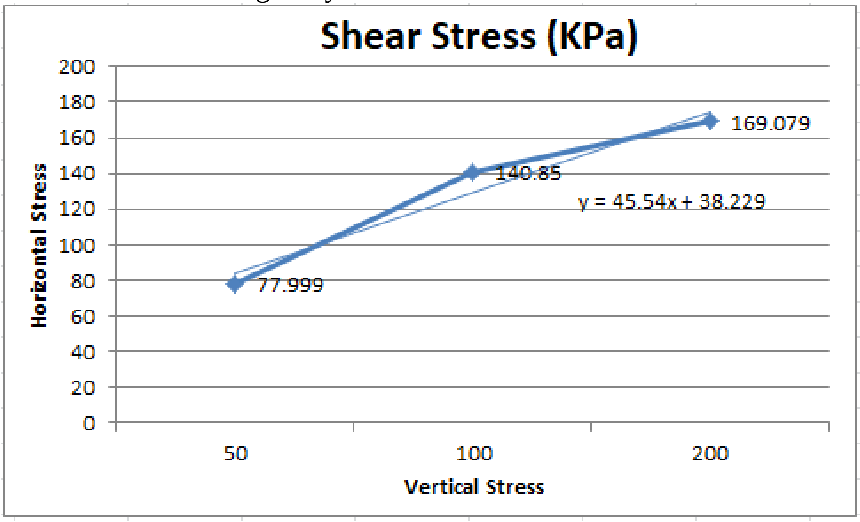
In this type of investigation two types of clayey soil samples were used for the direct shear test: one was normal (uncontaminated) and the other was contaminated with industrial effluent containing tannins and chromium. Lime and stone powder were added to the soils in increasing proportions of 0%, 3%, 6%, and 9% to improve their characteristics. The objective was to assess these additives' impact on the soils' shear strength and investigate the behavioural effects of contamination.

Table-5: DST on average clayey soil

Stress Type	1	2	3
Vertical stress (KPa)	50	100	200
Horizontal stress (KPa)	77.999	140.85	169.079

According to the study, industrial contaminants like chromium and tannins severely impede the shear strength improvement of clayey soils, even though lime and stone powder can successfully increase it. Higher doses or different remediation techniques could be required in contaminated soils to have comparable stabilizing effects. The direct shear test results of the ordinary and contaminated clayey soil follow.

Figure 11: Direct shear test on average clay soil

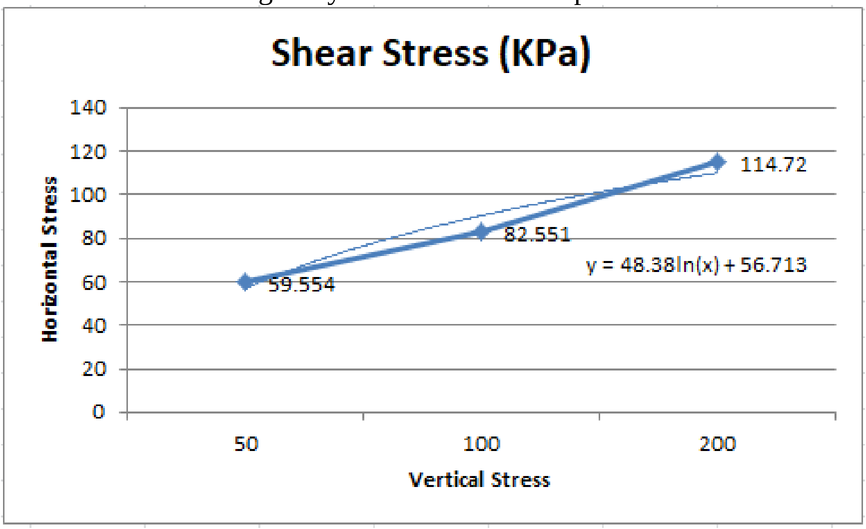


Cohesion (C) = 64
The angle of friction (θ) = 40

Table-6: DST on average clayey soil with 3% stone powder and lime

Stress Type	1	2	3
Vertical stress (KPa)	50	100	200
Horizontal stress (KPa)	59.554	82.551	114.72

Figure 12: Direct shear test on average clay soil with 3% stone powder and lime

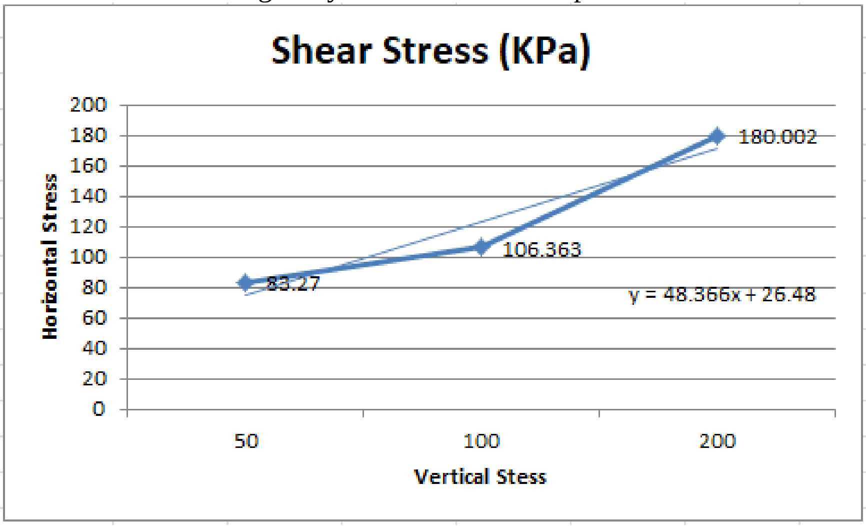


Cohesion (c) = 43
The angle of internal friction (θ) = 36

Table-7: DST on average clayey soil with 6% stone powder and lime

Stress Type	1	2	3
Vertical stress (KPa)	50	100	200
Horizontal stress (KPa)	83.270	106.363	180.002

Figure 13: Direct shear test on average clay soil with 6% stone powder and lime

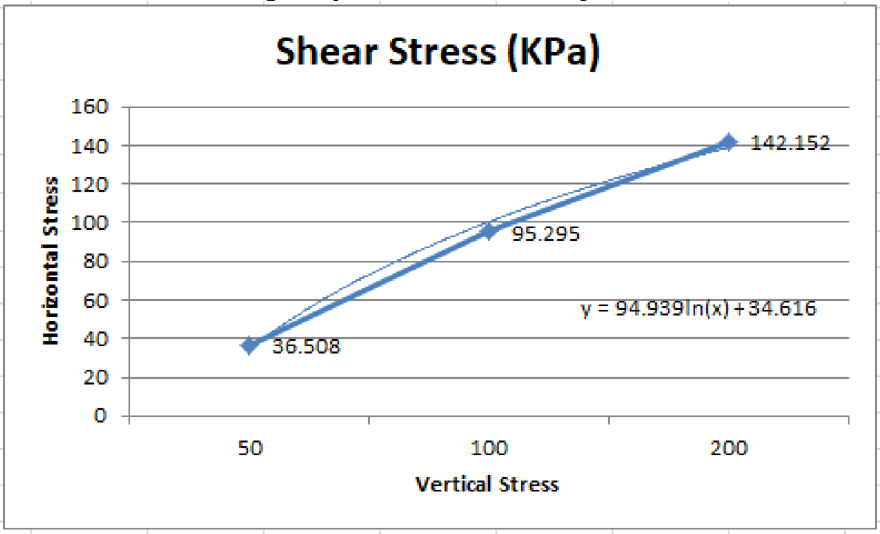


Cohesion (c) = 44
The angle of internal friction (θ) = 41

Table-8: DST on average clayey soil with 9% stone powder and lime

Stress Type	1	2	3
Vertical stress (KPa)	50	100	200
Horizontal stress (KPa)	36.508	95.295	142.152

Figure 14: Direct shear test on average clay soil with 9% stone powder and lime

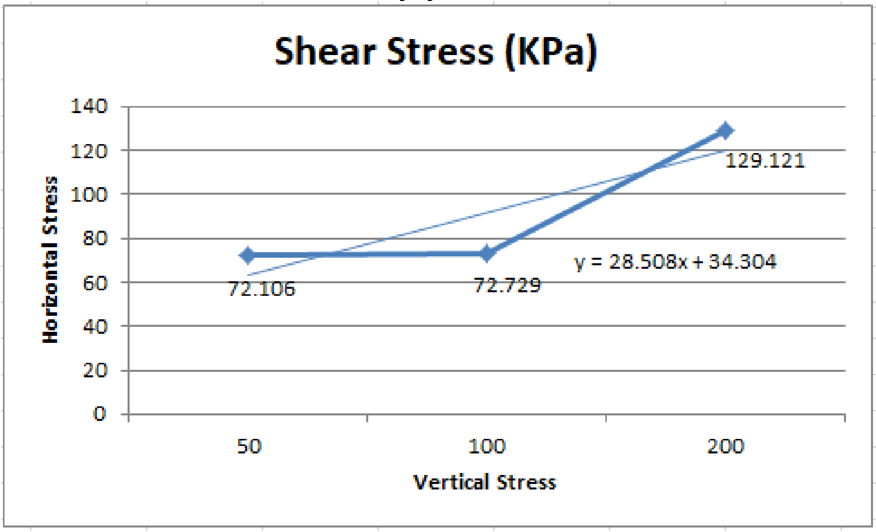


Cohesion (c) = 15
The angle of friction (θ**)** = 50

Table-9: DST on contaminated clayey soil

Stress Type	1	2	3
Vertical stress (KPa)	50	100	200
Horizontal stress (KPa)	72.106	72.729	129.121

Figure 15: Direct shear test on contaminated clayey soil

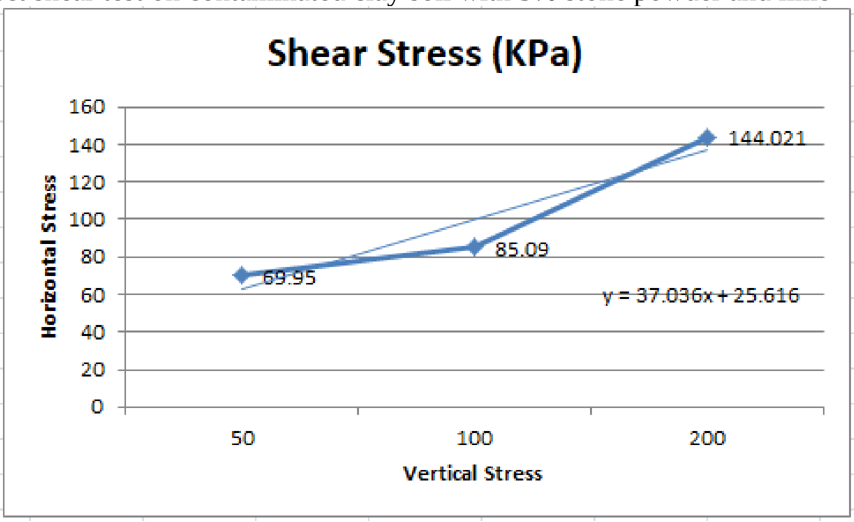


Cohesion (c) = 43
The angle of friction (θ) = 41

Table-10: DST on contaminated clayey soil 3% lime and stone powder

Stress Type	1	2	3
Vertical stress (Kpa)	50	100	200
Horizontal stress (Kpa)	69.950	85.090	144.021

Figure 16: Direct shear test on contaminated clay soil with 3% stone powder and lime

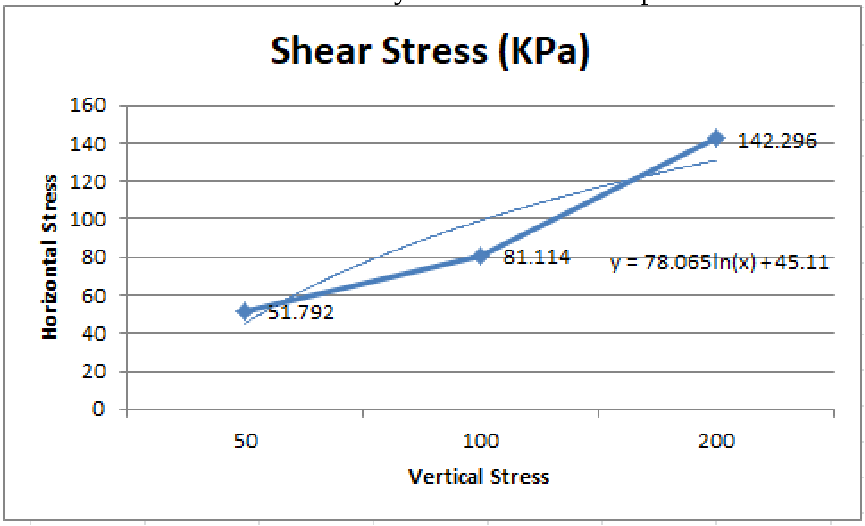


Cohesion (c) = 40
The angle of internal friction (θ) = 45

Table-11: DST on contaminated clayey soil 6% lime and stone powder

Stress Type	1	2	3
Vertical stress (KPa)	50	100	200
Horizontal stress (KPa)	51.792	81.114	142.296

Figure 17: Direct shear test on contaminated clay soil with 6% stone powder and lime

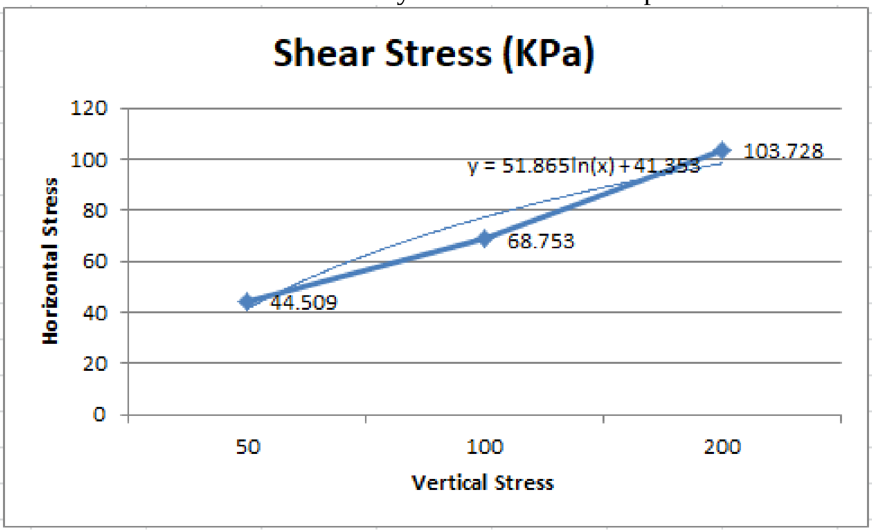


Cohesion (c) = 21
The angle of friction (θ) = 45

Table-12: DST on contaminated clayey soil 9% lime and stone powder

Stress Type	1	2	3
Vertical stress (Kpa)	50	100	200
Horizontal stress (Kpa)	44.509	68.753	103.728

Figure 18: Direct shear test on contaminated clay soil with 6% stone powder and lime



Cohesion (c) = 28
Angle of friction = 43

4. Conclusion

This experiment aimed to assess how cohesive soil geotechnical properties were impacted by tannery wastewater. Generally speaking, cohesive soils' geotechnical behaviour has been shown to degrade when they get contaminated with effluent, which poses a concern to both present and future safety at the building site. The following results provide an analytical summary of the effects on the various soil characteristics: There was an increasing trend in the liquid Limit and Plastic Limit of soil polluted by tannery effluent as contamination increased. The polluted soil's swelling increased from 27.27% to 127%. Thus, it suggests that the tannery effluent significantly impacts clay's swelling properties. When the soil was polluted with tannery effluent, its shear strength declined over many days. In the second part of the study, the possibility of stabilizing soil contaminated by effluent by adding waste stone powder and lime with concentrations of 0%, 3%, 6%, and 9% was examined. When waste stone powder (3%, 6%) and lime (9%) are added to contaminated soil to stabilize it, the soil's liquid limit value decreases.

5. Recommendations

The study recommendations are as follows.

- Adopt advanced treatment technologies: To successfully reduce environmental pollution, use advanced treatment technologies for tannery wastewater, such as physical, chemical, and biological processes.
- Improve monitoring and regulation: To guarantee strict adherence to environmental standards and appropriate disposal procedures for tannery effluents, strengthen monitoring and regulatory frameworks. Encourage the Adoption of Sustainable Practices: To reduce the environmental impact, encourage the leather sector to embrace sustainable practices such as using cleaner technology and alternative tanning chemicals.
- Invest in soil remediation technologies: To enhance the geotechnical characteristics of polluted soils, invest in developing soil remediation technologies, such as lime stabilization, using industrial by-products.
- Cooperate for knowledge sharing: Promote cooperation among government, business, and academic institutions to exchange innovations and knowledge in treating and managing tannery effluent.

Declaration of conflict of interest

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