EFFECTS OF LEACHATE ON COMPACTED CLAY LINER AND TEMPORARY COVER LAYER OF LANDFILL SYSTEMS STABILIZED WITH SODIUM LIGNOSULFONATE

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EFFECTS OF LEACHATE ON COMPACTED CLAY LINER AND TEMPORARY COVER LAYER OF LANDFILL SYSTEMS STABILIZED WITH SODIUM LIGNOSULFONATE

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ABSTRACT

Master Thesis

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This thesis aims to investigate the potential of sodium lignosulfonate (NLS) for stabilizing compacted clay liners against the adverse effects of leachate in municipal solid waste landfill structures. In addition, the potential use of NLS as a temporary cover layer was investigated using column model test. To do so, a series of tests, including particle size distribution, Atterberg limits, compaction, unconfined compressive strength, bender element, SEM, XRD, XRF, FTIR, pH, and EC, heavy metal concentration tests, were performed. In addition, the leaching behavior of the temporary layer stabilized with NLS was examined using the small column test designed for the study. In this research, for the untreated compacted clay liner, five scenarios were determined: (1) mixing the clay with water and testing it in a dry condition, (2) mixing the clay with leachate and testing it in a dry condition, (3) mixing the clay with water and testing it in a wet condition by soaking in water, (4)

mixing the clay with water and testing it in a wet condition by soaking in leachate, and (5) mixing the clay with leachate and testing it in a wet condition by soaking it in water. All these methods are also performed on NLS stabilized compacted clay liner, with testing conducted at various curing times, including 7, 28, and 90 days. For leaching behavior, the effects of various variables on pH, EC, flow rate, and heavy metal concentration were examined, including operation mode, leachate recirculation, thickness of temporary cover, curing time, and type of materials.

The results verified that, even in the worst-case scenario of soaking in leachate, the addition of 1% NLS significantly enhanced the performance of CCLs, reducing the voids percentage by 85.5% and increasing both strength and shear wave velocity by 52% and 40%, respectively. SEM-EDX and FTIR findings confirmed the potential of NLS, even in the presence of leachate, to create electrostatic attraction among the clay particles, develop polymer chains around them, and promote the formation of denser microstructures.

Among various variables, the operation modes and leachate recirculation were found to be very effective in changing the results of heavy metal concentrations in the landfill system, including a temporary cover layer made of a mixture of clay and 1% NLS. A higher temporary cover thickness led to a significant reduction in the amounts of Cd, Cu, and Zn. It was confirmed that curing time did not show substantial effects on changing the results of column model tests. Therefore, in the case of controlling heavy metals concentration, 7 days of curing can be considered adequate and optimum. It was found that the model with NLS alone as a temporary cover could perform better in terms of controlling heavy metal concentrations such as Zn, Ni, Cu, and Cd.

The results of the current project can illustrate the effects of leachate on the environmental, mechanical, physical, and dynamic responses of compacted clay liners in landfill systems, thereby enhancing designers' insights for future designs. Additionally, the project explores the potential of NLS, an industrial byproduct of a paper factory, to enhance the properties of both the compacted clay liner and the temporary cover layer, leading to recycling and reusing NLS for new applications.

Keywords : Sodium lignosulfonate, Landfill system, leachate, unconfined compressive strength, dynamic response, column test, heavy metal concentration.

Science Code :90315

ÖZET

Yüksek Lisans Tezi

SODYUM LIGNOSÜLFONAT İLE STABİLİZE EDİLMİŞ SIZINTI SUYUNUN ATIK DEPOLAMA ALANLARINDA SIKIŞTIRILMIŞ KİL ASTAR VE GEÇİCİ ÖRTÜ TABAKASI ÜZERİNDEKİ ETKİLERİ

Awass AWAM

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Bu çalışma ile sodyum lignosülfonatın (NLS) belediye katı atık depolama yapılarında sızıntı suyunun olumsuz etkilerine karşı sıkıştırılmış kil astarları stabilize etme potansiyeli araştırılmıştır. Buna ek olarak bu çalışmada NLS'nin geçici bir örtü tabakası olarak potansiyel kullanımı kolon test deneyleri ile belirlenmiştir. Hedeflenen amaçlara ulaşmak için çalışma kapsamında tane boyu boyutu dağılımı, Atterberg limitleri, kompaksiyon deneyi, tek eksenli basınç dayanımı, Bender Element Test, SEM, XRD, XRF, FTIR, pH ve EC, ve ağır metal konsantrasyon testlerini içeren bir dizi test gerçekleştirilmiştir. Ayrıca, NLS ile stabilize edilen geçici tabakanın liç davranışı, çalışma için tasarlanan küçük kolon testi kullanılarak incelenmiştir. Çalışma kapsamında, stabilize edilmemiş sıkıştırılmış kil astar için beş senaryo belirlenmiş olup bunlardan ilki; kilin suyla karıştırılıp kuru durumda test edilmesi, ikincisi; kilin sızıntı suyuyla karıştırılıp kuru durumda test edilmesi,

üçüncüsü kilin suyla karıştırılması ve suya batırılarak ıslak durumda test edilmesi, dördüncüsü; kilin suyla karıştırılması ve sızıntı suyuna batırılarak ıslak durumda test edilmesi ve beşincisi; kilin sızıntı suyuyla karıştırılması ve suya batırılarak ıslak durumda test edilmesi. Tüm bu yöntemler aynı zamanda NLS ile stabilize edilmiş sıkıştırılmış kil astar üzerinde de gerçekleştirilmiştir. Ayrıca tüm bu testler 7, 28 ve 90 gün olmak üzere çeşitli kürleme sürelerinde yapılmıştır. Sızıntı davranışı için, çalışma modu, sızıntı suyu devridaimi, geçici kaplamanın kalınlığı, kürleme süresi ve malzeme türü dahil olmak üzere çeşitli değişkenlerin pH, EC, akış hızı ve ağır metal konsantrasyonu üzerindeki etkileri incelenmiştir.

Sonuçlar, en kötü senaryo olan sızıntı suyuna batırılma durumunda bile %1 NLS ilavesinin, boşluk yüzdesini %85,5 oranında azalttığını ve hem mukavemeti hem de kayma dalgası hızını sırasıyla %52 ve %40 oranında artırarak Sıkıştırılmış Kil Tabakalarının performansını önemli ölçüde geliştirdiğini göstermektedir. SEM-EDX ve FTIR bulguları, sızıntı suyu varlığında bile NLS'nin kil parçacıkları arasında elektrostatik çekim oluşturma, bunların etrafında polimer zincirleri geliştirme ve daha yoğun mikro yapıların oluşumunu teşvik etme potansiyelini doğrulamaktadır.

Çeşitli değişkenler arasından çalışma modları ve sızıntı suyu yeniden sirkülasyonunun, kil ve %1 NLS karışımından oluşan geçici bir örtü tabakası da dahil olmak üzere depolama sistemindeki ağır metal konsantrasyonlarının sonuçlarını değiştirmede çok etkili olduğu değerlendirilmiştir. Artan geçici örtü kalınlığı, Cd, Cu ve Zn miktarlarında önemli bir azalmaya yol açmıştır. Kürleme süresinin kolon modeli testlerinin sonuçlarına önemli bir etkisinin olmadığı görülmektedir. Bu nedenle ağır metal konsantrasyonunun kontrol edilmesi durumunda 7 günlük kürün yeterli ve optimum olduğu düşünülebilir. Geçici örtü olarak tek başına NLS'nin kullanıldığı modelin Zn, Ni, Cu ve Cd gibi ağır metal konsantrasyonlarının kontrolü açısından daha iyi performans gösterebileceği sonucuna varılmıştır.

Çalışmanın sonuçları, sızıntı suyunun düzenli depolama sistemlerindeki sıkıştırılmış kil astarların çevresel, mekanik, fiziksel ve dinamik tepkileri üzerindeki etkilerini gösterebilir ve böylece tasarımcıların gelecekteki tasarımlar için öngörülerini geliştirebilir. Ayrıca proje, bir kağıt fabrikasının endüstriyel bir yan ürünü olan

NLS'nin hem sıkıştırılmış kil astarın hem de geçici örtü tabakasının özelliklerini geliştirme potansiyelini araştırarak NLS'nin yeni uygulamalar için geri dönüştürülmesine ve yeniden kullanılmasına yol açmaktadır.

Bu çalışmanın sonuçları, sızıntı suyunun depolama alanlarındaki sıkıştırılmış kil kaplamaların çevresel, mekanik, fiziksel ve dinamik tepkileri üzerindeki etkilerini ortaya koymakta ve tasarımcılara gelecekteki tasarımlar için tahminlerini geliştirmeleri konusunda fikir vermektedir. Ek olarak bu tezden elde edilen sonuçlar, bir kağıt fabrikasının endüstriyel bir yan ürünü olan NLS'nin, hem sıkıştırılmış kil kaplamanın hem de geçici kaplama katmanının özelliklerini iyileştirme potansiyelini ortaya koyarak, NLS'nin bu amaç için geri dönüştürülme ve yeni amaçlar için kullanılma potansiyelini ortaya koymaktadır.

Anahtar Kelimeler : Sodyum lignosülfonat, Depolama sistemi, sızıntı suyu, serbest basınç dayanımı, dinamik tepki, kolon testi, ağır metal konsantrasyonu.

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TABLE OF CONTENTS

Page

KABUL ii

ABSTRACT iv

ÖZET vii

ACKNOWLEDGMENT x

TABLE OF CONTENTS xi

FIGURE INDEX xiv

TABLE INDEX xix

SYMBOLS AND ABBREVITIONS INDEX xx

PART 1 1

INTRODUCTION 1

1.1. BACKGROUND 1

1.2. GENERAL PROBLEM STATEMENT 3

1.3. CURRENT GAP IN THE AREA OF STUDY AND NOVELTIES OF CURRENT STUDY 3

1.4. OBJECTIVES OF RESEARCH 5

1.5. SCOPE AND LIMITATIONS OF CURRENT STUDY 5

1.6. THESIS ORGANIZATION 7

PART 2 8

LITERATURE REVIEW 8

2.1. INTRODUCTION 8

2.2. GENERAL BACKGROUND OF LANDFILL SYSTEMS 10

2.3. GEOTECHNICAL AND ENVIRONMENTAL PROPERTIES OF CCL 12

2.4. GEOTECHNICAL AND ENVIRONMENTAL PROPERTIES OF LANDFILL TEMPORARY COVER 14

Page

2.5. EFFECTS OF LANDFILL LEACHATE ON CHARACTERISTICS OF CCL AND TEMPORARY COVER 15
2.6. STABILIZATION OF CCL 19
2.6.1. Traditional Stabilizers 20
2.6.2. Non-Traditional Stabilizers 22
2.7. RECYCLING and REUSING the WASTE BY-PRODUCTS for TEMPORARY COVER 24
2.8. GENERAL BACKGROUND of APPLICATION of LS IN SOIL STABILIZATION 25
2.8.1. LS Properties 26
2.8.2. The Findings of Main Studies Related to LS Stabilization 27
2.9. SUMMARY and FUTURE DIRECTIONS 28

PART 3 31
MATERIAL AND METHODS 31
3.1. INTRODUCTION 31
3.2. CLAY SAMPLES 34
3.3. LEACHATE SAMPLES 40
3.4. NLS SAMPLES 42
3.5. SAMPLE PREPARATION 44
3.6. UCS (UNCONFINED COMPRESSIVE STRENGTH) 49
3.7. BET (Bender Element Test) 52
3.8. COLUMN MODEL TEST 54
3.9. SUMMARY 60

PART 4 61
RESULTS AND DISCUSSIONS 61
4.1. EFFECTS of LEACHATE on PROPERTIES of CCL 61
4.2. EFFECTS of NLS on PROPERTIES of CCL 64
4.3. RESULTS OF COLUMN MODEL TESTS TO ASSESS THE POTENTIAL USE OF NLS AS A TEMPORARY COVER 69
4.3.1. Flow Rate Results 69

4.3.2. pH and EC Results 73
4.3.3. Heavy Metal Analysis 80
4.4. MICROSTRUCTURAL ANALYSIS 105

PART 5 109
CONCLUSION 109
5.1. INTRODUCTION 109
5.2. MAIN FINDINGS 109
5.3. RECOMMENDATIONS FOR FUTURE STUDIES 111
REFERENCES 113

RESUME 126

FIGURE INDEX

Page

Figure 2.1. Effectiveness of Liner Systems in Preventing Liquid Waste Contamination [48] 17

Figure 2.2. Snapshot and SEM Images of Untreated and Leachate-Treated CH Clays, a) Sample G1: The left panel depicts a snapshot of natural clay G1, while the right panel displays a scanning electron microscope (SEM) image of G1 clay treated with leachate. Both images are magnified at 4000 times.b) Sample G3: On the left, a snapshot of natural clay G3 is shown, while on the right, an SEM image exhibits G3 clay treated with leachate. The magnification for both images is 4000 times [52]. 18

Figure 2.3. Schematic of Landfill Systems Utilizing Compacted Clay Liner and Geosynthetic Clay Liner [63] 20

Figure 3.1. Roadmap for Study Organization 33

Figure 3.2. The geographic coordinates of the clayey site, along with a view of the clay at the site and the clayey sample collection 35

Figure 3.3. A view of the clayey sample preparation in the lab 37

Figure 3.4. A view of the hydrometer test performed on the clayey sample in the lab 37

Figure 3.5. Particle size distribution curve of the clayey sample 37

Figure 3.6: XRD patterns of CCL mixed with water (W) and leachate (L) 39

Figure 3.7. The geographic coordinate of the leachate site 41

Figure 3.8.General view of the leachate site and the collected leachate for the study 42

Figure 3.9. Shows a view of the NLS provided for the study 43

Figure 3. 10. Mixing the clayey samples with water 45

Figure 3.11. Applying the standard compaction test on the clayey samples 45

Figure 3.12. Compacted clay sample submerged in water 47

Figure 3.13.Compacted clay sample submerged in leachate7 47

Figure 3.14. The soil samples under draining procedure 48

Figure 3.15. Stabilizing the clayey samples with NLS 48

Figure 3.16. UCS and BE samples provided for the study 49

Figure 3.17. Figure 3.18. NLS-stabilized samples submerged in water or leachate before starting UCS test 51

Figure 3.19. A sample under UCS testing 51

Page

Figure 3.20. Failure mode of various samples after completing UCS test 52

Figure 3.21. Bender element test device 53

Figure 3.22. A sample under BE testing 54

Figure 3.23. The schematic of the planned small-scale column setup for the experiment 55

Figure 3.24. A view of the solid waste materials prepared for the study.................. 56

Figure 3.25. The features of the various column models designed and carried out in this study 58

Figure 3.26. The actual setup of the column models before and after being filled with the materials 59

Figure 4. 1. Variations in UCS of compacted clay samples across different scenarios and curing times. 62

Figure 4.2. Variations in Vs of compacted clay samples across different scenarios and curing times. 63

Figure 4.3. Effects of different NLS content and curing intervals on UCS of CCLs under DW condition. 65

Figure 4.4. Effects of different NLS content and curing intervals on UCS of CCLs under DL condition. 65

Figure 4.5. Effects of different NLS content and curing intervals on UCS of CCLs under WW condition. 66

Figure 4.6. Effects of different NLS content and curing intervals on UCS of CCLs under WL condition. 67

Figure 4.7. Effects of different NLS content and curing intervals on UCS of CCLs under LW condition. 67

Figure 4.8. Effects of NLS stabilization on CCLs durability in various scenarios.... 68

Figure 4.9. Variations in Vs of CCLs for various scenarios due to NLS addition (a) after 7 days; (b) after 28 days; and (c) after 90 days of curing 69

Figure 4.10. Effects of operation mode on flow rate over time for NLS-treated clay temporary cover. 70

Figure 4.11. Effects of leachate recirculation on flow rate over time for NLS-treated clay temporary cover.. 71

Figure 4.12. Effects of temporary cover thickness on flow rate over time for NLS-treated clay temporary cover 71

Figure 4.13. Effects of curing time on flow rate over time for NLS-treated clay temporary cover 72

Figure 4.14. Effects of temporary cover material type on flow rate over time.......... 73

Figure 4.15. Effects of operation mode on pH over time for NLS-treated clay temporary cover 74

Page

Figure 4.16. Effects of operation mode on EC over time for NLS-treated clay temporary cover. 74
Figure 4.17. Effects of leachate recirculation on pH over time for NLS-treated clay temporary cover 75
Figure 4.18. Effects of leachate recirculation on EC over time for NLS-treated clay temporary cover 76
Figure 4.19. Effects of temporary cover thickness on pH over time for NLS-treated clay temporary cover 77
Figure 4.20. Effects of temporary cover thickness on EC over time for NLS-treated clay temporary cover 77
Figure 4.21. Effects of curing time on pH over time for NLS-treated clay temporary cover 78
Figure 4.22. Effects of curing time on EC over time for NLS-treated clay temporary cover 79
Figure 4.23. Effects of temporary cover material type on pH over time 79
Figure 4.24. Effects of temporary cover material type on EC over time 80
Figure 4.25. Effects of operation mode on Pb over time for NLS-treated clay temporary cover 81
Figure 4.26. Effects of operation mode on Cd over time for NLS-treated clay temporary cover 82
Figure 4.27. Effects of operation mode on Hg over time for NLS-treated clay temporary cover 83
Figure 4.28. Effects of operation mode on as over time for NLS-treated clay temporary cover 83
Figure 4.29. Effects of operation mode on Cr over time for NLS-treated clay temporary cover 84
Figure 4.30. Effects of operation mode on Cu over time for NLS-treated clay temporary cover 85
Figure 4.31. Effects of operation mode on Ni over time for NLS-treated clay temporary cover 85
Figure 4.32. Effects of operation mode on Zn over time for NLS-treated clay temporary cover 86
Figure 4.33. Effects of leachate recirculation on Pb over time for NLS-treated clay temporary cover 87
Figure 4.34. Effects of leachate recirculation on Cd over time for NLS-treated clay temporary cover 88
Figure 4.35. Effects of leachate recirculation on Hg over time for NLS-treated clay temporary cover 88

Page

Figure 4.36. Effects of leachate recirculation on As over time for NLS-treated clay temporary cover 89
Figure 4.37. Effects of leachate recirculation on Cr over time for NLS-treated clay temporary cover 90
Figure 4.38. Effects of leachate recirculation on Cu over time for NLS-treated clay temporary cover 90
Figure 4.39. Effects of leachate recirculation on Ni over time for NLS-treated clay temporary cover 91
Figure 4.40. Effects of leachate recirculation on Zn over time for NLS-treated clay temporary cover 91
Figure 4.41. Effects of temporary cover thickness on Pb content over time for NLS-treated clay temporary cover 92
Figure 4.42. Effects of temporary cover thickness on Cd content over time for NLS-treated clay temporary cover 93
Figure 4.43. Effects of temporary cover thickness on Hg content over time for NLS-treated clay temporary cover 93
Figure 4.44. Effects of temporary cover thickness on As content over time for NLS-treated clay temporary cover 94
Figure 4.45. Effects of temporary cover thickness on Cr content over time for NLS-treated clay temporary cover 94
Figure 4.46. Effects of temporary cover thickness on Cu content over time for NLS-treated clay temporary cover 95
Figure 4.47. Effects of temporary cover thickness on Ni content over time for NLS-treated clay temporary cover 95
Figure 4.48. Effects of temporary cover thickness on Zn content over time for NLS-treated clay temporary cover 96
Figure 4.49. Effects of curing time on Pb content over time for NLS-treated clay temporary cover 96
Figure 4. 50. Effects of curing time on Cd content over time for NLS-treated clay temporary cover 97
Figure 4.51. Effects of curing time on Hg content over time for NLS-treated clay temporary cover 97
Figure 4.52. Effects of curing time on As content over time for NLS-treated clay temporary cover 98
Figure 4.53. Effects of curing time on Cr content over time for NLS-treated clay temporary cover 98
Figure 4.54. Effects of curing time on Cu content over time for NLS-treated clay temporary cover 99
Figure 4.55. Effects of curing time on Ni content over time for NLS-treated clay temporary cover 99

Page

Figure 4.56. Effects of curing time on Zn content over time for NLS-treated clay temporary cover 100

Figure 4.57. Effects of temporary cover material type on Pb content over time 101

Figure 4.58. Effects of temporary cover material type on Cr content over time 101

Figure 4.59. Effects of temporary cover material type on Hg content over time 102

Figure 4.60. Effects of temporary cover material type on As content over time 102

Figure 4.61. Effects of temporary cover material type on Cr content over time 103

Figure 4.62. Effects of temporary cover material type on Cu content over time 104

Figure 4.63. Effects of temporary cover material type on Ni content over time 105

Figure 4.64. Effects of temporary cover material type on Zn content over time 105

Figure 4.65. SEM-EDX, image processing, and FTIR results of various samples .. 108

TABLE INDEX

Page

Table 2.1. The comparison of traditional stabilizers.. 22

Table 3. 1. Test types and corresponding standards.. 35

Table 3.2. The main properties of two clayey samples provided for the study: one mixed with water and the other with leachate.. 37

Table 3.3. The main chemical compositions of two clayey samples provided for the study: one mixed with water and the other with leachate 38

Table 3. 4. Chemical characteristics of the leachate samples collected for the study 42

Table 3.5. The features of the various models designed for this study 58

SYMBOLS AND ABBREVITIONS INDEX

CCL	: compacted clay liner
NLS	: sodium lignosulfonate
UCS	: unconfined compressive strength
BE	: bender element
WC	: wet conditions
DC	: dry conditions
HISWL	: hazardous industrial solid waste leachate
MSW	: Municipal solid waste

PART 1

INTRODUCTION

1.1. BACKGROUND

A landfill, an area designated for the burial of waste materials, plays a pivotal role in waste management practices. To mitigate odors and prevent the scattering of debris, waste is systematically compacted and then overlaid with soil or other suitable materials. However, while landfills are indispensable in waste management, inadequate management practices can precipitate adverse environmental repercussions [1].

To prevent the inadvertent release of waste into the surrounding environment, landfills are equipped with a specialized lining system known as a landfill cover system. Typically applied to the uppermost layer of landfills, this multi-layered system serves as a barrier to contain waste materials securely within the landfill boundaries [1].

Comprising various layers meticulously engineered to address specific concerns, the landfill cover system typically encompasses a bottom layer composed of compacted clay, which serves as an impermeable barrier. This is complemented by layers of materials such as gravel and sand, strategically positioned to impede the infiltration of moisture into the waste mass. Finally, a top layer of soil and vegetation is employed to encapsulate the landfill, providing both physical coverage and aiding in water runoff management [2].

The implementation of a robust landfill cover system not only contributes to the stabilization of waste within the landfill but also serves to prevent potential leaks and significantly diminish the environmental footprint of the landfill site [2].

In developing countries, the establishment of effective landfill systems presents a significant hurdle, compounded by limited resources and infrastructure. This underscores the critical need for innovative approaches to bolster the integrity of these systems. Incorporating enhancements such as mechanical interventions or the utilization of chemical additives becomes not just beneficial, but imperative in fortifying compacted clay liners (CCLs). These enhancements aim to counteract the adverse effects of leachate, which can compromise the structural integrity and containment capabilities of landfill systems [3], [4]. By implementing these strategies, developing nations can better address the challenges associated with waste management, ultimately fostering more sustainable and environmentally conscious practices within their communities.

Lignosulfonate (LS) stands as a notable byproduct stemming from the pulp and paper industry, originating from lignin, a complex organic polymer fundamental in providing structural integrity to plants. The manufacturing process of lignosulfonate involves subjecting lignin to treatment with sulfite compounds under elevated temperatures and pressures [5]. However, as waste and rainwater amalgamate within landfills, they give rise to a potent liquid termed municipal solid waste leachate. Given its composition laden with harmful compounds, this leachate poses a significant risk of contaminating groundwater or surface water sources. Consequently, effective treatment becomes imperative to safeguard both the environment and public health [6]. Depending on the unique composition of the leachate, varied treatment strategies must be employed, underscoring the necessity for meticulous management practices in environmental protection efforts.

As referenced in [7], this study delved into the impact of varying quantities of LS, on the strength and compaction characteristics of clay. Additionally, the researchers explored the influence of factors such as moisture content, ageing, and wetting/drying cycles on both treated and untreated clay specimens.

The citation [2] investigates the role of LS, an unconventional stabilizer, in altering the behavior of expansive soil. The study reveals that LS mitigates swelling tendencies by restricting water absorption within the clay matrix, consequently imparting a waterproofing attribute attributed to LS's inherent hydrophobic properties.

In reference [8], laboratory models simulated clay-sand liners with varying clay content, revealing their effectiveness in reducing percolating water.

Furthermore, in Egypt, an investigation was conducted on the impact of hazardous industrial solid waste leachate (HISWL) on clayey soil, revealing a 10.53% decrease in the plasticity index (PI) of clay contaminated with 100% HISWL [9].

In reference [10], the study examined the impact of leachate seepage on the strength characteristics of a landfill temporary cover material crafted from solidified sewage sludge combined with soda residue, ground granulated blast furnace slag, and quicklime.

1.2. GENERAL PROBLEM STATEMENT

The study addresses the pressing challenge of managing the detrimental impacts stemming from leachate in municipal solid waste landfill structures. Specifically, it delves into the complexities of bolstering the efficacy and resilience of compacted clay liners and temporary cover layers within these landfill systems. The primary objective revolves around harnessing the potential of sodium lignosulfonate (NLS) as a stabilizing agent, aiming to fortify the structural integrity and functional capacity of these essential components. By exploring the intricate interplay between NLS application and landfill soil dynamics, the research endeavours to offer novel insights and innovative solutions to optimize waste containment and environmental protection strategies.

1.3. CURRENT GAP IN THE AREA OF STUDY AND NOVELTIES OF CURRENT STUDY

The current study bridges a significant gap in the understanding of landfill system stabilization techniques by focusing on the efficacy of sodium lignosulfonate (NLS) in mitigating the adverse impacts of leachate in municipal solid waste landfill structures. This gap arises from the limited research and application of NLS as a stabilizing agent for both compacted clay liners and temporary cover layers within landfill systems, particularly concerning their mechanical, dynamic, and geo-environmental analyses. By delving into this underexplored area, the study aims to offer novel insights into the utilization of NLS to fortify the structural integrity and environmental resilience of landfill components.

Furthermore, the study introduces several innovative aspects:

Comprehensive Testing Regimen: By conducting a diverse array of tests encompassing particle size distribution, Atterberg limits, compaction, unconfined compressive strength, and various analytical techniques such as SEM, XRD, XRF, FTIR, pH, and EC tests, the research provides a holistic understanding of the effects of NLS stabilization on compacted clay liners and temporary cover layers.

Small Column Leaching Behavior Examination: Through the utilization of a small column test model designed specifically for this study, the research investigates the leaching behavior of temporary layers stabilized with NLS, offering insights into the long-term environmental implications of NLS utilization in landfill systems.

Exploration of Industrial Byproduct Utilization: The study explores the potential of utilizing sodium lignosulfonate (NLS) as a stabilizing agent, an industrial byproduct of paper manufacturing, highlighting its cost-effectiveness and potential for recycling and reusing waste materials in landfill engineering practices.

Multi-dimensional Approach: By examining the geotechnical, environmental, and mechanical responses of stabilized soil under varying NLS content levels and curing times, the study adopts a multi-dimensional approach to comprehensively evaluate the efficacy of NLS in landfill stabilization, thereby enhancing the robustness of future landfill designs.

Overall, the current study not only addresses critical gaps in existing knowledge but also introduces innovative methodologies and perspectives to advance the field of landfill engineering and environmental sustainability.

1.4. OBJECTIVES OF RESEARCH

1- To examine the effects of landfill leachate on geotechnical characteristics of compacted clay liner i.e., dynamic response, and mechanical strength, considering the dry and wet conditions.

2- To examine the effects of different percentages of NLS content and curing times in mitigating the effects of landfill leachate and wet conditions on geotechnical characteristics of compacted clay liners, i.e., dynamic response and mechanical strength.

3- To investigate the effects of various scenarios, including operation mode, leachate recirculation, curing time, thickness of temporary cover, and type of material, on the environmental and hydraulic parameters (i.e., pH, EC, heavy metal content, and flow rate) of leachate passing through the landfill temporary cover layer stabilized with NLS using small-scale column model tests.

1.5. SCOPE AND LIMITATIONS OF CURRENT STUDY

The scope of this study is to comprehensively investigate the efficacy of sodium lignosulfonate (NLS) as a stabilizing agent for compacted clay liners and temporary cover layers in landfill systems, particularly in mitigating the adverse effects of leachate. The study encompasses various laboratory tests, small-scale column experiments, and analytical techniques to evaluate the geotechnical characteristics, leaching behavior, and mechanical strength of NLS-treated soil.

Scope:

Geotechnical Evaluation: The study examines the dynamic response, mechanical strength, and hydraulic conductivity of compacted clay liners stabilized with different percentages of NLS content. This includes assessing the influence of curing time intervals on the geotechnical properties of NLS-treated soil.

Environmental Analysis: Environmental characteristics such as pH, electrical conductivity (EC), and heavy metal content of NLS-stabilized compacted clay liners are evaluated to understand the environmental implications of NLS utilization in landfill systems.

Mechanical Strength Testing: The mechanical strength of landfill temporary cover layers stabilized with NLS is investigated using column tests. This provides insights into the structural integrity and load-bearing capacity of NLS-treated temporary cover layers.

Leaching Behavior Examination: The leaching behavior of temporary cover layers stabilized with NLS is analyzed through small-scale column experiments. This includes studying the short-term and long-term leaching behavior, as well as variations in pH, EC, heavy metal content, and flow rate of collected leachate.

Limitations:

Generalizability: The findings of this study may be limited to the specific conditions and materials tested, such as the type of clay, NLS content levels, and curing times. Extrapolating the results to different soil types or NLS formulations should be done cautiously.

Laboratory Scale: The laboratory tests and small-scale column experiments conducted in this study provide insights into the performance of NLS-treated soil under controlled conditions. However, actual field conditions may vary, and further validation through field-scale studies is warranted.

Short-Term Evaluation: While the study includes short-term assessments of leaching behavior and mechanical strength, long-term performance and durability of NLS-treated soil in landfill systems may require extended monitoring beyond the scope of this research.

Single Stabilizing Agent: The study focuses exclusively on the utilization of sodium lignosulfonate as a stabilizing agent. Investigating the comparative effectiveness of NLS against other stabilizers or combination treatments could provide additional insights into optimal stabilization strategies.

Despite these limitations, the study aims to contribute valuable insights into the potential use of sodium lignosulfonate for enhancing the performance and sustainability of landfill systems, paving the way for further research and practical applications in the field of geoenvironmental engineering.

1.6. THESIS ORGANIZATION

In this thesis, the structure unfolds with a systematic progression, beginning with Chapter Two, where an exhaustive literature review sets the stage. Chapter Three meticulously delves into the materials and methods employed, offering a comprehensive understanding of the research framework. Chapter Four presents the culmination of efforts, intertwining results and discussions to unveil insights gleaned from the study. Finally, Chapter Five encapsulates the essence of the entire endeavor, distilling it into a conclusive narrative that ties together key findings and implications.

PART 2

LITERATURE REVIEW

2.1. INTRODUCTION

The proper construction of landfill systems poses a formidable challenge in developing countries, where resources and infrastructure may be limited. Central to the functionality of these systems is the compacted clay liner (CCL), a crucial component designed to safeguard against the transmission of contaminants from the leachate of municipal solid wastes (MSW) into the surrounding environment [3]. However, CCLs are susceptible to potential cracking, a vulnerability stemming from the intricate interplay of their geotechnical and microstructural properties, which can be compromised by leachate penetration and submersion from landfill leachates [3], [4]. Consequently, there is a pressing need to augment the characteristics of CCLs through mechanical interventions or the integration of chemical additives to mitigate the adverse effects of leachate.

In this context, researchers have focused on exploring the efficacy of both traditional and environmentally friendly stabilizers in fortifying CCLs. Through a multidisciplinary lens encompassing geotechnical and environmental engineering, investigations have been undertaken to assess the impact of these stabilizers [11]. Traditional stabilizers, often comprising a range of synthetic compounds, have been scrutinized for their effectiveness in bolstering the structural integrity of CCLs. Concurrently, environmentally friendly alternatives, which leverage sustainable materials and processes, have emerged as promising candidates for mitigating the environmental footprint associated with landfill construction and maintenance.

By systematically evaluating the geotechnical and environmental ramifications of various stabilizers, researchers seek to elucidate their efficacy in enhancing CCL performance. Geotechnical considerations encompass an array of factors, such as shear strength, permeability, and compaction characteristics, all of which influence the structural stability and impermeability of the liner [12]. Environmental engineering perspectives delve into the interactions between stabilizers and leachate, assessing their ability to inhibit the migration of contaminants and mitigate potential environmental hazards [13], [14].

Ultimately, the search to optimize CCL performance represents a pivotal endeavor in advancing sustainable waste management practices, particularly in regions grappling with the complex challenges of waste containment and environmental protection. Through rigorous research and innovation, the development of robust and resilient landfill systems can be realized, offering a vital safeguard against the proliferation of pollutants and safeguarding the health and integrity of ecosystems for generations to come [15], [16].

Lignosulfonates (LS), regarded as waste biopolymers and derived from the wood and paper industries, have garnered attention for their effectiveness in soil stabilization. Numerous studies have explored the potential of LS in remedying various problematic soil types, yielding promising results [2], [17]. Despite the extensive research on LS and its long-term implications, its applicability for enhancing CCLs in the presence of landfill leachate remains unexplored, highlighting a critical gap in current research. Therefore, there is a pressing need to investigate the potential of non-lignin lignosulfonates (NLS) in bolstering the performance of CCLs under conditions of leachate exposure [18].

Moreover, understanding the influence of wetting conditions on CCL parameters is crucial for simulating real-world scenarios such as natural disasters or the development of plastic cracks [19]. By subjecting both compacted stabilized and un-stabilized samples to soaking in water and leachate, as well as testing CCL samples mixed with water or leachate under drying conditions, researchers can replicate various environmental conditions encountered in landfill settings. This comprehensive approach enhances the relevance and applicability of the research findings, providing valuable insights into the behavior of CCLs under different circumstances [15], [20], [21],[21].

In this study, in addition to investigating microstructural changes resulting from the application of different scenarios, researchers also assessed the mechanical strength and dynamic properties of the samples. By evaluating these parameters, the study aims to provide a holistic understanding of how LS and NLS treatments influence the structural integrity and performance of CCLs. This multifaceted approach not only enhances the scientific rigor of the research but also offers practical insights for improving the design and construction of landfill containment systems.

2.2. GENERAL BACKGROUND OF LANDFILL SYSTEMS

Landfills are engineered disposal sites designed for the safe and controlled disposal of solid waste. They are the most common method of waste disposal worldwide, particularly in urban areas where waste generation is high. Landfills are carefully planned and constructed to minimize environmental impact and protect public health [22], [23].

As mentioned by [23], [24], [25], [26], the key components of a landfill system include:

1. Liner System: Landfills are lined with impermeable materials such as clay or synthetic liners to prevent leachate, which is the liquid that forms as water percolates through the waste, from contaminating surrounding soil and groundwater.

2. Leachate Collection and Treatment System: Leachate that accumulates at the bottom of the landfill is collected through a network of pipes and directed to a treatment facility to remove pollutants before being released into the environment.

3. Gas Collection System: Landfills produce methane and other gases as organic waste decomposes anaerobically. These gases are collected through a system of pipes and can be used as a source of renewable energy or flared to prevent release into the atmosphere, where methane is a potent greenhouse gas.

4. Cover System: Once a landfill section is filled, it is covered with several layers of soil and other materials to minimize odor, prevent erosion, and discourage pests. Landfill covers also help to control leachate migration and manage gas emissions.

5. Monitoring and Maintenance: Landfills require ongoing monitoring and maintenance to ensure that they remain in compliance with environmental regulations and continue to protect public health and the environment. This includes regular inspections, groundwater monitoring, gas monitoring, and maintenance of infrastructure.

Landfills are classified into different types based on factors such as the type of waste accepted, the technology used for waste treatment, and the level of environmental protection provided. As noted by[23], [27], [28], the common types of landfills include:

1. Sanitary Landfills: These are designed to minimize environmental impact by incorporating liner systems, leachate collection and treatment systems, and gas collection systems. Sanitary landfills are typically used for the disposal of municipal solid waste (MSW) and non-hazardous industrial waste.

2. Industrial Landfills: These are used to dispose of specific types of industrial waste, such as construction and demolition debris, contaminated soil, and other non-hazardous industrial waste.

3. Hazardous Waste Landfills: These are designed to safely dispose of hazardous waste materials that pose a threat to human health and the environment. Hazardous waste landfills must meet stringent regulatory requirements to prevent soil and groundwater contamination.

Landfill systems are crucial in managing solid waste and protecting the environment and public health. However, efforts to reduce waste generation and promote recycling and composting are essential to minimize the need for landfilling and extend the lifespan of existing landfills.

2.3. GEOTECHNICAL AND ENVIRONMENTAL PROPERTIES OF CCL

The geotechnical and environmental properties of CCLs play a crucial role in determining their effectiveness as barriers against contaminant migration in landfill systems. Proper selection of liner materials and construction techniques is essential to ensure the long-term performance and environmental sustainability of CCLs. Here's some information about the geotechnical and environmental properties of CCLs:

- According to references[21], [29], [30], [31], [32], the geotechnical properties in CCL are as follows:

1) Permeability: One of the most critical geotechnical properties of CCLs is their permeability, which refers to the rate at which water can flow through the liner material. Compacted clay liners typically exhibit low permeability, making them effective barriers against the migration of leachate and contaminants from the waste material into the surrounding environment.

2) Compaction Characteristics: The compaction characteristics of CCLs, including factors such as optimal moisture content and maximum dry density, are essential for achieving the desired engineering properties. Proper compaction ensures uniform density and thickness throughout the liner, enhancing its stability and impermeability.

3) Shear Strength: The shear strength of CCLs determines their resistance to internal and external forces, such as settlement, erosion, and slope stability. Adequate shear strength is crucial for maintaining the integrity of the liner system and preventing failure under load.

4) Settlement Behavior: Understanding the settlement behavior of CCLs is essential for predicting long-term performance and ensuring the integrity of the landfill structure. Factors such as consolidation settlement and creep deformation can influence the stability and effectiveness of the liner system over time.

- As mentioned by [21], [33], [34], the environmental properties in CCL are as follows:

1) Chemical Compatibility: CCLs must be chemically compatible with the waste materials they contain to prevent the leaching of harmful substances into the surrounding soil and groundwater. The clay minerals used in CCLs should be inert and non-reactive with the waste constituents to maintain the containment integrity.

2) Resistance to Leachate Penetration: CCLs should effectively resist penetration by leachate, which contains various contaminants derived from decomposing waste materials. The ability of the liner to withstand leachate infiltration is crucial for preventing environmental pollution and protecting groundwater quality.

3) Long-Term Stability: Environmental factors such as temperature variations, biological activity, and chemical reactions can impact the long-term stability of CCLs. The liner material should demonstrate durability and resistance to degradation over time to ensure continued effectiveness in waste containment.

4) Flexibility and Compatibility with Vegetation: In some cases, CCLs may be required to support vegetation cover for erosion control and aesthetic purposes. Therefore, the liner material should exhibit sufficient flexibility and compatibility with vegetation growth to maintain its integrity while supporting plant life.

2.4. GEOTECHNICAL AND ENVIRONMENTAL PROPERTIES OF LANDFILL TEMPORARY COVER

Landfill temporary covers serve as interim protective barriers placed over waste disposal areas to mitigate environmental impacts during active landfill operation and after closure. These covers are crucial for minimizing erosion, controlling odors, reducing leachate generation, and preventing wildlife intrusion. As mentioned by [35], [36], the geotechnical properties of landfill temporary covers:

1) Erosion Resistance: Landfill temporary covers must possess adequate erosion resistance to withstand the erosive forces of wind, rainfall, and surface runoff. Materials with good cohesion and particle interlock are often used to minimize erosion and maintain cover integrity.

2) Permeability: While landfill temporary covers aim to minimize water infiltration to reduce leachate generation, they should still allow for controlled drainage to prevent ponding and erosion. The cover material's permeability is typically engineered to strike a balance between minimizing infiltration and facilitating drainage.

3) Compaction Characteristics: Proper compaction of the temporary cover material is essential to ensure uniform density and thickness across the cover surface. Adequate compaction enhances stability and resistance to settling, erosion, and deformation under load.

4) Load Bearing Capacity: Landfill temporary covers may need to support equipment and personnel during maintenance activities. Therefore, the cover material should possess sufficient load-bearing capacity to withstand these loads without compromising its integrity.

Moreover, as noted by [10], [36], [37], [38], [39], the environmental properties of landfill temporary covers:

1) Chemical Compatibility: Temporary cover materials should be chemically compatible with the underlying waste and leachate to prevent the release of harmful substances into the environment. Compatibility ensures that the cover maintains its effectiveness in controlling leachate migration and environmental pollution.

2) Gas Management: Landfills produce methane and other gases during waste decomposition, which can accumulate beneath temporary covers. The cover material should allow for proper gas venting and management to prevent the buildup of gas pressure and mitigate the risk of subsurface migration and emissions.

3) Vegetation Support: In some cases, landfill temporary covers may be vegetated to enhance erosion control and aesthetic value. The cover material should support vegetation growth by providing adequate soil moisture retention, nutrient availability, and root penetration while maintaining cover integrity.

4) Long-Term Durability: Temporary covers are subjected to environmental stressors such as UV exposure, temperature fluctuations, and biological activity. Therefore, the cover material should demonstrate durability and resistance to degradation over time to ensure continued effectiveness throughout the operational and post-closure phases of the landfill.

Landfill temporary covers play a vital role in minimizing environmental impacts and promoting the sustainable management of solid waste. By carefully selecting and engineering cover materials with appropriate geotechnical and environmental properties, landfill operators can effectively protect surrounding ecosystems and public health while optimizing landfill performance.

2.5. EFFECTS OF LANDFILL LEACHATE ON CHARACTERISTICS OF CCL AND TEMPORARY COVER

The effects of landfill leachate on the characteristics of CCLs and temporary covers are significant considerations in landfill engineering and environmental management.

- **Effects on CCLs:**

CCLs play a crucial role in landfill engineering, serving as a primary barrier to prevent the migration of contaminants into the surrounding environment. However, their effectiveness can be compromised by various factors associated with leachate infiltration[9], [21]. Firstly, leachate infiltration can lead to changes in the permeability of CCLs. As landfill leachate permeates through the waste materials, it interacts with the clay minerals within the liner, potentially increasing its hydraulic conductivity over time. This alteration in permeability undermines the CCL's ability to effectively contain contaminants, posing a significant environmental risk [9], [21], [40], [41], [42]. Secondly, chemical interactions between leachate constituents and clay minerals in CCLs can induce mineralogical changes and alter the properties of the liner. The complex mixture of organic and inorganic compounds present in leachate can contribute to the degradation of CCLs, reducing their containment effectiveness and further exacerbating environmental concerns [9], [21], [43]. Additionally, prolonged exposure to leachate can cause mechanical degradation of CCLs. The structural integrity of the liner weakens over time, leading to issues such as cracking, settlement, and deformation. Factors such as wetting and drying cycles, as well as biological activity within the liner, contribute to the deterioration process, posing challenges to the long-term performance of CCLs [3], [9], [21], [44]. Moreover, some clay minerals within CCLs may exhibit swelling behavior in response to leachate infiltration. This swelling-induced volumetric expansion can lead to loss of compaction and compromise the uniformity and impermeability of the liner, ultimately increasing the risk of leachate migration into the surrounding environment [9], [21], [45], [46], [47].

The effects of leachate on CCLs highlight the need for thorough assessment and mitigation strategies to ensure the long-term integrity and effectiveness of landfill containment systems. By addressing these challenges, we can better safeguard human health and the environment from the potential hazards associated with landfill leachate [9], [21]. The figure 2-1 indicates that all three liner systems are equally effective at preventing liquid waste from contaminating the underlying soil and groundwater. However, this is not the case. Slurry trench/vertical cutoff walls are the most effective liner system, followed by compacted soil liners, and then natural soil liners [48].

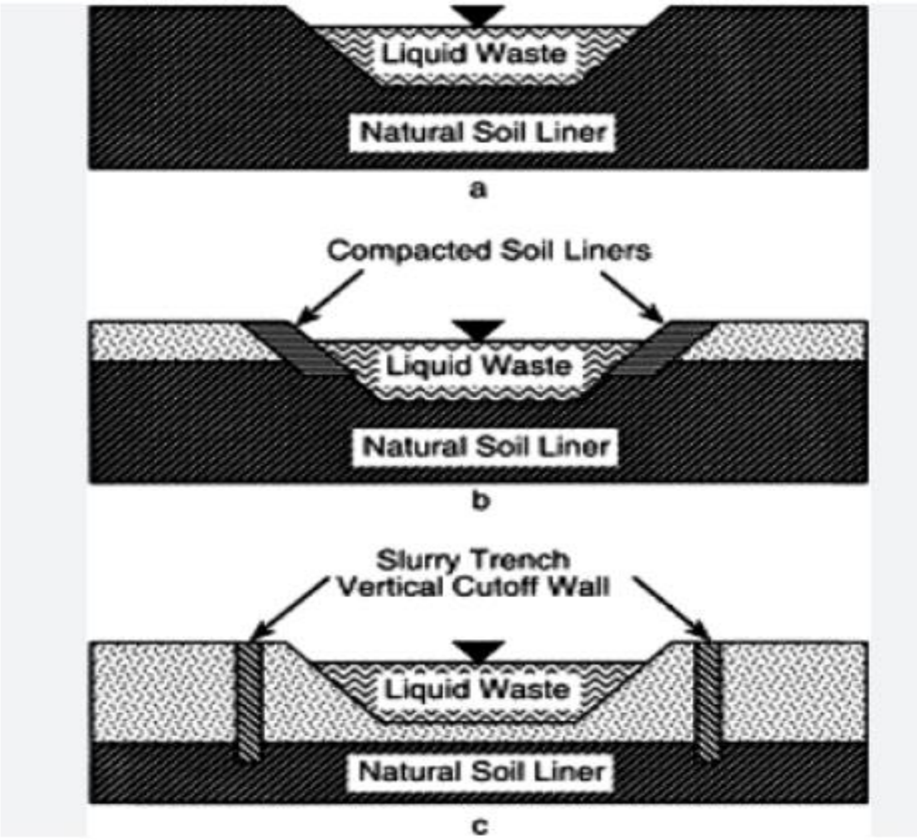


Figure 2.1. Effectiveness of Liner Systems in Preventing Liquid Waste Contamination [48]

- **Effects on Temporary Covers:**

Temporary covers within CCLs are subject to various impacts resulting from landfill leachate infiltration. Moreover, these effects are interrelated, collectively influencing the integrity and performance of the cover system[9], [21]. Leachate infiltration can compromise the stability and erosion resistance of temporary covers. As soil saturation increases and shear strength decreases due to leachate penetration, there is a heightened risk of surface runoff, erosion, and sediment transport. This phenomenon can undermine the integrity of the cover system, potentially exposing underlying waste materials [10], [49]. Furthermore, the establishment and growth of vegetation on temporary covers are adversely affected by leachate infiltration. Alterations in soil pH, nutrient availability, and microbial activity caused by leachate can hinder plant germination and root development. Consequently, the establishment of vital vegetative cover for erosion control and aesthetic enhancement becomes challenging [50], [51]. Figure 2-2 Snapshot and SEM Images of High-Plasticity Clays Before and After Leachate Treatment [52].

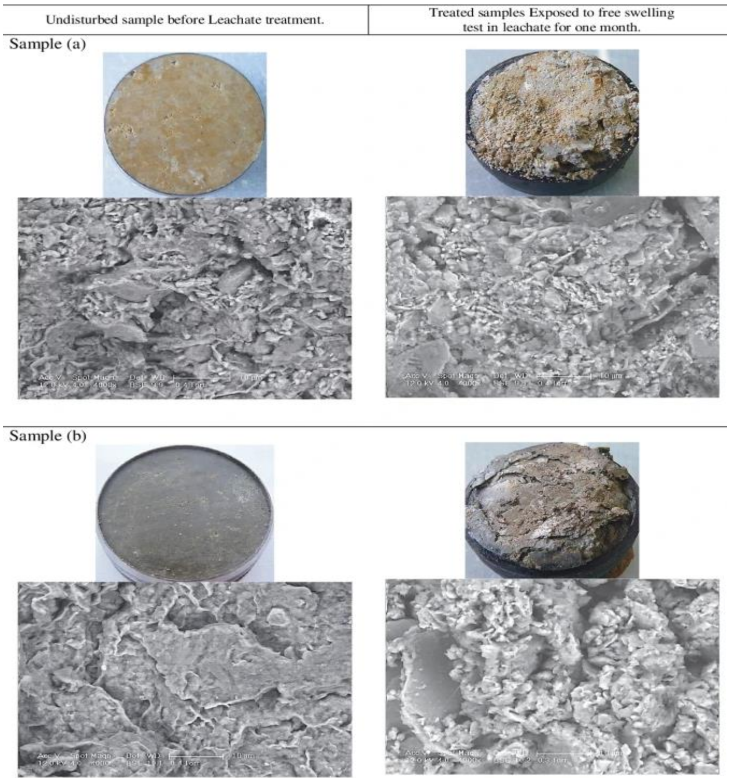


Figure 2.2. Snapshot and SEM Images of Untreated and Leachate-Treated CH Clays, a) Sample G1: The left panel depicts a snapshot of natural clay G1, while the right panel displays a scanning electron microscope (SEM) image of G1 clay treated with leachate. Both images are magnified at 4000 times.b) Sample G3: On the left, a snapshot of natural clay G3 is shown, while on the right, an SEM image exhibits G3 clay treated with leachate. The magnification for both images is 4000 times [52].

Additionally, landfill leachate contributes to the generation of odorous gases like hydrogen sulfide and ammonia, which may permeate through temporary covers. Effective management strategies, such as gas venting and odor control systems, are essential to mitigate potential odor issues and ensure the safety of workers [53], [54]. Moreover, leachate-induced degradation processes, including soil erosion, compaction loss, and vegetation suppression, can significantly impact the long-term durability of temporary covers. Regular maintenance and monitoring are crucial to address these effects and sustain the performance of covers throughout the landfill's operational and post-closure phases [9], [21].

The impacts of landfill leachate on temporary covers emphasize the importance of taking proactive steps and implementing engineering solutions to maintain the integrity and efficiency of landfill containment systems.

2.6. STABILIZATION OF CCL

Stabilization of Compacted Clay Liners (CCLs) involves enhancing their geotechnical properties to improve their performance as barriers against contaminant migration in landfill systems [55], [56]. Additionally, mechanical stabilization methods are commonly employed, such as compaction and reinforcement with geosynthetic materials [57]. Compaction increases the soil's shear strength and reduces its permeability, while reinforcement with materials like geotextiles and geomembranes provides additional stability and resistance to deformation under load [58].

Moreover, chemical stabilization techniques play a significant role in enhancing CCLs [59]. Bentonite, a natural clay mineral, is often used to improve liner impermeability, either by mixing it with the liner material or applying it as a slurry [60]. Polymer additives, such as polyacrylamide and polyethylene, increase cohesion and reduce permeability, while lime and cement react with clay minerals to enhance strength and durability[61].

Furthermore, biological stabilization methods, including microbial treatment and vegetative cover, can enhance CCL performance. Microbial treatments introduce beneficial microorganisms to promote biodegradation and improve soil stability, while vegetative cover stabilizes the soil surface, reduces erosion, and enhances long-term liner effectiveness [62].

Stabilization techniques for CCLs aim to enhance geotechnical properties, increase resistance to leachate penetration, and improve long-term performance in landfill applications [21]. Proper selection and implementation of stabilization methods are crucial to ensure the effectiveness and sustainability of landfill liner systems [27]. Figure 2-3 Schematic Diagram of Landfill Systems Utilizing Compacted Clay Liner and Geosynthetic Clay Liner. The figure depicts landfill systems employing both compacted clay liners (CCLs) and geosynthetic clay liners (GCLs), illustrating their respective roles in waste containment and environmental protection [63].

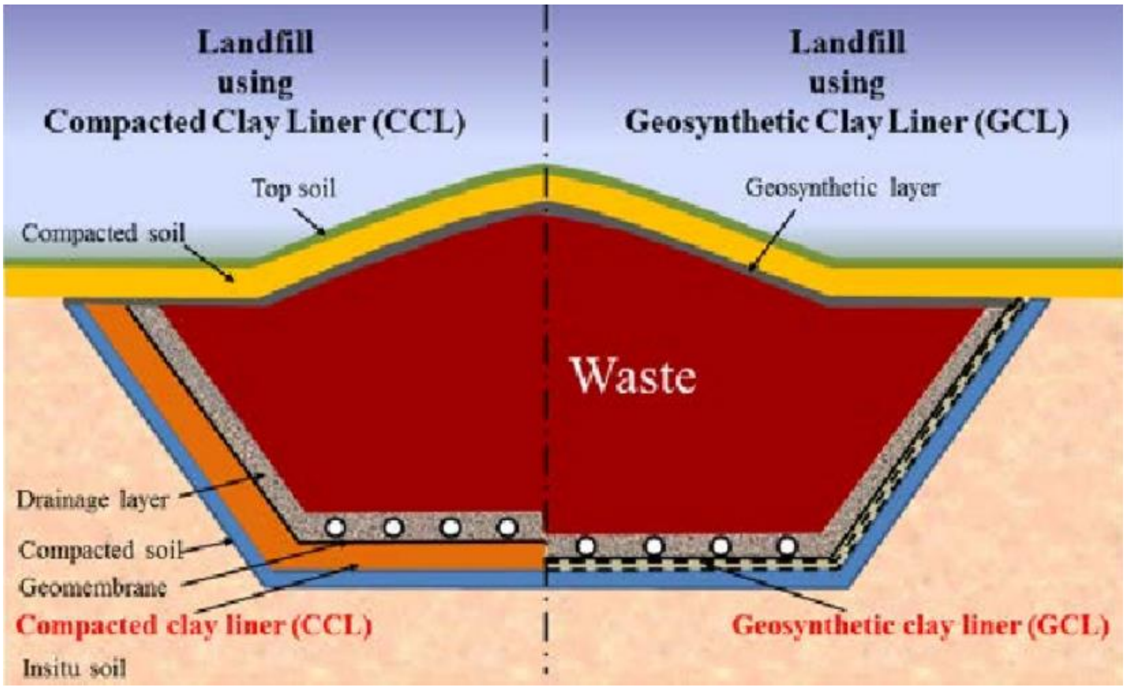


Figure 2.3. Schematic of Landfill Systems Utilizing Compacted Clay Liner and Geosynthetic Clay Liner [63]

2.6.1. Traditional Stabilizers

Traditional stabilizers are widely used to construct CCLs to enhance their geotechnical properties and improve their performance as containment barriers in landfill systems [64]. These stabilizers typically comprise natural or synthetic materials that are added to the clay liner material during construction [65]. Table 2-1 provides a comprehensive comparison of all traditional stabilizers collectively. Here's some information about traditional stabilizers commonly used for CCLs:

1. Bentonite: Bentonite is a naturally occurring clay mineral known for its high swelling capacity and low permeability [66]. When hydrated, bentonite forms a gel-like barrier that effectively seals CCLs against leachate migration. Bentonite can be mixed with the clay liner material or applied as a slurry to the liner surface during construction [67].

2. Lime: Lime, often in the form of quicklime (calcium oxide) or hydrated lime (calcium hydroxide), is used as a chemical stabilizer to improve the strength and durability of CCLs [68]. The lime reacts with clay minerals to form stable compounds [69], enhancing the liner's resistance to deformation and reducing its susceptibility to leachate penetration [70].

3. Cement: Cementitious materials, such as Portland cement, are commonly used as stabilizers for CCLs [71]. The cement reacts with clay minerals and water to form a hardened matrix, increasing the liner's compressive strength and reducing permeability [72]. Cement stabilization is particularly effective in areas with high mechanical stresses or where additional strength is required [73].

4. Synthetic Polymers: Synthetic polymers, such as polyacrylamide and polyethylene, are often added to CCLs to improve their mechanical properties and reduce permeability [74]. Polymer additives increase cohesion and adhesion between clay particles, creating a more stable and impermeable liner [75]. These materials are particularly useful in areas with high hydraulic gradients or where enhanced durability is needed [76].

5. Fly Ash: Fly ash, a byproduct of coal combustion, is sometimes used as a stabilizer for CCLs [77]. Fly ash contains reactive components that can improve soil compaction, increase strength, and reduce permeability when mixed with clay liners [78]. However, the effectiveness of fly ash as a stabilizer may vary depending on its chemical composition and particle size distribution [79].

Table 2.1. The comparison of traditional stabilizers

Stabilizer	Type	Description	Benefits	Ref
Bentonite	Natural Clay Mineral	High swelling capacity and low permeability	Reduces leachate migration by forming a gel-like barrier	[80]
Lime	Chemical Stabilizer	Often used as quicklime (calcium oxide) or hydrated lime (calcium hydroxide)	Improves strength, and durability, and reduces deformation and leachate penetration	[81]
Cement	Cementitious Material (e.g., Portland cement)	Increases compressive strength and reduces permeability	Effective in high-stress areas or where additional strength is required	[82]
Synthetic Polymers (e.g., polyacrylamide, polyethylene)	Additives	Improves mechanical properties and reduces permeability	Enhances cohesion and adhesion of clay particles for a more stable liner	[83]

Traditional stabilizers are crucial in enhancing the geotechnical properties and performance of CCLs in landfill applications. Proper selection and application of stabilizers are essential to ensure landfill containment systems' long-term effectiveness and sustainability.

2.6.2. Non-Traditional Stabilizers

Non-traditional stabilizers represent innovative approaches to enhancing the performance of CCLs in landfill applications [84]. These stabilizers typically consist of alternative materials or methods that offer advantages such as environmental sustainability, cost-effectiveness, or improved performance compared to traditional stabilizers [85].

Here's some information about non-traditional stabilizers used for CCLs:

1. Bio-based Polymers: Bio-based polymers derived from renewable sources, such as starches, cellulose, and lignin, are gaining attention as environmentally friendly alternatives to synthetic polymers [86]. These polymers can improve the mechanical properties and reduce the permeability of CCLs while minimizing environmental impact [87].

2. Waste-Derived Additives: Waste-derived additives, such as recycled plastics, tire crumbs, and industrial byproducts, are being investigated for their potential to enhance CCL performance [88]. These materials offer a sustainable solution for stabilizing clay liners while diverting waste from landfills and reducing environmental pollution.

3. Nano-Materials: Nano-materials, including nano-clays, nano-silica, and carbon nanotubes [89], are being explored for their ability to modify the microstructure and properties of CCLs at the molecular level [90]. These materials can improve mechanical strength, reduce permeability, and enhance the durability of clay liners, offering innovative solutions for advanced landfill containment systems [91].

4. Enzyme-Based Stabilizers: Enzyme-based stabilizers utilize biological catalysts to promote soil stabilization and improve CCL performance [92]. These enzymes can enhance soil structure, increase shear strength, and reduce permeability by facilitating chemical reactions and microbial activity within the liner material [93].

5. Geosynthetic Reinforcement: Non-traditional stabilizers may also include geosynthetic reinforcement techniques such as geotextiles, geogrids, and geomembranes [94]. These materials provide additional tensile strength, stability, and resistance to deformation, complementing traditional stabilization methods and improving overall liner performance [95].

Non-traditional stabilizers offer innovative solutions for enhancing the geotechnical properties and performance of CCLs in landfill applications. Their use can contribute to environmental sustainability, cost savings, and improved long-term durability of landfill containment systems. Continued research and development in this area are essential to identify and optimize non-traditional stabilizers for widespread application in the field of waste management.

2.7. RECYCLING AND REUSING THE WASTE BY-PRODUCTS FOR TEMPORARY COVER

Recycling and reusing waste by-products for temporary cover in landfill systems is an environmentally sustainable practice that offers several benefits, including waste diversion, cost savings, and reduced environmental impact [96].

various waste materials generated from industrial, agricultural, and municipal activities can be recycled or reused for temporary cover in landfills [36]. Examples include construction and demolition debris, coal combustion residues, agricultural residues, and industrial by-products [97]. These materials offer viable alternatives for covering landfill waste, contributing to waste diversion, cost savings, and reduced environmental impact [98]. Moreover, recycling and reusing waste by-products for temporary cover provides several benefits. This practice helps divert materials from landfill disposal, reducing waste volume and extending landfill lifespan. Additionally, it can lead to cost savings for landfill operators by reducing the need to purchase new materials and disposal fees. Furthermore, it helps minimize environmental pollution, conserve natural resources, and mitigate greenhouse gas emissions associated with waste disposal and material production [99].

Regulatory considerations are crucial when considering the use of recycled materials for temporary cover. Landfill operators must comply with regulatory requirements and guidelines governing the use of recycled materials to ensure environmental protection and public health. Regulatory agencies may establish standards for material quality, compaction, and leachate management to mitigate potential risks associated with recycled materials.

Effective implementation of recycling and reusing waste by-products for temporary cover requires careful planning and quality control measures. Landfill operators should assess the suitability and performance of recycled materials, develop engineering specifications, and monitor cover construction to ensure compliance with regulatory requirements and achieve desired outcomes. By incorporating recycled materials into cover systems, landfill operators can promote sustainable waste management practices and contribute to the transition to a circular economy.

2.8. GENERAL BACKGROUND OF APPLICATION OF LS IN SOIL STABILIZATION

Lignosulfonates (LS) are natural polymers obtained from lignin; a complex organic compound found in the cell walls of plants [100]. They are typically extracted during the pulping process in the paper industry, making them abundant and readily available [101]. Lignosulfonates are water-soluble polymers with a high degree of molecular flexibility and reactivity [102]. Moreover, they undergo sulfonation processes to introduce sulfonic acid groups into the lignin structure, imparting water solubility and anionic character [103]. This property makes lignosulfonates highly dispersible and reactive in aqueous solutions [103].

Furthermore, lignosulfonates function as soil stabilizers through various mechanisms. They act as dispersing agents, reducing electrostatic forces between soil particles and promoting particle dispersion [104]. This improves the workability and compaction of soil mixtures [104]. Additionally, lignosulfonates can form chemical bonds with soil particles, increasing cohesion and strength in stabilized soils [105]. Moreover, they have hygroscopic properties, allowing them to absorb and retain moisture within stabilized soil mixtures, improving workability, reducing dust generation, and enhancing long-term durability.

Moreover, lignosulfonates find widespread applications in civil engineering, including road construction, embankments, railway tracks, and slope stabilization [106]. They are commonly used as additives to soil-cement, soil-lime, and soil-aggregate mixtures to improve engineering properties and performance [107]. Additionally, lignosulfonates are considered environmentally friendly soil stabilizers due to their natural origin and biodegradability [108]. They pose minimal risk to ecosystems and groundwater quality compared to synthetic stabilizers [109]. Additionally, lignosulfonates can be derived from renewable sources, contributing to sustainable waste utilization in the wood and paper industries[110].

2.8.1. LS Properties

The properties of lignosulfonates (LS) are crucial in their effectiveness as soil stabilizers and various other applications [111].

Here's some information about the properties of LS:

Water Solubility: One of the key properties of LS is its water solubility [112]. LS are water-soluble polymers due to sulfonic acid groups introduced during the sulfonation process [112]. This property makes LS highly dispersible and reactive in aqueous solutions, facilitating their application in soil stabilization and other industries [113].

Anionic Character: LS exhibits anionic character, meaning they carry a negative charge in solution [114]. This anionic nature allows LS to interact with positively charged ions and surfaces in soils, enhancing their dispersing and binding capabilities [114]. The anionic character of LS contributes to their effectiveness as dispersants and binding agents in soil stabilization applications [115].

Dispersing and Binding Properties: LS acts as a dispersing agent in soil stabilization by reducing the electrostatic forces between soil particles and promoting particle dispersion [116]. This improves the workability and compaction of soil mixtures. Additionally, LS can form chemical bonds with soil particles, acting as binding agents to increase cohesion and strength in stabilized soils [117]. These dispersing and binding properties make LS effective in improving soil stability and reducing erosion.

Hygroscopicity: LS possess hygroscopic properties, meaning they have the ability to absorb and retain moisture from the surrounding environment [118]. This property allows LS to improve the workability of soil mixtures by maintaining optimal moisture content. Additionally, the hygroscopic nature of LS contributes to dust suppression and enhances long-term durability in stabilized soil applications [119].

Biodegradability: LS are biodegradable polymers derived from lignin, a natural component of plant cell walls [120]. LS are environmentally friendly and pose minimal risk to ecosystems and groundwater quality compared to synthetic stabilizers [121]. The biodegradability of LS contributes to their sustainability and makes them attractive options for soil stabilization and other applications [122].

the properties of LS, including water solubility, anionic character, dispersing and binding capabilities, hygroscopicity, and biodegradability, make them effective soil stabilizers and environmentally friendly alternatives in various industries. Understanding these properties is essential for optimizing the use of LS in soil stabilization and other applications [123].

2.8.2. The Findings of Main Studies Related to LS Stabilization

Studies related to LS stabilization have investigated its effectiveness in improving soil properties and its applicability in various engineering applications.

Here are some key findings from primary studies related to LS stabilization:

Soil Stabilization Performance: Several studies have demonstrated the effectiveness of LS in stabilizing soil and enhancing its engineering properties[124]. LS has been shown to improve soil workability, increase shear strength, reduce permeability, and enhance compaction characteristics. These improvements improve soil stability and durability in various engineering applications, including road construction, embankments, and slope stabilization[125].

Impact on Soil Microstructure: Studies have investigated the impact of LS on soil microstructure and mineralogy [126]. LS treatment has been found to alter the soil matrix by promoting particle dispersion and modifying the arrangement of soil particles [126]. This results in improved soil structure increased soil-aggregate stability, and reduced soil erosion potential. Understanding the effects of LS on soil microstructure is essential for optimizing its application in soil stabilization [127].

Compatibility with Other Additives: Research has examined the compatibility of LS with other soil stabilizers and additives, such as cement, lime, and fly ash [128]. Studies have shown that LS can be effectively combined with other stabilizers to achieve synergistic effects and enhance soil stabilization performance [129]. The compatibility of LS with other additives allows for the development of tailored stabilization methods to meet specific engineering requirements and site conditions [129].

Environmental Impact: Investigations have evaluated the environmental impact of LS stabilization, including its potential effects on soil and groundwater quality [130]. Studies have shown that LS is environmentally friendly and poses minimal risk to ecosystems and groundwater compared to synthetic stabilizers [130]. LS is biodegradable and derived from renewable sources, making it a sustainable option for soil stabilization and reducing the environmental footprint of construction activities [131].

Cost-effectiveness: Studies have assessed the cost-effectiveness of LS stabilization compared to conventional stabilization methods [132]. LS has been found to offer cost savings in material procurement, construction, and maintenance. Using LS as a soil stabilizer can reduce overall project costs while providing comparable or superior engineering performance, making it an attractive option for infrastructure development projects [123].

2.9. SUMMARY AND FUTURE DIRECTIONS

Properly constructing landfill systems remains a significant challenge, especially in developing countries [133]. Compacted Clay Liners (CCLs) are fundamental components designed to control the transmission of contaminants from landfill leachate to the surrounding environment [3]. However, CCLs are susceptible to potential cracking and degradation due to leachate penetration and submersion, necessitating enhancements to their characteristics.

Traditional stabilizers, such as bentonite, lime, cement, and synthetic polymers, have been extensively used to improve CCL performance [84]. Additionally, non-traditional stabilizers, including bio-based polymers, waste-derived additives, nano-materials, enzyme-based stabilizers, and geosynthetic reinforcements, offer innovative approaches to soil stabilization with potential environmental and economic benefits [134].

Moreover, lignosulfonates (LS), derived from waste biopolymers in the wood and paper industries, have emerged as effective soil stabilizers [135]. LS exhibits water solubility, anionic character, dispersing and binding properties, hygroscopicity, and biodegradability, making them suitable for soil stabilization applications [135]. Studies have shown that LS can improve soil workability, increase shear strength, reduce permeability, and enhance compaction characteristics [136].

Future directions in soil stabilization include further research to optimize traditional and non-traditional stabilizers in landfill systems and other engineering applications, including LS [119]. This includes investigating the compatibility of stabilizers with different soil types, exploring the synergistic effects of combined stabilizers, and assessing long-term performance and environmental sustainability [137], [138].

Additionally, advancements in stabilization techniques, such as innovative stabilization methods and novel materials, will continue to improve landfill construction practices [139]. Furthermore, research efforts should focus on developing sustainable and cost-effective solutions to address the challenges associated with landfill leachate management and environmental protection [140]. Continued research and development in soil stabilization techniques and materials will play a crucial role in advancing the construction and management of landfill systems, ensuring environmental protection, and promoting sustainable waste management practices in the future [141].

PART 3

MATERIAL AND METHODS

3.1. INTRODUCTION

This chapter serves as a comprehensive elucidation of the materials and methodologies applied throughout the study, aiming to scrutinize and ascertain the efficacy of alternative materials in the treatment of compacted clay liners (CCLs) within landfill systems. It not only delineates the characteristics of the primary components involved, including the clay samples, leachate samples, and the sodium lignosulfonate (NLS), but also provides an intricate insight into the sample preparation techniques employed and the diverse array of laboratory tests conducted to meticulously evaluate the mechanical, physical, and environmental attributes of the specimens under investigation.

The characterization of clay samples forms a pivotal aspect of the study, as it lays the foundation for understanding their intrinsic properties and potential suitability for CCL applications [142]. Through detailed analysis, including classification based on the Unified Soil Classification System and elemental composition assessments via X-ray fluorescence (XRF) analysis, the unique characteristics of the clay samples from Karabuk, Turkey, were meticulously elucidated. Moreover, X-ray diffraction (XRD) patterns were scrutinized to discern any structural alterations arising from the interaction of clay with leachate, providing invaluable insights into the behavior of the material under realistic landfill conditions.

In parallel, the procurement and characterization of leachate samples hold paramount importance, as they emulate the real-world conditions encountered within landfill environments. Obtained from a landfill site in Karabuk, Turkey, these samples encapsulate the diverse array of contaminants and chemical constituents present within landfill leachate, thereby facilitating a comprehensive evaluation of the interaction between leachate and CCL materials.

Furthermore, the utilization of sodium lignosulfonate (NLS) as an alternative material for CCL stabilization introduces a novel dimension to the study. Originating from lignin through a sulfite treatment process, NLS offers promising prospects for enhancing the mechanical and environmental performance of CCLs. The varying concentrations of NLS incorporated into the clay samples are meticulously controlled and systematically analyzed to ascertain their impact on the stabilization mechanisms and overall efficacy of the CCL materials.

Beyond characterization, the chapter meticulously delineates the sample preparation techniques adopted to ensure uniformity and reproducibility in the experimental setup. From the determination of optimum moisture content (OMC) to the compaction of samples to achieve maximum dry density (MDD), each step is meticulously outlined to maintain consistency and accuracy across the experimental trials [143].

Moreover, a comprehensive array of laboratory tests is conducted to delve into the multifaceted properties of the specimens under investigation. These include Unconfined Compressive Strength (UCS) tests, which provide insights into the mechanical integrity of the CCL materials under varying curing conditions and NLS concentrations. Additionally, Bender Element Test (BET) analysis offers insights into the dynamic response of compacted clay liners under varying curing conditions, leachate effects, and NLS treatment.

Furthermore, column model tests were conducted to simulate leachate percolation through the landfill temporary layer, facilitating an in-depth assessment of their hydraulic behavior and contaminant transport mechanisms. Complementing these mechanical and hydraulic evaluations, environmental tests were meticulously conducted to assess the pH, electrical conductivity (EC), and heavy metal content of the samples, ensuring compliance with stringent environmental standards and regulations [144].

The flowchart shown in Figure 3-1 is used to guide the study's step-by-step organization.

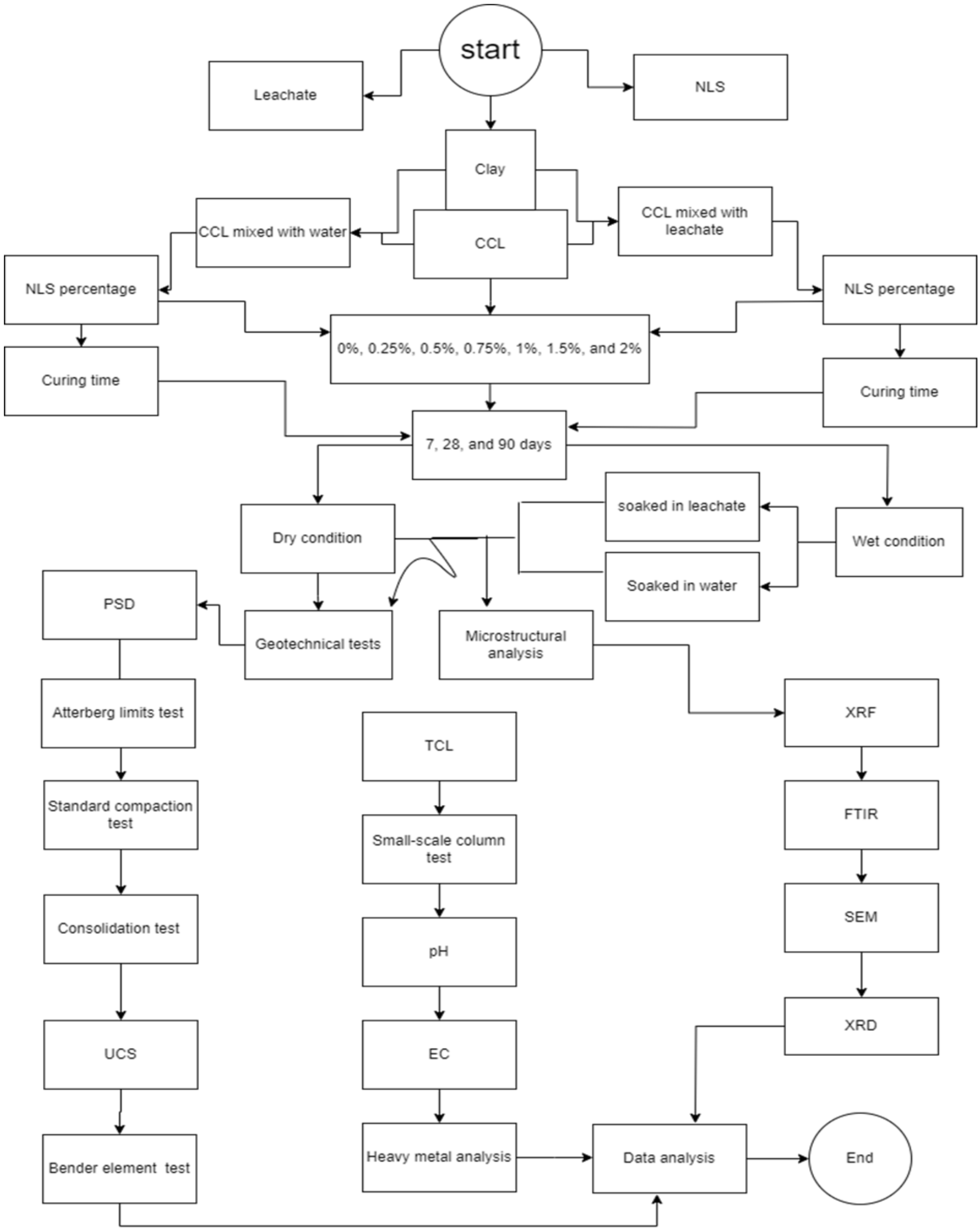


Figure 3.1. Roadmap for Study Organization

In essence, this chapter serves as a comprehensive roadmap delineating the materials, methodologies, and experimental procedures employed in the study. Integrating advanced analytical techniques with meticulous sample preparation and testing protocols lays the groundwork for the subsequent analysis and discussion of the study findings, thereby advancing our understanding of the potential applications of alternative materials in landfill engineering and environmental remediation efforts.

3.2. CLAY SAMPLES

Clay samples were first collected from the field (Karabuk City, Turkey), and their characteristics were determined through physical, chemical, and mechanical tests. Figure 3.2 shows the geographic coordinates of the site, along with views of the clay at the site and the sample collection process. Upon collection, stringent protocols were followed to prevent contamination and ensure the integrity of the samples.

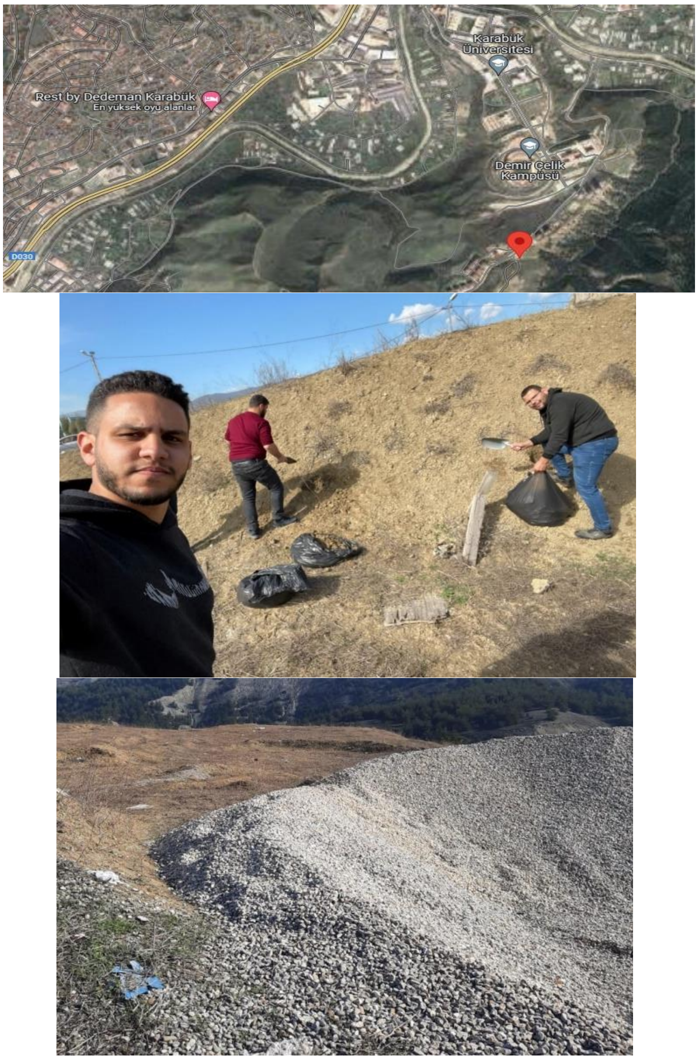


Figure 3.2. The geographic coordinates of the clayey site, along with a view of the clay at the site and the clayey sample collection

The clayey samples collected from the site were subjected to various tests, including particle size distribution tests in accordance with ASTM D422, Atterberg limits tests in accordance with ASTM D4318, standard compaction tests in accordance with ASTM D698, unconfined compressive strength tests in accordance with ASTM D2166, and bender element tests in accordance with ASTM D8259. Additionally, XRF, SEM, FTIR, and XRD analysis were used to look at the samples' chemical compositions, microstructure, and mineralogy. Table 3-1 shows the standard of different tests used in this study.

Table 3. 1. Test types and corresponding standards

Test type	Standard
Particle size distribution test	ASTM D 422
Atterberg limits tests	ASTM D 4318
standard compaction test	ASTM D 698
Unconfined compressive strength test	ASTM D 2166
Bender element test	ASTM D 8295

Figure 3.3 shows the preparation of the clayey samples for the basic geotechnical tests, whereas Figure 3.4 shows a view of the hydrometer test conducted to achieve the particle size distribution curve of the clayey samples collected for the study. The particle size distribution curve of the clay is shown in Figure 3.5. The preliminary results of the collected clayey samples are summarized in Table 3.2. Table 3.3 shows the main chemical compositions obtained from XRF analysis for two clayey samples, one mixed with water and the other with leachate.

Figure 3.3. A view of the clayey sample preparation in the lab

Figure 3.4. A view of the hydrometer test performed on the clayey sample in the lab

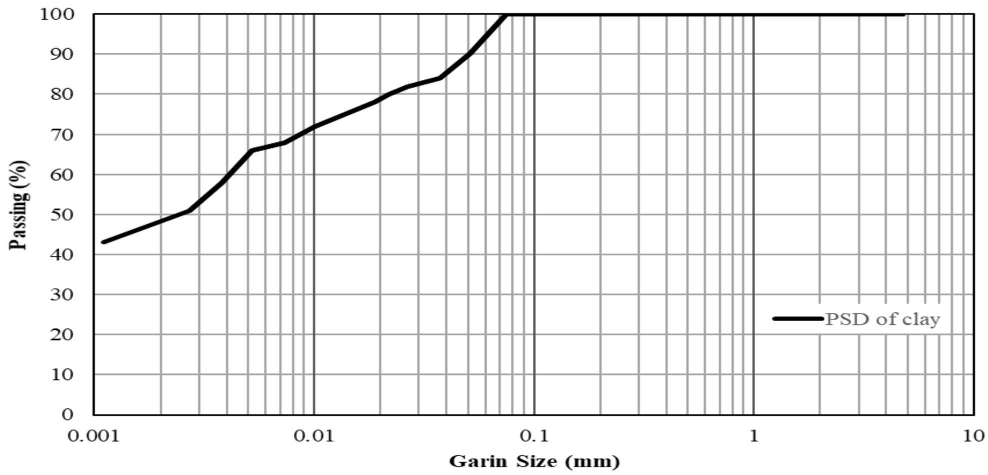


Figure 3.5. Particle size distribution curve of the clayey sample

Table 3.2. The main properties of two clayey samples provided for the study: one mixed with water and the other with leachate

Soil property	Value	
	Mixed with water	**Mixed with leachate**
Passing #200 sieve (%)	99.25	99.25
Sand content (%)	0.75	0.75
Liquid limit (%)	53	50
Plastic limit	36.6	27.1
Plasticity index (%)	16.8	22.9
Colour	Gray	Gray
Soil classification based on USCS	CH	CH
Maximum dry density (g/cm3)	1.56	1.56
Optimum moisture content (%)	22.5	22.5
UCS (kPa)	163	139

Table 3.3. The main chemical compositions of two clayey samples provided for the study: one mixed with water and the other with leachate

Component	Value	
	Mixed with water	**Mixed with leachate**
Na	1.052 %	10.29%
Mg	2.87%	1.89%
Al	14.76%	8.39%
Si	38.45%	20.73%
P	0.14%	0.065%
S	2.26%	4.52%
Cl	0.53%	12.07%
K	4.97%	3.46%
Ca	17.93%	14.69%
Ti	1.31%	1.18%
Mn	0.25%	0.21%
Fe	15.13%	9.37%
Ni	0.06%	0%
Zn	0.040%	0
Rb	0.046%	0.024%
Sr	0.10%	0.07%
Zr	0.036%	0.0275%
B	0%	13.01%

Classified as high plasticity clay (CH) based on the Unified Soil Classification System, they are considered suitable candidates for evaluation as potential materials for a CCL in landfill systems. The results of the XRF test showed that the clayey samples are predominantly composed of Si (38.5%), followed by Ca (17.9%), Fe (15.1%), and Al (14.8%). However, when mixed with leachate, the sample composition changed to 20.7%Si, 14.7%Ca, 13%B, 12%Cl, 10.3%Na, 9.4%Fe, 8.4%Al, and 4.5%S.

Moreover, the interaction between the clayey samples and leachate, a crucial aspect of their performance in landfill environments, was investigated through XRD analysis. This technique allows for the identification and characterization of crystalline phases present within the samples. The XRD patterns obtained revealed intriguing insights into the structural alterations induced by the mixing of clay with leachate. Notably, the emergence of new peaks, such as Gobbinsite, suggested the formation of novel mineral phases or chemical compounds resulting from the interaction between the clay minerals and the constituents of the leachate. The XRD patterns provided in Figure 3-2 confirm the emergence of new peaks, such as Gobbinsite, resulting from the mixing of CCL with leachate.

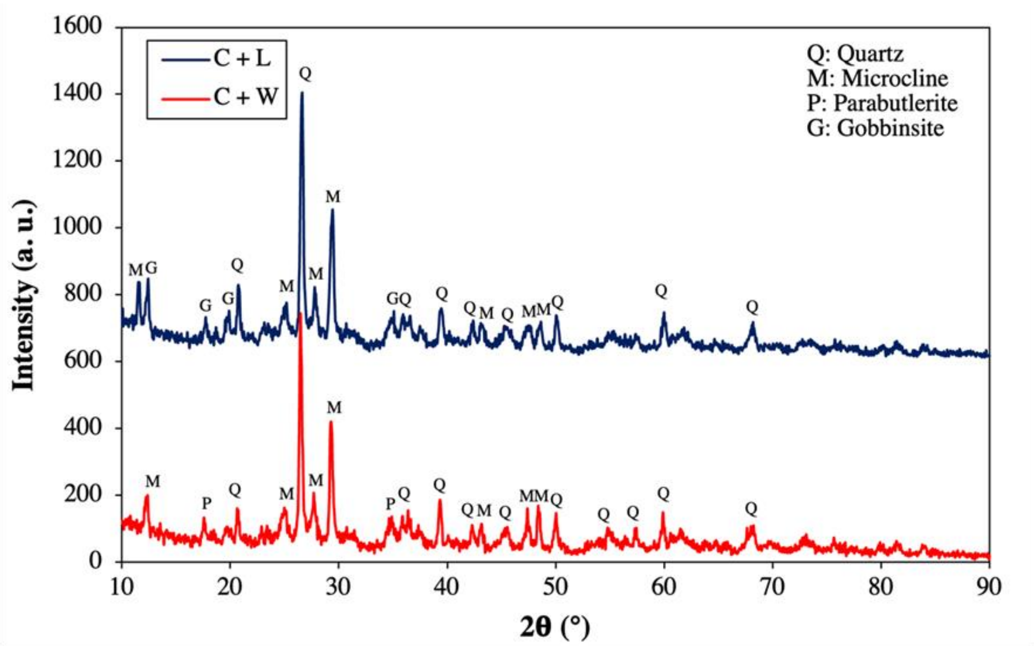


Figure 3.6: XRD patterns of CCL mixed with water (W) and leachate (L)

The comprehensive characterization of the clayey samples from Karabuk, Turkey, through XRF and XRD analyses, provided invaluable insights into their composition, structure, and reactivity. These findings serve as a foundational framework for understanding the behavior and performance of the clayey materials in landfill applications, guiding subsequent investigations into their potential for mitigating environmental contamination and enhancing the integrity of landfill liner systems.

3.3. LEACHATE SAMPLES

Obtaining representative leachate samples from the landfill in Karabuk, Türkiye, was a crucial step in the study's methodology, as it aimed to capture the complex composition and characteristics of the landfill effluent. The landfill, serving as a repository for both municipal and industrial waste, presented an ideal setting for sampling leachate, given its diverse range of waste types and decomposition processes. To ensure the integrity and representativeness of the samples, stringent sampling protocols were followed during the collection process. Multiple sampling points within the landfill site were identified to capture any spatial variability in leachate composition.

The collected leachate samples underwent thorough characterization and analysis to assess their physicochemical properties, including pH, conductivity, organic and inorganic pollutant concentrations, and microbial content. These analyses provided a comprehensive understanding of the leachate's composition, allowing for the identification of potential contaminants and their concentrations.

Furthermore, the integration of leachate samples with clay samples in laboratory experiments aimed to replicate real-world conditions encountered within landfill liner systems. By incorporating leachate into the experimental setup, researchers sought to simulate the dynamic interaction between CCL materials and landfill leachate, thereby evaluating the performance and effectiveness of the clay samples in mitigating contaminant migration and maintaining environmental integrity.

The inclusion of leachate samples from the landfill in Karabuk was integral to the study's methodology, as it facilitated the investigation of CCL materials under realistic landfill conditions. Through careful sampling, characterization, and integration into laboratory experiments, researchers were able to gain valuable insights into the behavior and performance of clay liners in landfill environments, ultimately contributing to the development of effective waste containment strategies and environmental management practices. The leachate samples taken from the landfill in Karabuk, which is a few kilometers from residential areas and accepts both municipal and industrial waste, are used in this study. Figure 3.7 shows the geographic coordinates of the leachate site, while Figure 3.8 provides some views of the site and the collected leachates for the study. In addition, the chemical characteristics of the collected leachate are given in Table 3.4.

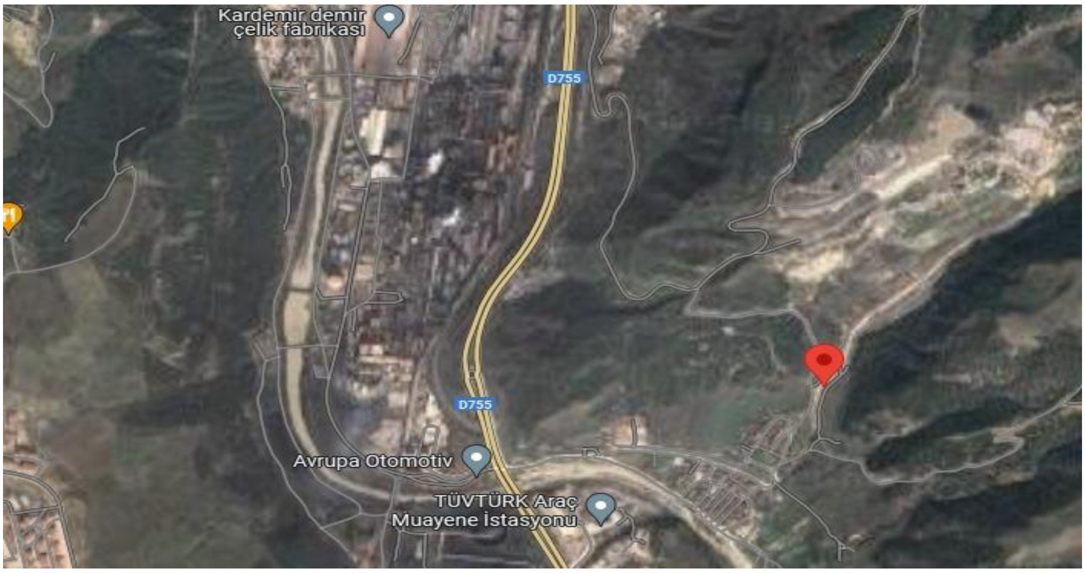


Figure 3.7. The geographic coordinate of the leachate site

Figure 3.8.General view of the leachate site and the collected leachate for the study

Table 3. 4. Chemical characteristics of the leachate samples collected for the study

Component	Value
Cd	0.09
Ni	2.36
Pb	0.97
Cr	0.22
Co	0.2
Cu	0.05
Mn	0.03
Zn	0.28
Fe	0.27
B	23.14

3.4. NLS SAMPLES

In this investigation, sodium lignosulfonate (NLS) was supplied by a Turkish company in Istanbul. Figure 3.9. shows a view of the NLS provided for the study.

Figure 3.9. Shows a view of the NLS provided for the study

Sodium lignosulfonate (NLS) emerged as a pivotal component in the study, serving as a novel alternative material for the treatment and stabilization of CCLs in landfill systems. Derived from lignin, a complex organic polymer abundant in plant cell walls, NLS offers a sustainable and eco-friendly solution for enhancing the performance and environmental compatibility of CCL materials.

In the experimental setup, NLS was incorporated into the clay samples at varying concentrations, ranging from 0.25% to 2% of the clay dry mass. This strategic variation in NLS content allowed researchers to evaluate its impact on the mechanical, physical, and environmental properties of the CCL materials. By systematically altering the NLS dosage, researchers aimed to ascertain the optimal concentration for achieving desired stabilization effects while minimizing adverse effects on the overall integrity and performance of the CCL specimens.

The incorporation of NLS into the clay samples was carried out through meticulous mixing and blending procedures, ensuring uniform dispersion and homogeneity of the additive within the clay matrix. This step was crucial for maximizing NLS's effectiveness in enhancing the CCL materials' engineering properties, such as strength, permeability, and durability.

Subsequent laboratory tests and analyses, including unconfined compressive strength (UCS) tests, bender element tests, microstructural examinations, and environmental assessments, provided valuable insights into the efficacy and mechanisms of NLS-mediated stabilization of CCLs. Through systematic experimentation and analysis, researchers aimed to elucidate the underlying mechanisms governing the interaction between NLS and clay minerals, thereby informing the development of optimized stabilization protocols for landfill liner systems.

The utilization of NLS as an alternative material for treating CCLs represents a paradigm shift towards sustainable and environmentally conscious waste containment solutions. By harnessing the unique properties of NLS derived from lignin, researchers aim to advance the state-of-the-art in landfill engineering, paving the way for more effective and sustainable waste management practices.

3.5. SAMPLE PREPARATION

The preparation of clay samples constituted a critical phase in the experimental methodology, ensuring the uniformity and reproducibility of the specimens for subsequent testing and analysis. This process involved a series of meticulous steps to achieve the desired moisture content and density, essential parameters influencing the mechanical and environmental behavior of the clay samples.

The following are the sample preparation steps:

1- The clayey samples were mixed with various percentages of distilled water and then subjected to a standard compaction test to determine the optimum moisture content (OMC) and maximum dry density (MDDW) of the samples (Figures 3.10 and 3.11).

Figure 3. 10. Mixing the clayey samples with water

Figure 3.11. Applying the standard compaction test on the clayey samples

2- Concurrently, the clayey samples were mixed with various percentages of leachate content and subjected to a standard compaction test to measure optimum moisture content (hereafter called OLC) and maximum dry density (MDDL) of the samples.

3- In the first, second, and third groups, the clayey soil samples were first mixed with the distilled water required to obtain the optimum moisture content (OMC) and then compacted in the UCS mold with the standard energy to reach the maximum dry density (MDDW). Subsequently, the compacted clay soils were placed in airtight plastic bags and subjected to different curing times of 7, 28, and 90 days. Upon completing the specified curing time, the first group of samples underwent UCS and BET testing in a dry condition, i.e., without any additional actions. While the second group of samples was tested under wet conditions, involving submerging the samples in distilled water for 10 minutes and draining them using a sieve for 5 minutes before initiating the test, the third group of samples underwent similar wet testing procedures but with the distinction that they were submerged in leachate instead of water. Figure 3.12 shows a sample submerged in water, while Figure 3.13 shows another sample submerged in leachate. In addition, the drainage procedure applied in this study is shown in Figure 3.14.

4- In the fourth and fifth groups, the clayey soil samples were initially mixed with the required leachate content to achieve the optimum leachate content (OLC), after which they were compacted in the UCS mold using the standard energy to attain the maximum dry density (MDDL). Subsequently, the compacted clay soils were placed in airtight plastic bags and subjected to different curing times of 7, 28, and 90 days. Following the specified curing period, the fourth group of samples underwent UCS and BET testing in a dry condition, while the fifth group of samples was tested under wet conditions by immersing them in water.

5- The steps from 3 and 4 were replicated with clayey samples stabilized using various NLS content levels, including 0.25%, 0.5%, 1%, 1.5%, and 2% of the clay dry mass (Figure 3.15).

Laboratory tests were conducted on samples from the aforementioned five groups to evaluate the effectiveness of sodium lignosulfonate as a soil stabilizer for compacted clay liners in landfill systems, taking into account the impact of landfill leachate and mechanical and dynamic responses. Figure 3.16 shows the samples prepared for UCS and BE tests covered with airtight plastic bags and aluminum foils for starting various curing times.

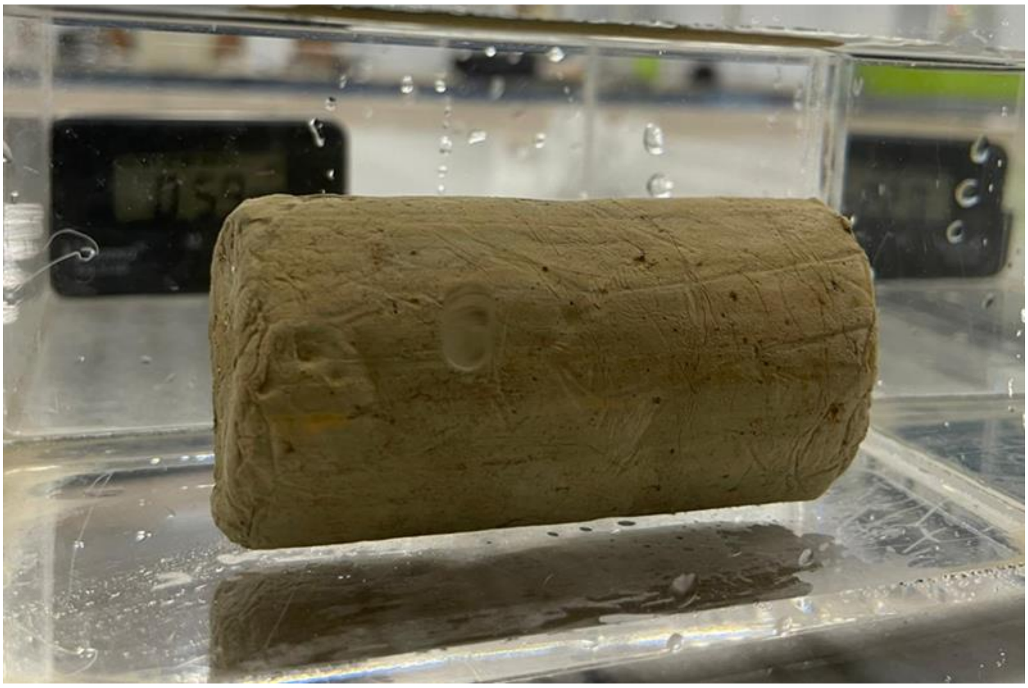


Figure 3.12. Compacted clay sample submerged in water

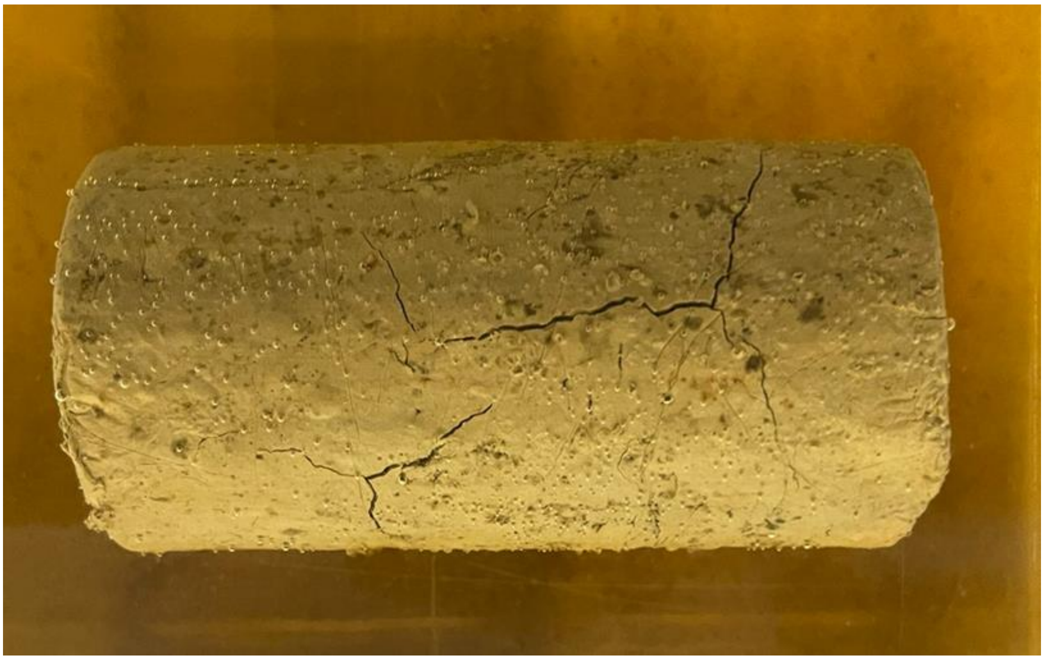


Figure 3.13.Compacted clay sample submerged in leachate7

Figure 3.14. The soil samples under draining procedure

Figure 3.15. Stabilizing the clayey samples with NLS

Figure 3.16. UCS and BE samples provided for the study

The study examines the relationship between the amount of NLS, the curing process, and the curing times at which the soil was stabilized. The tests include bender element tests and unconfined compressive strength tests. Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD), and X-ray fluorescence (XRF) tests were used to examine the microstructural changes and stabilization mechanisms brought on by the addition of sodium lignosulfonate additives and/or leachate content.

3.6. UCS (UNCONFINED COMPRESSIVE STRENGTH)

Unconfined compressive strength (UCS) tests represented a cornerstone of the experimental methodology, providing crucial insights into the mechanical properties and stability of the clay samples under varying curing conditions and NLS concentrations. The UCS tests were conducted using standard procedures and equipment, following established protocols to ensure the accuracy and reproducibility of results. Before testing, the prepared clay samples were carefully removed from their respective curing environments and allowed to equilibrate to room temperature to minimize potential thermal effects on the test results.

Subsequently, the samples were subjected to axial loading in a uniaxial compression testing apparatus, applying a constant deformation rate of 1mm/min until failure occurred. During the testing process, meticulous care was taken to ensure uniform loading and alignment of the samples, minimizing the influence of any external factors on the test results. The UCS tests were conducted on multiple sets of clay samples, each subjected to different curing conditions and NLS concentrations. Specifically, the influence of curing time on UCS was evaluated by testing samples subjected to different curing durations, ranging from 7 to 90 days. Furthermore, the effect of NLS concentration on UCS was investigated by testing samples prepared with varying levels of NLS additive, ranging from 0.25% to 2% of the clay dry mass. This allowed researchers to ascertain the optimal concentration of NLS for enhancing the mechanical properties of the clay samples while also evaluating any potential drawbacks or limitations associated with higher concentrations. Through meticulous analysis of the UCS test results, researchers were able to draw valuable conclusions regarding the influence of leachate, various curing conditions and NLS concentrations on the mechanical behavior of the clay samples. These insights provided crucial guidance for optimizing stabilization protocols and enhancing the performance of clay liners in landfill applications, ultimately contributing to the development of more sustainable and effective waste containment strategies. Figure 3.17 shows the NLS-stabilized samples submerged in water or leachate, considering the effects of wet conditions on UCS test results prior to starting the test.

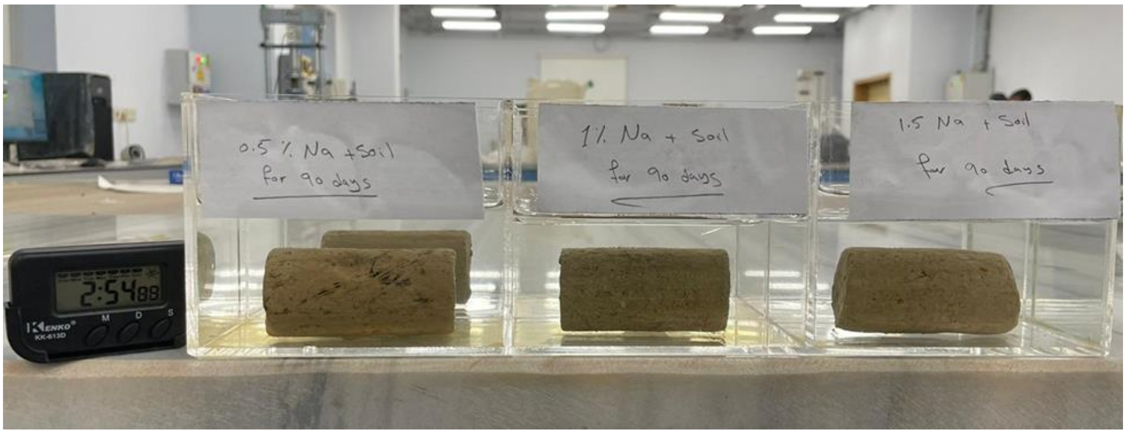


Figure 3.17. Figure 3.18. NLS-stabilized samples submerged in water or leachate before starting UCS test

Figure 3.18 represents a sample under UCS test, while the failure mode of various samples after completing the test is shown in Figure 3.19.

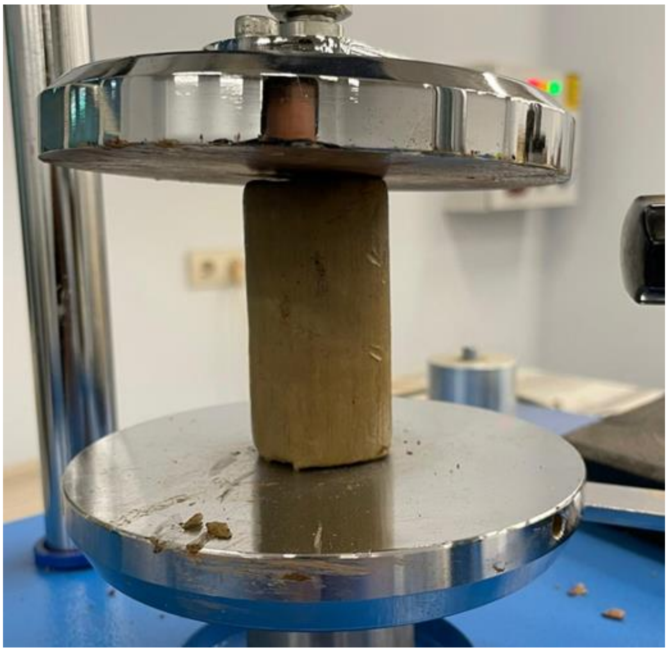


Figure 3.19. A sample under UCS testing

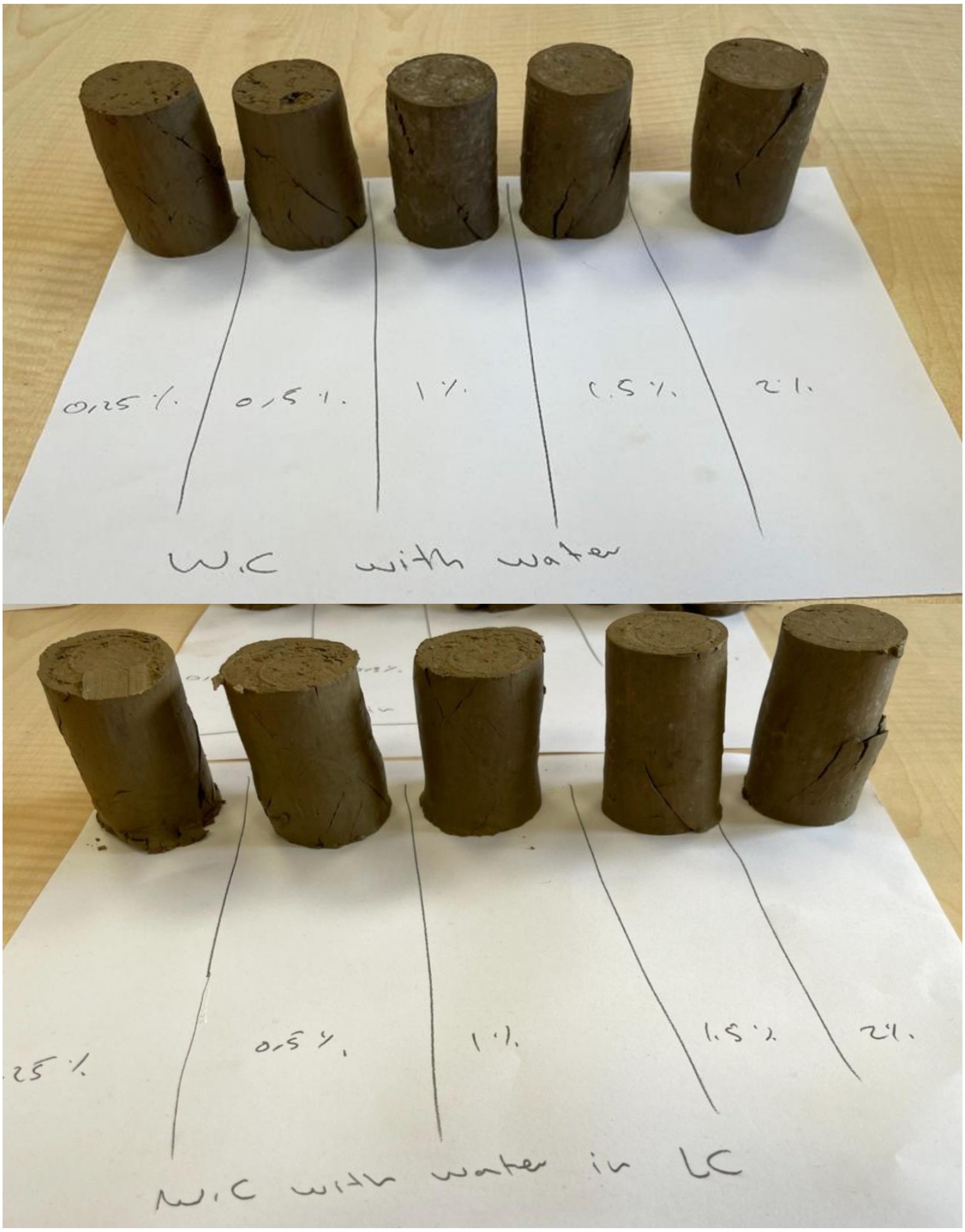


Figure 3.20. Failure mode of various samples after completing UCS test

3.7. BET (Bender Element Test)

To evaluate the effects of leachate, NLS stabilization, curing time, and wet conditions on the dynamic response of compacted clay liners, the bender element test was conducted in this study. After analyzing the test results, the shear wave velocity of the samples, as an acceptable representative of the dynamic behavior, was compared, providing insight into the effects of the aforementioned parameters on CCL performance. Figure 3.20 shows a general view of the bender element device, while Figure 3.21 shows a sample under BE testing.

Figure 3.21. Bender element test device

Figure 3.22. A sample under BE testing

3.8. COLUMN MODEL TEST

In this section, column model tests were conducted to simulate leachate percolation through the CCL specimens, aiming to evaluate their hydraulic conductivity and contaminant retention capabilities. These tests provided crucial insights into the performance of the cover materials under realistic landfill conditions, facilitating a comprehensive assessment of their effectiveness in mitigating contaminant migration and maintaining environmental integrity. The column model tests were conducted using a specialized apparatus designed to simulate the vertical percolation of leachate through the specimens under controlled conditions.

The short-term and long-term leaching behavior of the temporary cover layer of the landfill system, stabilized with NLS, are examined in this study using a small column test model specifically designed for this research. The schematic view of the small-scale column model is shown in Figure 3-22.

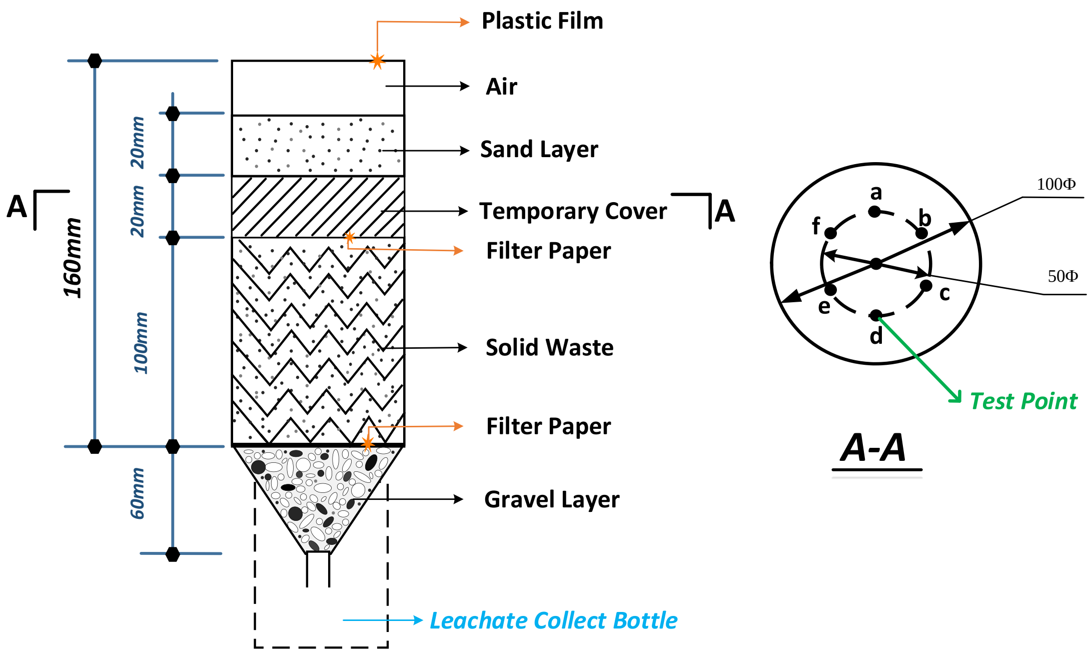


Figure 3.23. The schematic of the planned small-scale column setup for the experiment

To perform this test, the following steps were carried out:

1. The gravel material in the size between 6-8 mm was first washed and dried, and it was subsequently placed in the cone at the bottom of the model with a height of 8 cm. This part provides for the free drainage conditions of leachate.

2. A filter paper was used to separate this layer from the solid waste layer. The main reason for using filter paper was to prevent the potential clogging of the drainage system due to the migration of fine particles from the waste layer.

3. The next layer was associated with the solid waste and had a height of 10 cm. The solid waste was compacted in multiple layers using a hand tamper to achieve a dry density of 0.6 g/cm3 for each layer. Figure 3.23 shows some of the solid waste materials prepared for the study. Note that after completing each layer, the predetermined amount of water needed to reach the initial moisture content of 60% was uniformly sprayed onto each layer. Upon the completion of the entire solid waste layer and prior to the placement of the filter paper on top of this layer, it was allowed to sit for 1 day to ensure that the water has been evenly distributed throughout the layer.

Figure 3.24. A view of the solid waste materials prepared for the study

4. Subsequently, the temporary cover, made of NLS, was compacted by a hand tamper to reach a 2 cm height. For this layer, compaction continues until no visible pores were observed with the naked eye.

5. Finally, a 2 mm top layer was added over the temporary cover using prewashed sand material sized between 1-2 mm. This layer facilitates better distribution

of leachate and water during the test procedure. It's important to note that an additional 2 cm height at the top of the sand layer was intentionally left empty to serve as an air chamber.

6. Every 3 days, tap water was sprayed onto the top layer of the column at a rate of 20 ml. Once a sufficient amount of leachate was collected at the bottom of the column, it was then used and recirculated in place of tap water.

7. The collected leachate at the bottom of the column was analyzed for pH, EC, and heavy metal content at intervals of 25 days, up to 150 days. Additionally, the leachate flow rate was measured every week for up to 150 days.

To perform column model test, following variable are considered:

1. Different curing times for of NLS-stabilized clay samples including 7, 28, and 90 days.

2. Different thickness for the temporary cover. The thickness ratio of the temporary cover to the solid waste layer was arranged as 1:5, 1:2, and 1:8.

3. Recirculation of collected leachate. In some test the recirculation of leachate was not applied and only tap water was used in whole process.

4. Different operation modes. Two different operation modes were applied, namely, anaerobic and semi-aerobic. In anaerobic conditions, the top of the column was sealed with plastic film. However, in semi-aerobic mode, the top of the column was left open.

In doing so, ten column models were generally conducted to achieve the designed aims of the current study. Figure 3-24 and Table 3.5 show the features of the various models designed and carried out in this study.

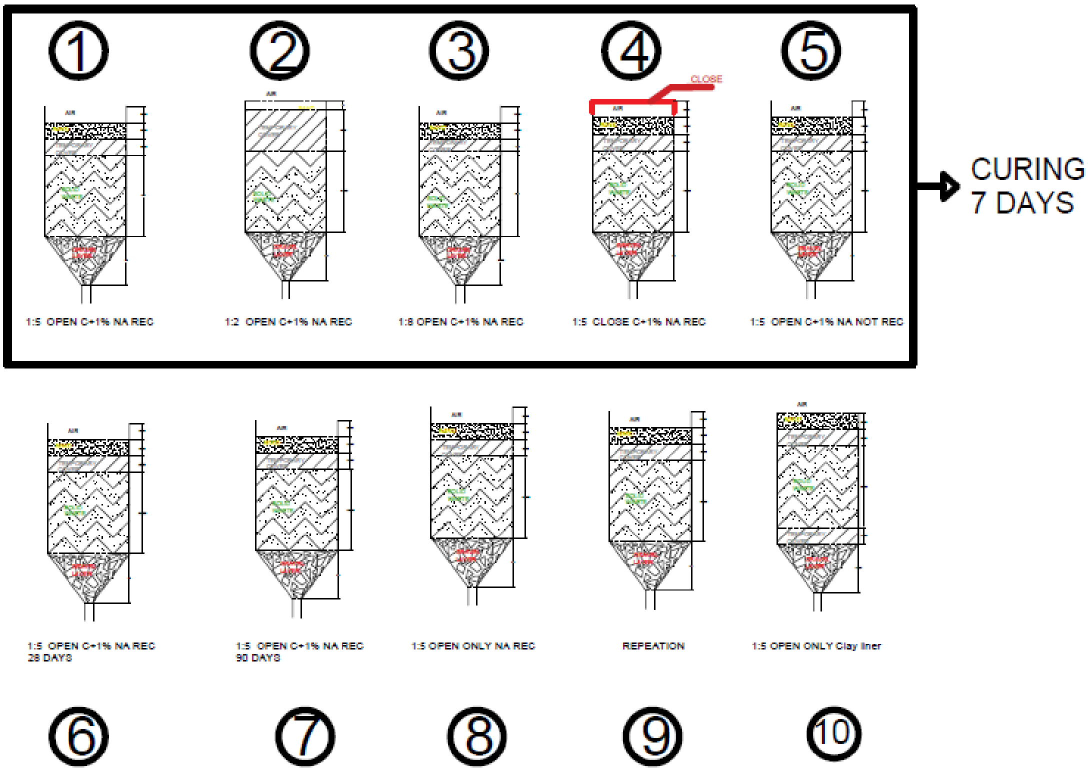


Figure 3.25. The features of the various column models designed and carried out in this study

Table 3.5. The features of the various models designed for this study

Model symbol	Thickness ratio	Operation mode	Rercerculation	Material type	Curing time
1	1:5	Open	Yes	Clay mixed with 1%NLS	7 days
2	1:8	Open	Yes	Clay mixed with 1%NLS	7 days
3	1:2	Open	Yes	Clay mixed with 1%NLS	7 days
4	1:5	Closed	Yes	Clay mixed with 1%NLS	7days
5	1:5	Open	No	Clay mixed with 1%NLS	7 days
6	1:5	Open	Yes	Clay mixed with 1%NLS	28 days

7	1:5	Open	Yes	Clay mixed with 1%NLS	90 days
8	1:5	Open	Yes	NLS	----
9 (repeated)	1:5	Open	Yes	Clay mixed with 1%NLS	7 days
10	1:5	Open	Yes	Clay mixed with 1%NLS	----

Figure 3-25 shows the actual setup of the column models before and after being filled with the materials based on the aforementioned procedures.

Figure 3.26. The actual setup of the column models before and after being filled with the materials

The environmental tests conducted provided crucial insights into the environmental compatibility of the clay samples and their suitability for use in landfill liner systems. By evaluating parameters such as pH, EC, and heavy metal content, researchers could assess the potential environmental impacts of the samples and make informed decisions regarding their application and management. These findings are integral to ensuring the sustainability and effectiveness of waste containment strategies in landfill engineering, ultimately contributing to the protection of human health and the environment.

3.9. SUMMARY

This chapter provides a comprehensive overview of the materials and methods utilized in the study, encompassing a range of critical procedures and analyses. The characterization of clay and leachate samples, the incorporation of sodium lignosulfonate (NLS) as a soil stabilizer, meticulous sample preparation techniques, and the execution of various laboratory tests were all integral components of the research methodology.

Through meticulous characterization, the physical and chemical properties of the clay and leachate samples were elucidated, providing a solid foundation for subsequent analyses. The utilization of NLS as a soil stabilizer represented an innovative approach aimed at enhancing the performance of compacted clay liners (CCLs) in landfill systems, highlighting the study's focus on sustainable waste containment strategies.

Furthermore, sample preparation techniques were meticulously implemented to ensure the uniformity and reproducibility of the specimens, laying the groundwork for reliable and consistent experimental results. Various laboratory tests, including mechanical, physical, and environmental assessments, were conducted to evaluate the performance and suitability of the specimens for landfill applications.

PART 4

RESULTS AND DISCUSSIONS

This chapter presents the findings obtained from the experimental investigations on the effects of leachate and NLS on CCL properties. The results are discussed concerning their implications for CCL performance and the potential benefits of NLS stabilization.

4.1. EFFECTS of LEACHATE on PROPERTIES of CCL

This section delves into the influence of leachate exposure on the mechanical and dynamic attributes of CCLs, differentiating between dry and wet conditions. The introduction of landfill leachate into CCLs presents significant hurdles to their mechanical robustness and overall effectiveness. Examination of UCS and BE test outcomes underscores the adverse consequences of leachate effects on CCL properties. Figure 4.1 shows the UCS values of the untreated compacted clay samples tested under various scenarios and cured for different periods. The UCS of the untreated sample mixed with water and tested under dry conditions (DW) was measured as 163 kPa after 7 days of curing, and it reached 204 kPa after 90 days of curing. The UCS values of the samples dropped due to mixing with leachate under dry conditions and/or testing under wet conditions, reflecting the adverse effects of both leachate penetration and wet conditions. For instance, the UCS of the sample cured for 90 days decreased from 204 kPa to 165 kPa due to mixing with leachate (DL) instead of water, highlighting about a 20% strength reduction and demonstrating the negative impact of leachate on CCL performance. However, the strength reduction for the sample mixed with water and tested under wet conditions (WW) was about 3% compared to the sample tested under dry conditions (WD). Further reduction in strength was recorded under wet conditions when the sample was submerged in leachate (WL) instead of water, with a decrease of approximately

17%. This case (WL) was found to be the worst across all curing times, and the strength of this sample was even lower than that of the sample mixed with leachate and submerged in water (LW). The UCS testing serves as a pivotal gauge of the inherent mechanical resilience of CCLs, measuring the maximal axial compressive stress they can withstand under unconfined circumstances. This metric offers crucial insights into the initial strength and stability of CCLs, providing a benchmark for assessing the efficacy of subsequent treatments like NLS.

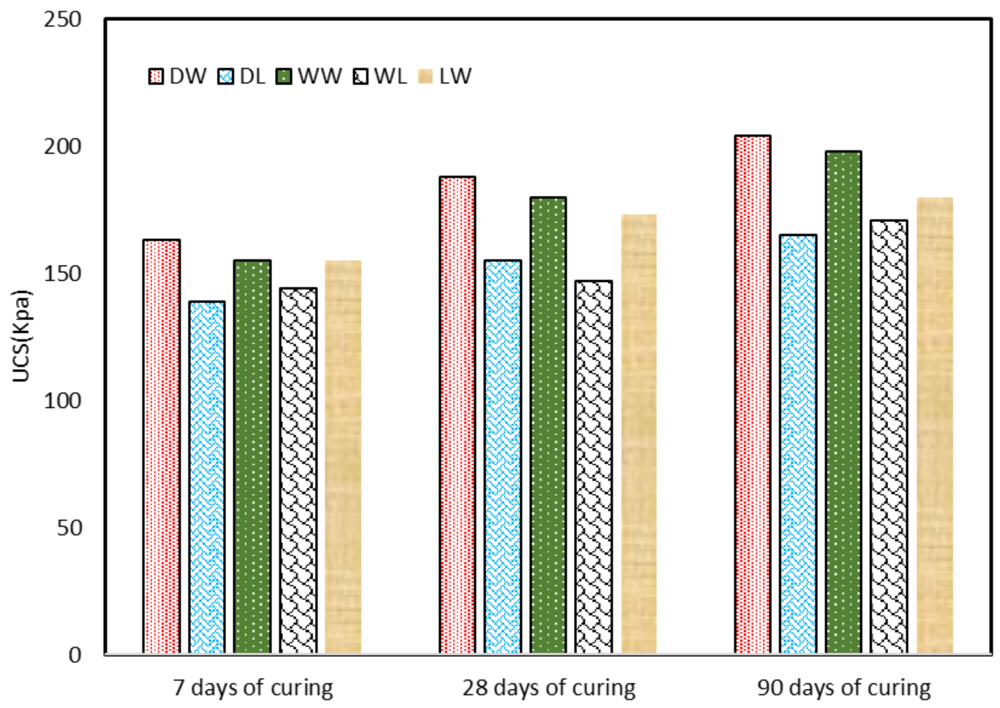


Figure 4. 1. Variations in UCS of compacted clay samples across different scenarios and curing times.

Figure 4.2 shows the results of the BE test in terms of Vs values for the untreated compacted clay samples, tested under various scenarios and cured for different periods. The Vs of the untreated sample mixed with water and tested under dry conditions (DW) was measured at 91 m/s after 7 days of curing, reaching 98 m/s and 109 m/s after 28 and 90 days of curing, respectively. It was found that leachate penetration and wet conditions could adversely affect the dynamic response of CCLs, as evidenced by the reduction in Vs values of the samples resulting from mixing with leachate under dry conditions and/or testing under wet conditions. There was a gradual reduction in Vs values of the samples due to mixing with leachate and testing in dry condition (DL), followed by mixing with water and submerging in water (WW), mixing with water and submerging in leachate (WL), and finally mixing with leachate and submerging in water (LW). The Vs of the sample after 90 days of curing was measured as 109 under DW condition. It dropped to 92, 87.5, 78, and 78 respectively for DL, WW, WL, and LW conditions, revealing reductions of 16%, 20%, 29%, and 29% respectively.

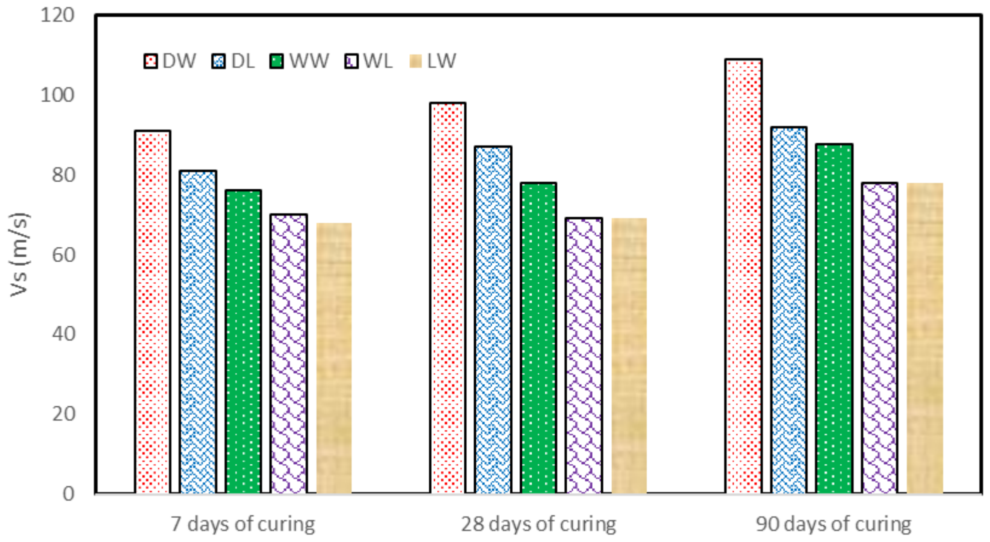


Figure 4.2. Variations in Vs of compacted clay samples across different scenarios and curing times.

Furthermore, the dynamic response, notably the shear wave velocity (Vs), offers valuable clues into the stiffness and elasticity of CCLs under dynamic loading conditions. Vs delineates the speed at which shear waves propagate through the material, offering insights into its density, stiffness, and internal structure. Evaluating Vs under pristine conditions enables researchers to characterize the material's dynamic behavior and its response to seismic or vibrational forces, crucial for gauging performance under scenarios involving dynamic loadings, such as seismic events or heavy machinery operation.

4.2. EFFECTS OF NLS ON PROPERTIES OF CCL

In this detailed section, we embark on a thorough exploration of the effects of NLS Stabilizer on the intricate properties of CCLs. Our objective is to conduct an exhaustive analysis to shed light on the nuanced ways in which the integration of NLS impacts the fundamental characteristics of CCLs. Specifically, we delve into how the incorporation of NLS influences two critical aspects: the Unconfined Compressive Strength (UCS), which serves as a key indicator of structural integrity, and the dynamic response, focusing on the shear wave velocity (Vs), which provides insights into the material's resilience and elasticity. Through meticulous examination and detailed scrutiny, we endeavor to unravel the multifaceted relationship between NLS and the performance of CCLs, thereby contributing to a deeper understanding of their behavior in various environmental conditions.

Based on Figure 4.3, the mechanical strength of the CCL showed significant improvement with the addition of NLS, with the best results observed for the 1% NLS concentration across all curing times. The strength improvement factor for the samples stabilized with the optimum percentage of NLS was measured as 1.83 and 2.12 after 7 and 90 days of curing, respectively.

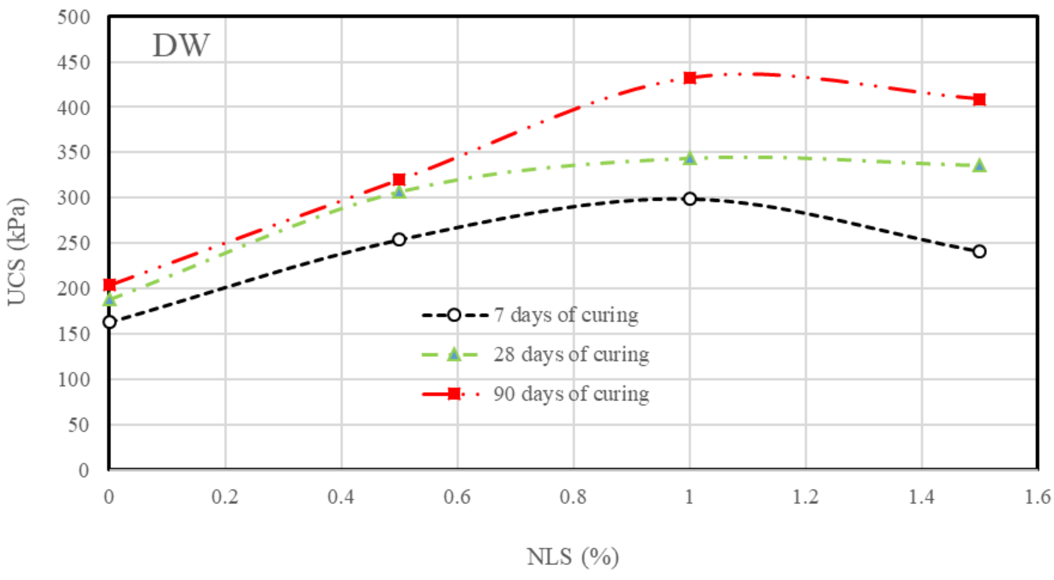


Figure 4.3. Effects of different NLS content and curing intervals on UCS of CCLs under DW condition.

Figure 4.4 shows the effects of leachate on the strength of NLS-treated CCLs. The strength of the sample treated with 1% NLS and cured for 90 days was determined as 346 kPa, which is 110% higher than the strength of the untreated sample tested under the same conditions, revealing the good performance of NLS even in the presence of leachate. Therefore, it can be noted that NLS shows high potential in mitigating the adverse effects of leachate on the performance of CCLs.

The performance of NLS stabilization in wet conditions is shown in Figure 4.5. As seen, the best results were achieved for the sample cured for 90 days, indicating a significant improvement in strength between 28 and 90 days of curing, specifically for the sample stabilized with 1% NLS. The strength of this sample was 339 kPa, about 22% lower than the strength of the same sample tested under dry conditions, but 72% higher than the strength of the untreated sample tested under the same circumstances.

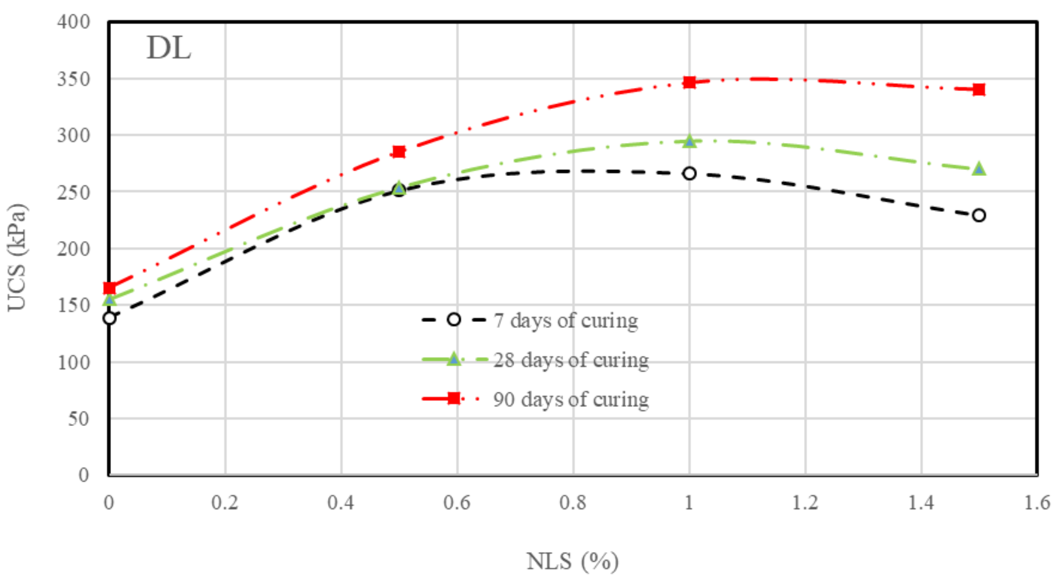


Figure 4.4. Effects of different NLS content and curing intervals on UCS of CCLs under DL condition.

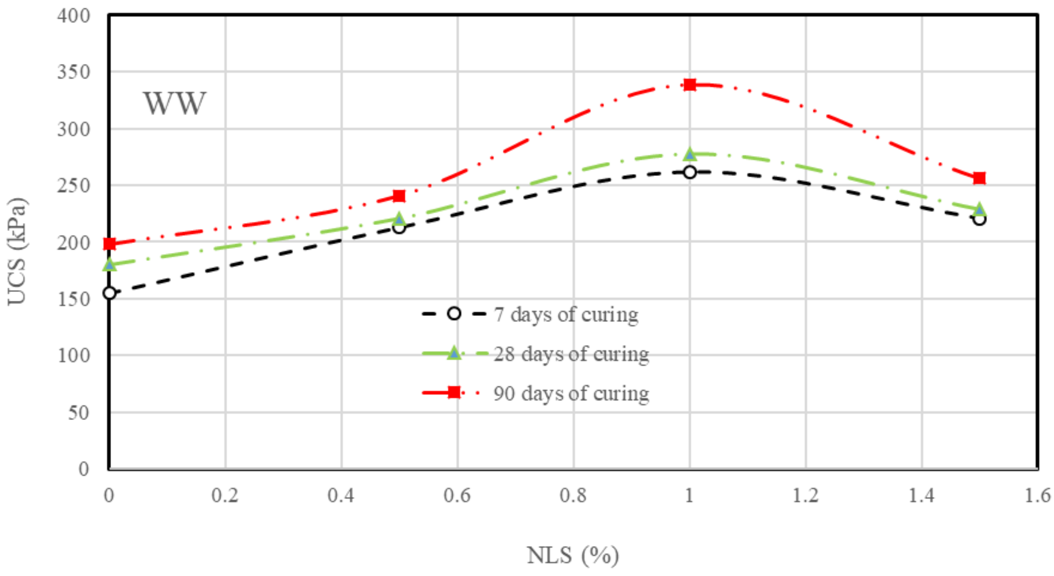


Figure 4.5. Effects of different NLS content and curing intervals on UCS of CCLs under WW condition.

Figures 4.6 and 4.7 present the impacts of NLS stabilization on the performance of CCLs under WL and LW conditions. By comparing the results given in both figures, it was confirmed that even in the case of NLS stabilization, the worst-case scenario was WL, which involved mixing the clayey soil with water and submerging it in leachate. However, even in this case, the strength of the 90-day-cured sample was 260 kPa, about 52% higher than the strength of the untreated sample, signifying the significant performance of NLS in enhancing the strength of CCLs against harsh environmental effects.

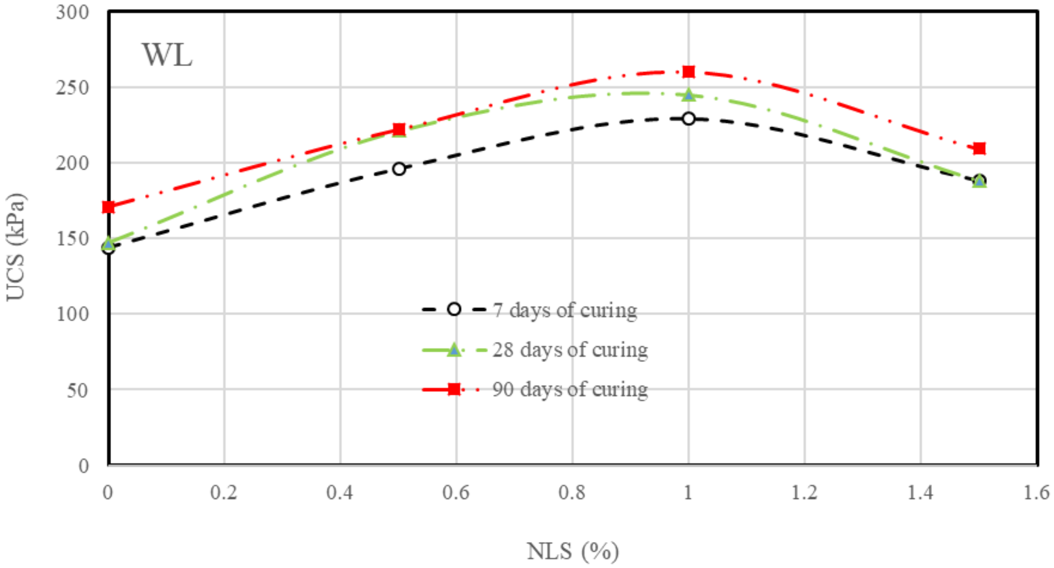


Figure 4.6. Effects of different NLS content and curing intervals on UCS of CCLs under WL condition.

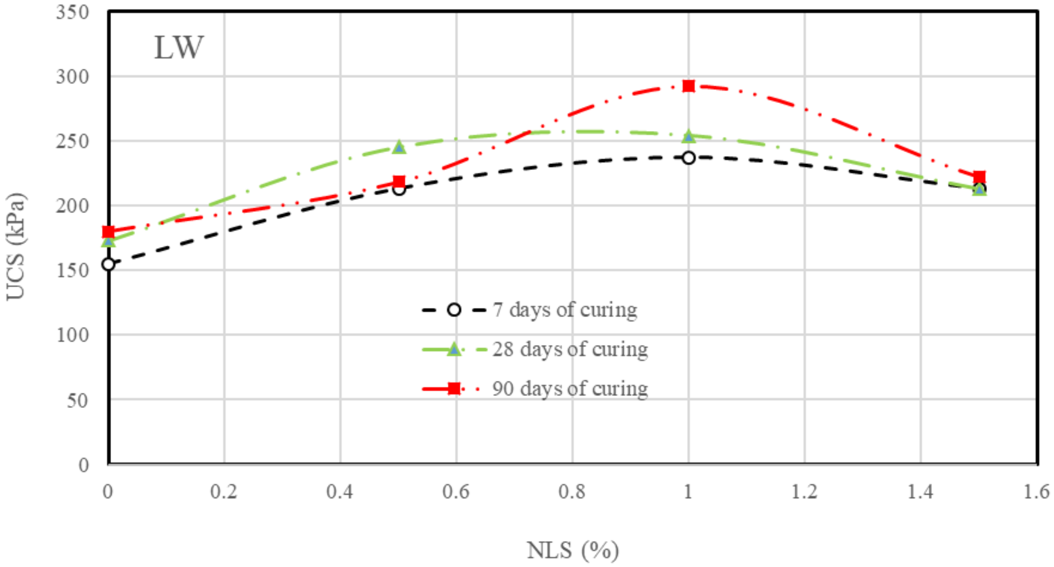


Figure 4.7. Effects of different NLS content and curing intervals on UCS of CCLs under LW condition.

Fig. 4.8. illustrates the durability of NLS in enhancing the efficiency of CCLs against the adverse effects of landfill leachate. In addition, by comparing the results of the untreated sample with the samples treated with 1% NLS as the optimum content, this figure provides better insight into the effects of NLS application in stabilizing the

CCLs. Although applying WCs by both water and leachate resulted in mitigating the strength of CCLs, the NLS-stabilized CCLs exhibited acceptable ranges of strength, with the improvement rate due to NLS addition being at least 50%. The strength of all samples containing NLS was higher than 200 kPa, meeting the minimum standard strength for CCLs, while almost all untreated samples failed to meet this requirement, particularly after being mixed with leachate. The findings of this study revealed that NLS holds notable potential in preventing the strength reduction of CCLs due to leachate exposure, as reported here for the first time.

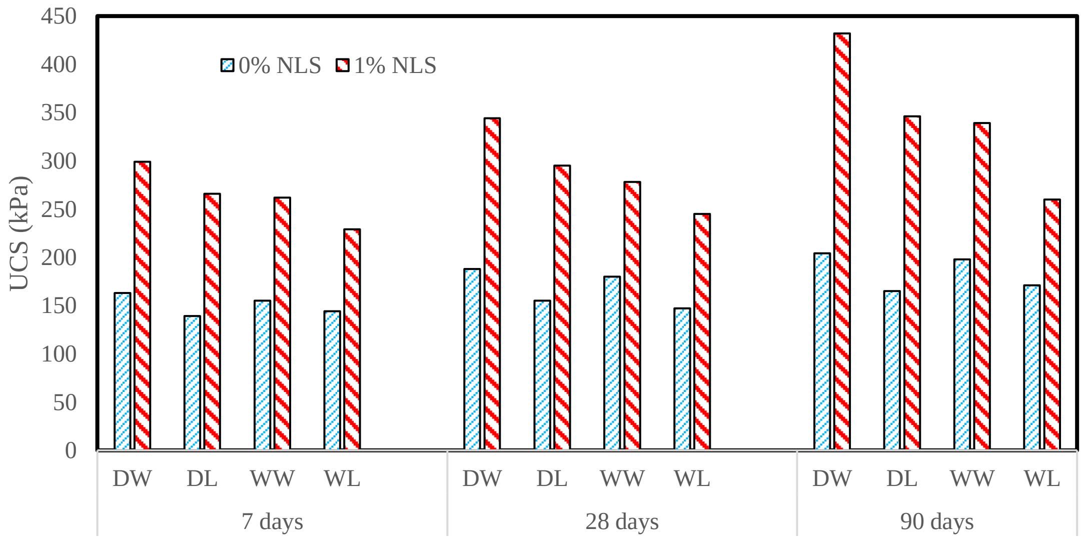


Figure 4.8. Effects of NLS stabilization on CCLs durability in various scenarios.

According to Figures 4-9a-c, the dynamic response of the CCLs under various conditions suggests that the penetration of leachate through existing cracks can lead to a reduction in the shear wave velocity (Vs) of the samples. However, the worst-case scenario occurred when wetting conditions were applied, involving submerging the samples first in leachate followed by water. The latter finding indicates that WCs have a more detrimental effect on the characteristics of CCLs. The dynamic response of the samples improved significantly due to both NLS stabilization and curing time. In the worst-case scenario (i.e., WCs submerged in leachate), the addition of only 1% NLS resulted in a 20%, 30.5%, and 40% improvement in the Vs of CCLs with curing time compared to that of the untreated sample. These results guarantee the potential of NLS against adverse effects of both natural disasters and leachate submergence.

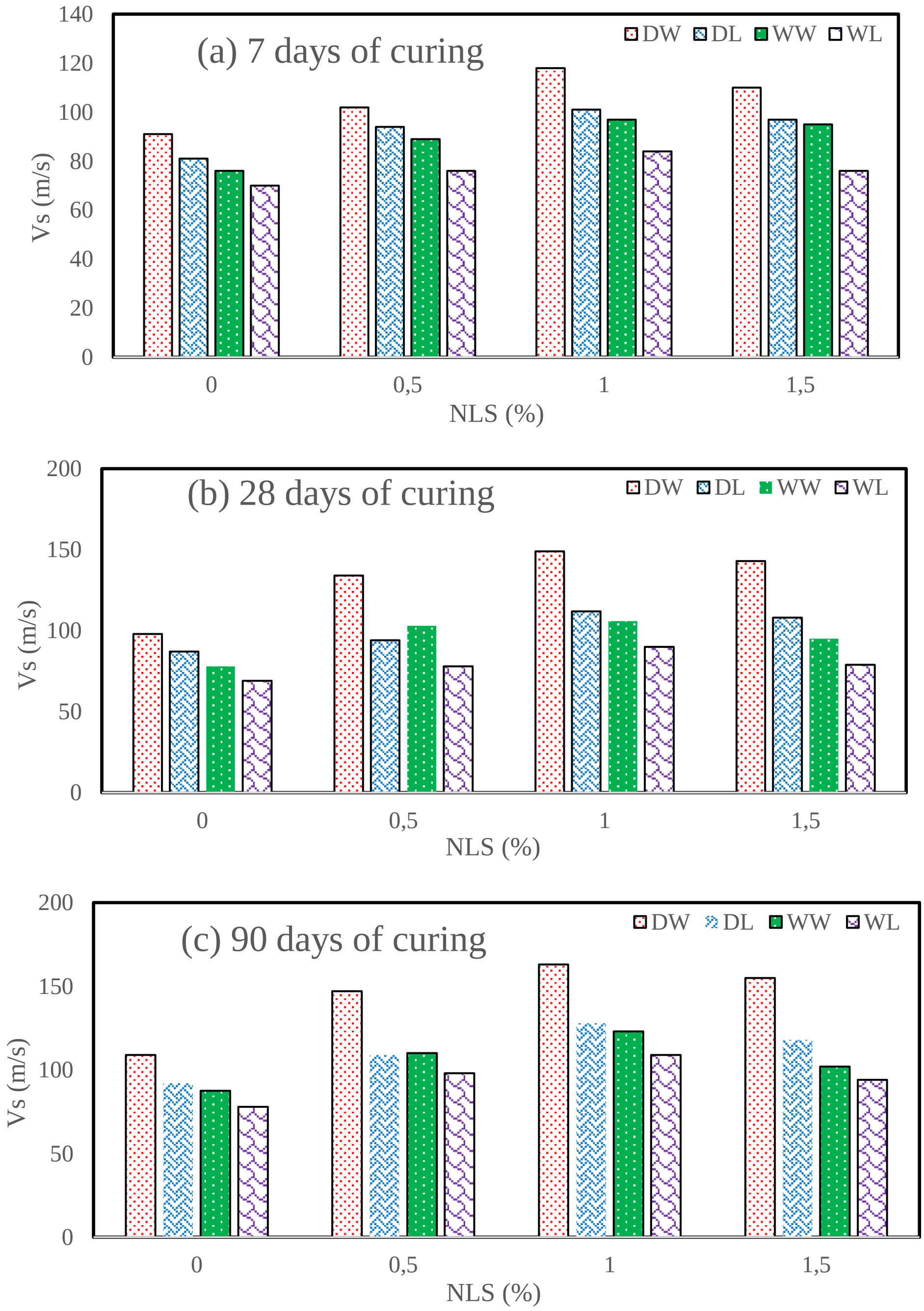


Figure 4.9. Variations in Vs of CCLs for various scenarios due to NLS addition (a) after 7 days; (b) after 28 days; and (c) after 90 days of curing

4.3. RESULTS OF COLUMN MODEL TESTS TO ASSESS THE POTENTIAL USE OF NLS AS A TEMPORARY COVER

4.3.1. Flow Rate Results

The flow rate outcomes obtained from the research provide valuable insights into the permeability and drainage characteristics of temporary cover layer clayey under various conditions. These findings are crucial for understanding how leachate and NLS influence the flow dynamics within the liners. By offering data on hydraulic conductivity, the flow rate measurements clarify the liners' ability to either retain fluids or facilitate their passage in different scenarios. Figure 4.10 represents the effects of operation mode on the results of the column test, and therefore, the performance of a temporary cover made of a mixture of clay and 1% NLS cured for 7 days.

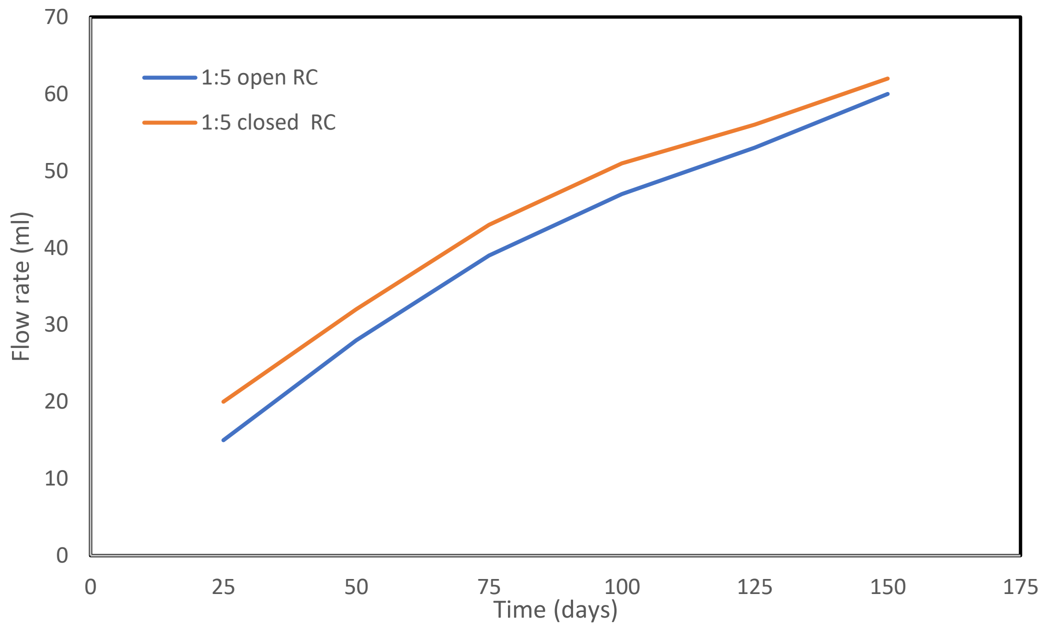


Figure 4.10. Effects of operation mode on flow rate over time for NLS-treated clay temporary cover.

Generally, a higher flow rate was recorded for the closed mode than the open one, highlighting the effects of operation mode on the performance of the temporary cover in terms of flow rate. The lower flow rate or the collection of less leachate in the open model can be attributed to the possibility of evaporation.

Figure 4-11 compares the application of leachate recirculation during the column test with the model that was not subjected to recirculation, where water was used instead. As can be seen, there is no difference in the flow rate or volume of collected leachate between the recirculation and non-recirculation models.

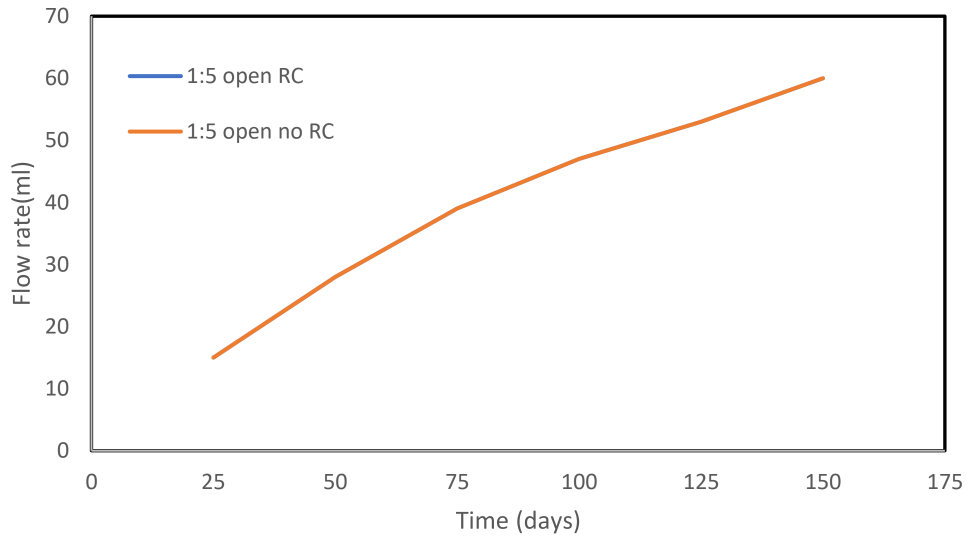


Figure 4.11. Effects of leachate recirculation on flow rate over time for NLS-treated clay temporary cover

Figure 4-12 shows the effects of temporary cover thickness on the volume of collected leachate and flow rate. The results confirmed that a higher thickness for the temporary cover result in a lower flow rate. Based on the results obtained, even a thickness ratio of 1:8 (temporary cover to solid waste layer) can lead to effective performance.

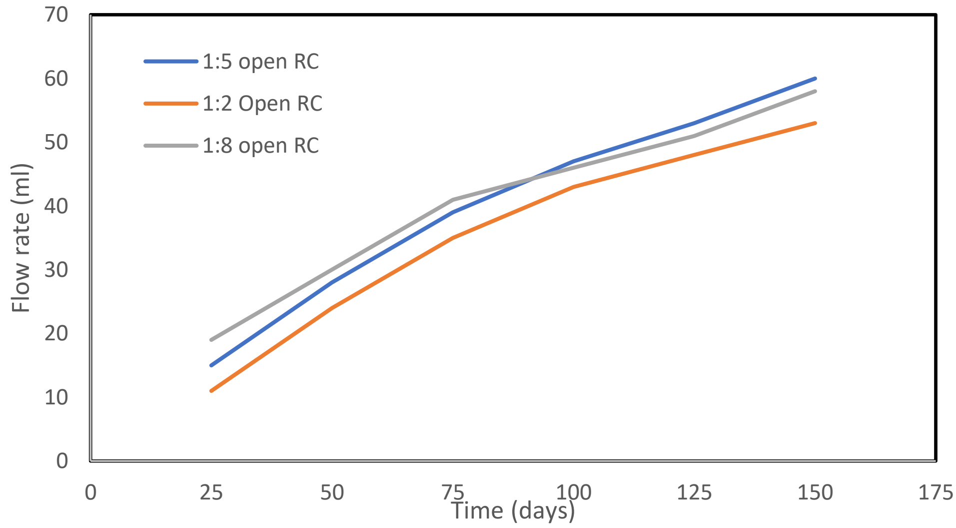


Figure 4.12. Effects of temporary cover thickness on flow rate over time for NLS-treated clay temporary cover

Figure 4-13 examines the effects of curing time on the performance of the NLS-treated temporary cover. Although there is no significant difference between the recorded flow rate results, for operation times less than 75 days, the model with the sample cured for 90 days resulted in a lower flow rate. However, for operation times greater than 75 days, it seems that the model with the sample cured for 28 days performed better.

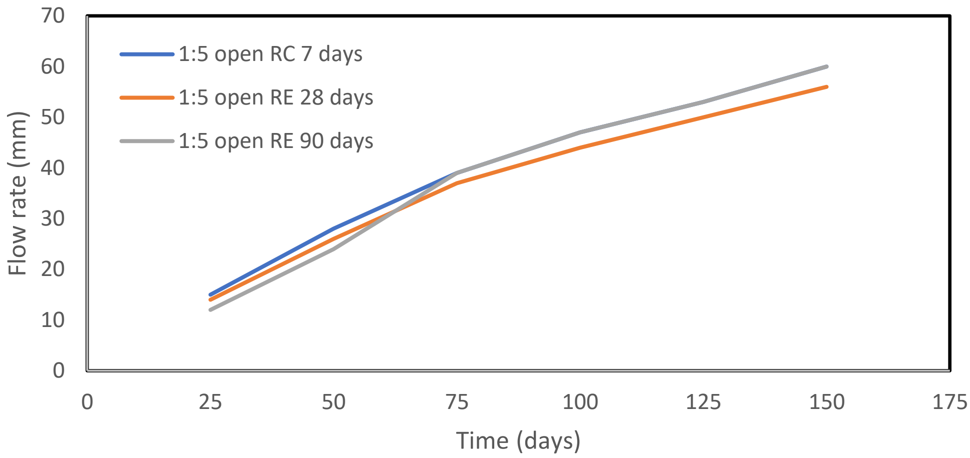


Figure 4.13. Effects of curing time on flow rate over time for NLS-treated clay temporary cover

Finally, the effect of material types used for making the temporary cover is shown in Figure 4-14. For the first 125 days of operation, less leachate was collected for the models consisting of NLS alone and clay alone, demonstrating lower hydraulic conductivity for these models. However, there was a rapid and significant increase in flow rate for the model that included the untreated clay sample, confirming the significant adverse effects of leachate in the long term and highlighting the necessity of stabilization.

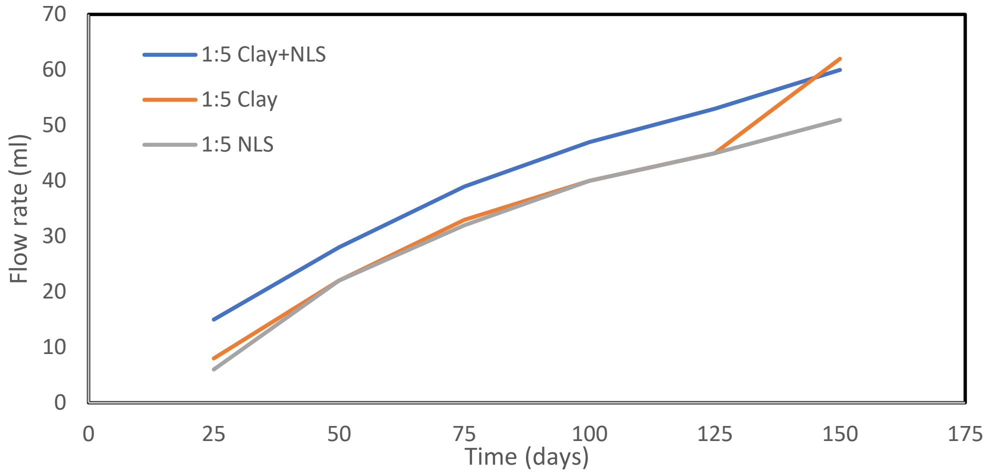


Figure 4.14. Effects of temporary cover material type on flow rate over time

4.3.2. pH and EC Results

The pH and electrical conductivity (EC) findings serve as invaluable tools for understanding the chemical makeup of both the temporary covers and the surrounding leachate environment. Through these measurements, we gain critical insights into the fluctuations in pH levels and variations in ion concentrations within the liners caused by leachate infiltration. Additionally, these findings allow us to gauge the efficacy of NLS in mitigating the adverse effects of leachate exposure. By examining how NLS influences pH levels and EC within the liners, we can ascertain its effectiveness in maintaining favorable chemical conditions and enhancing the overall resilience of the liners against the detrimental impacts of leachate infiltration. Figures 4-15 and 4-16 present the impact of operation mode on the variation of pH and EC over time, respectively.

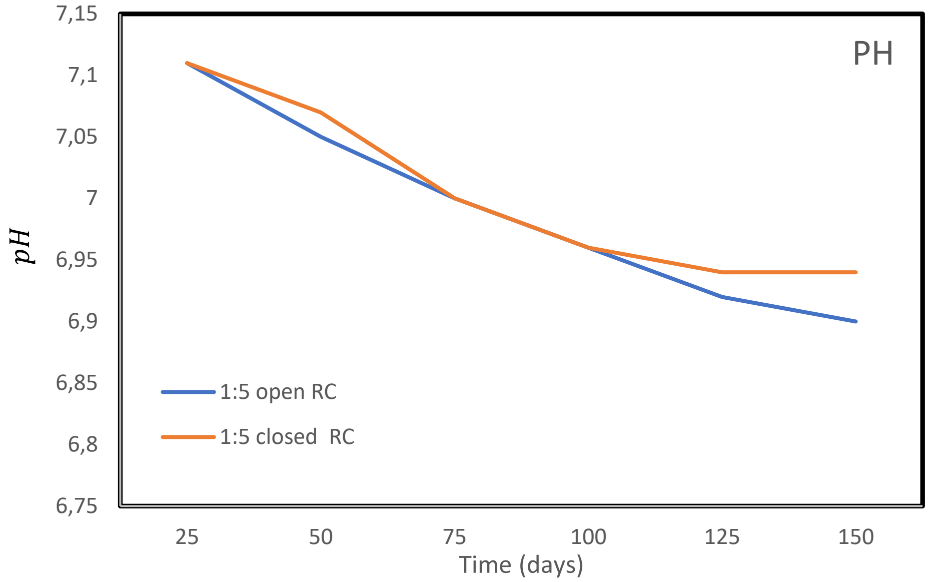


Figure 4.15. Effects of operation mode on pH over time for NLS-treated clay temporary cover

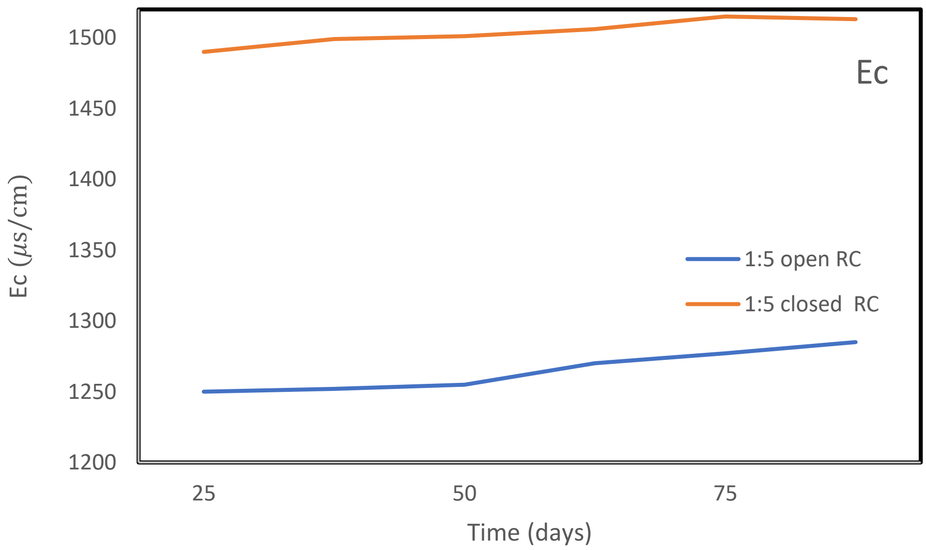


Figure 4.16. Effects of operation mode on EC over time for NLS-treated clay temporary cover.

Despite a general decreasing trend in pH value for both models up to 100 days, the changes in pH of the closed model became negligible and reached a constant value after 125 days, with no further changes observed. However, the pH value of the open system gradually decreased even up to 150 days, although the rate of change was higher in the first 100 days than between 100 and 150 days. On the other hand, a significant difference was recorded in EC values due to changes in operation mode, with higher EC values determined for the leachate collected from the closed model. Additionally, there was a gradual increase in EC values for both models.

The effects of leachate recirculation on the variation of pH and EC are shown in Figures 4-17 and 4-18, respectively. It can be seen that for both models, the pH values decreased as operation time increased. However, at any given time, the pH value measured for the model subjected to leachate recirculation was lower, demonstrating the effect of leachate circulation in the landfill system in decreasing the pH value of the outflow and therefore providing a more acidic environment for the surrounding area.

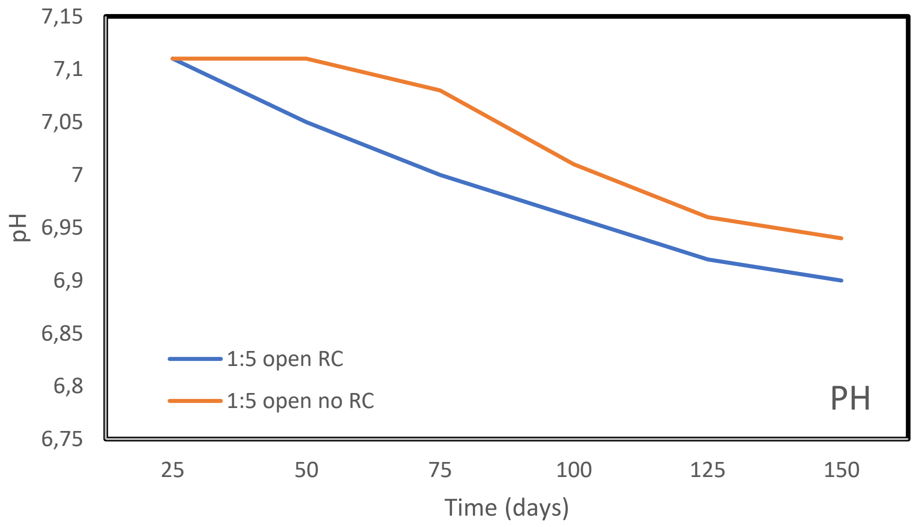


Figure 4.17. Effects of leachate recirculation on pH over time for NLS-treated clay temporary cover

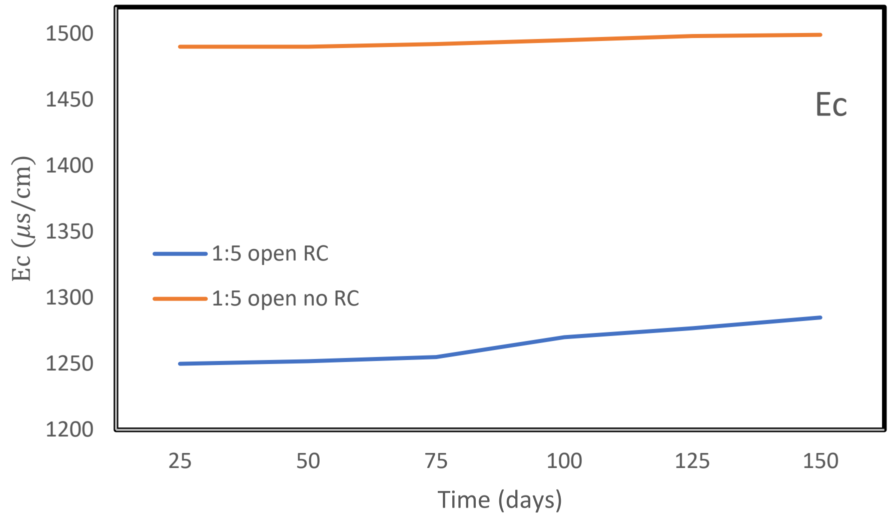


Figure 4.18. Effects of leachate recirculation on EC over time for NLS-treated clay temporary cover

The EC results given in Figure 4-18 confirm that the EC values for the leachate recirculation case showed a slight increasing trend over time, specifically for the operation period beyond 75 days. In contrast, the recorded results for the model with no recirculation were relatively constant, with no noticeable changes over time.

Figures 4-19 and 4-20 represent the impact of temporary cover thickness on the pH and EC values over the operation time. Despite the similarity in the obtained pH results, which showed a decreasing trend over time with relatively similar values at any given time, the EC values for the models with low and medium thickness showed a relatively similar increasing trend over time. However, for the model with the highest cover thickness, there was only a very slight increase in EC values over time.

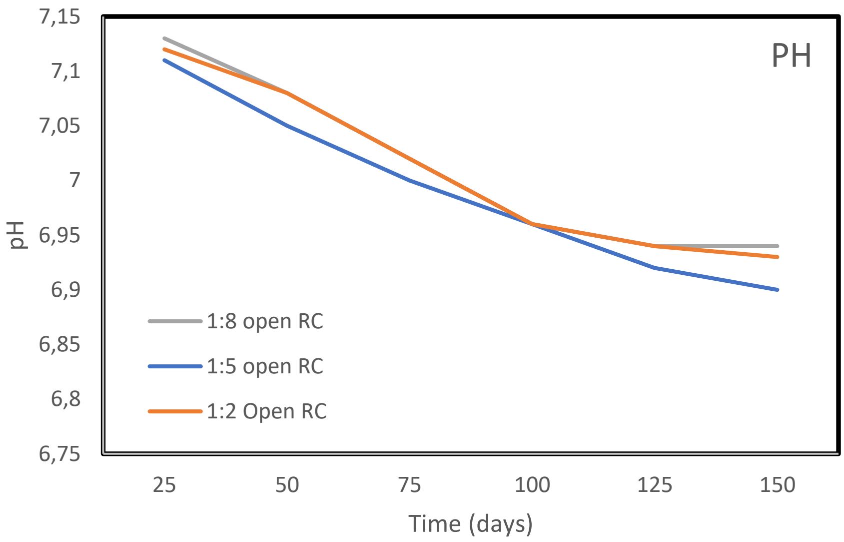


Figure 4.19. Effects of temporary cover thickness on pH over time for NLS-treated clay temporary cover

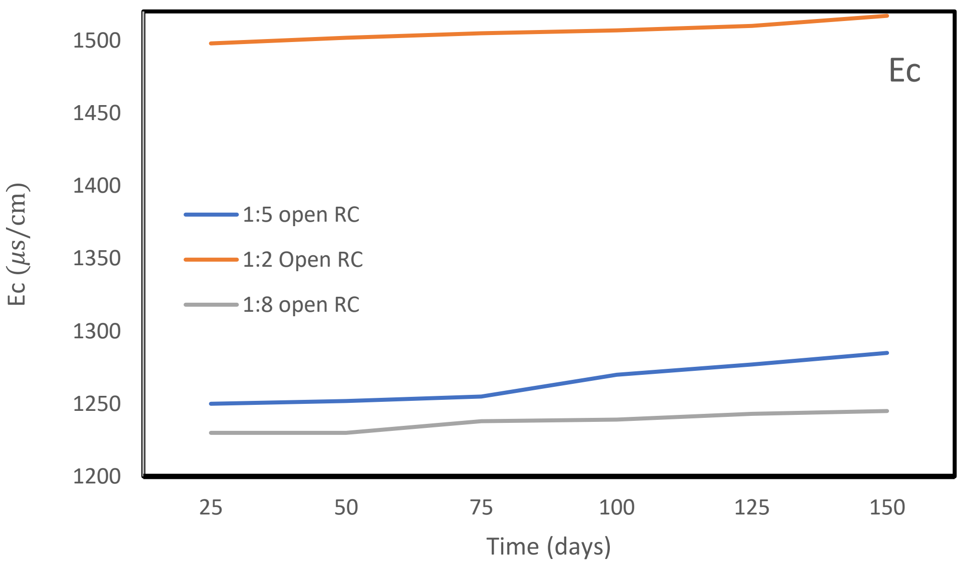


Figure 4.20. Effects of temporary cover thickness on EC over time for NLS-treated clay temporary cover

The changes in pH and EC values resulting from applying various curing times for the NLS stabilization of temporary cover material are indicated in Figures 4-21 and 4-22, respectively. For a long operation time, such as 150 days, the cover material made from the NLS-stabilized sample cured for a long period, such as 90 days, showed a relatively higher pH value, resulting in less acidic conditions for the surrounding environment. The results confirmed that the longer the operation time, the lower the pH value and the higher the EC value.

The pH and EC changes resulting from the application of various materials as temporary cover in the column model tests are shown in Figures 4-23 and 4-24, respectively. The model that included only NLS as a temporary cover exhibited a higher pH value, while the results for the models made of clay or clay mixed with 1% NLS were relatively similar. It should be noted that all three models showed a very slight increasing trend in EC value over time, but the EC values recorded for the model including the mixture of clay and NLS were significantly higher than those of the models including clay and NLS individually.

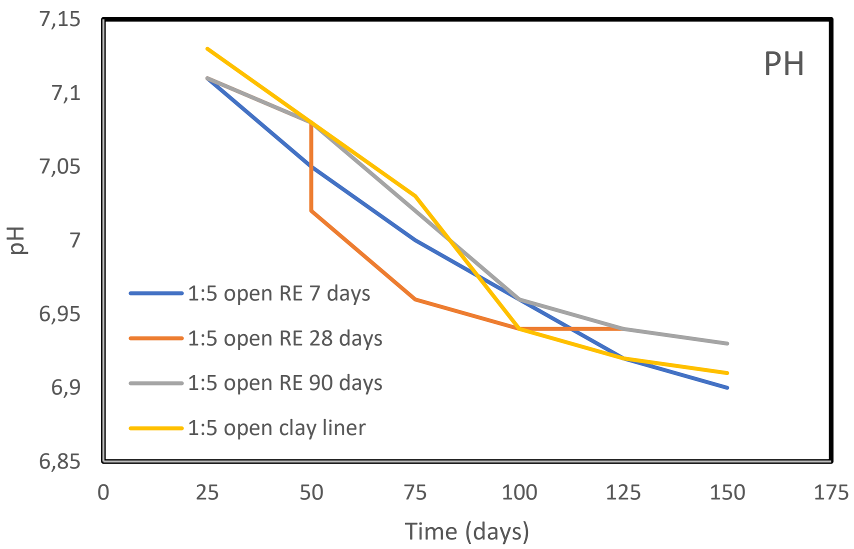


Figure 4.21. Effects of curing time on pH over time for NLS-treated clay temporary cover

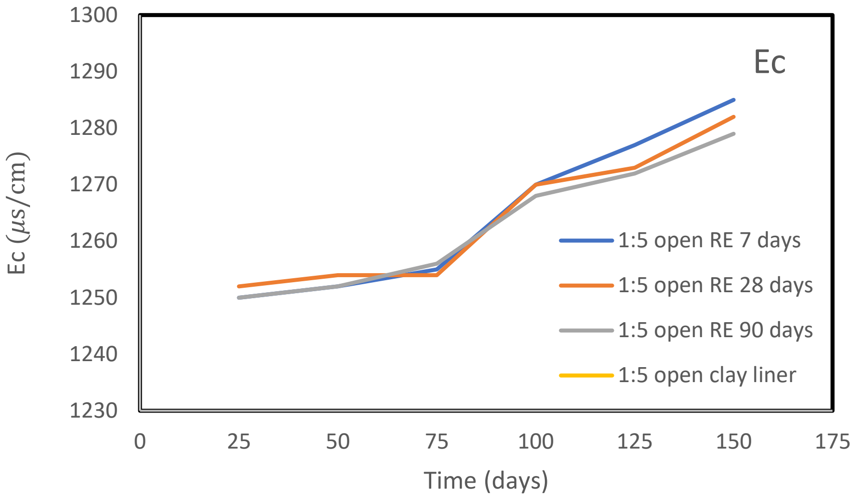


Figure 4.22. Effects of curing time on EC over time for NLS-treated clay temporary cover

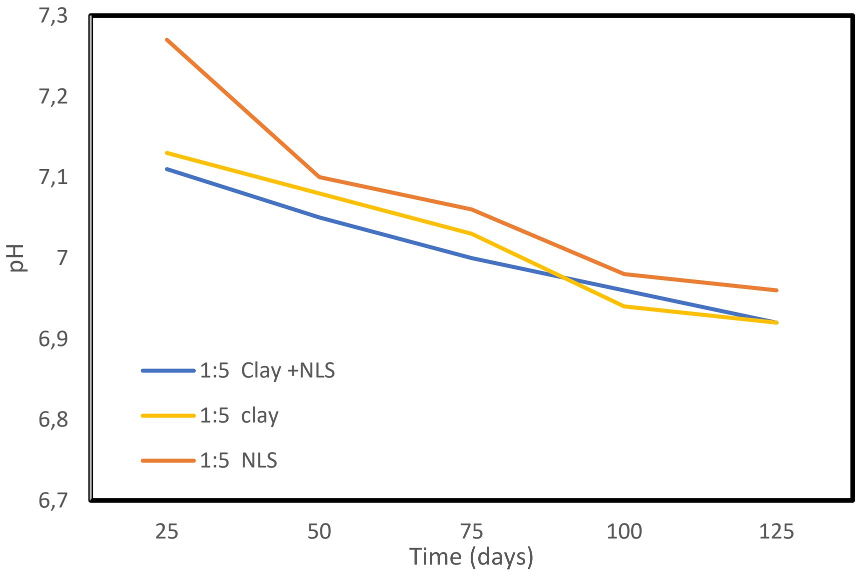


Figure 4.23. Effects of temporary cover material type on pH over time

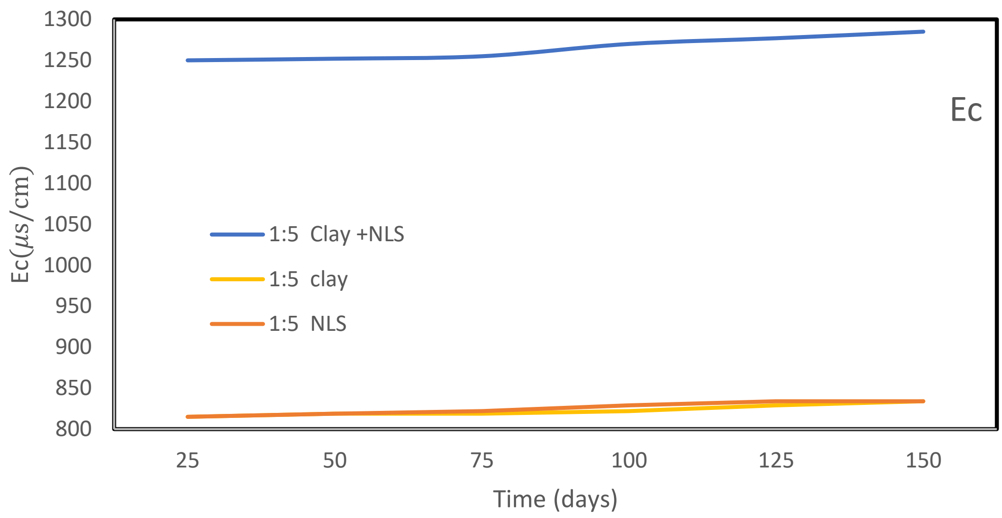


Figure 4.24. Effects of temporary cover material type on EC over time

4.3.3. Heavy Metal Analysis

Heavy metal concentrations act as pivotal indicators of pollution severity, providing valuable insights into the efficacy of NLS in impeding their dispersion through the liners. Through a comprehensive evaluation of heavy metal levels, researchers can effectively gauge the environmental ramifications of leachate infiltration, thereby elucidating NLS's capacity to mitigate the leaching of metals into the surrounding soil and groundwater. Figures 4-25 to 4-32 present the effects of operation mode on heavy metal concentrations in landfill systems made of NLS-treated clay temporary cover. These figures investigate the variations of heavy metal elements such as Pb, Cd, Hg, As, Cr, Cu, Ni, and Zn over time, respectively. In Figure 4-25, the concentration of Pb in the collected leachate increased significantly by five times with almost linear changes as the operation time increased from 25 days to 50 days from the start of the test. However, the rate of increment dropped significantly between 50 and 125 days, although the concentration of the element continued to increase. Beyond 125 days, there was a significant decrease in Pb concentration. Except for the first 50 days when the results were the same, the Pb concentration of the closed model was lower than that of the open model.

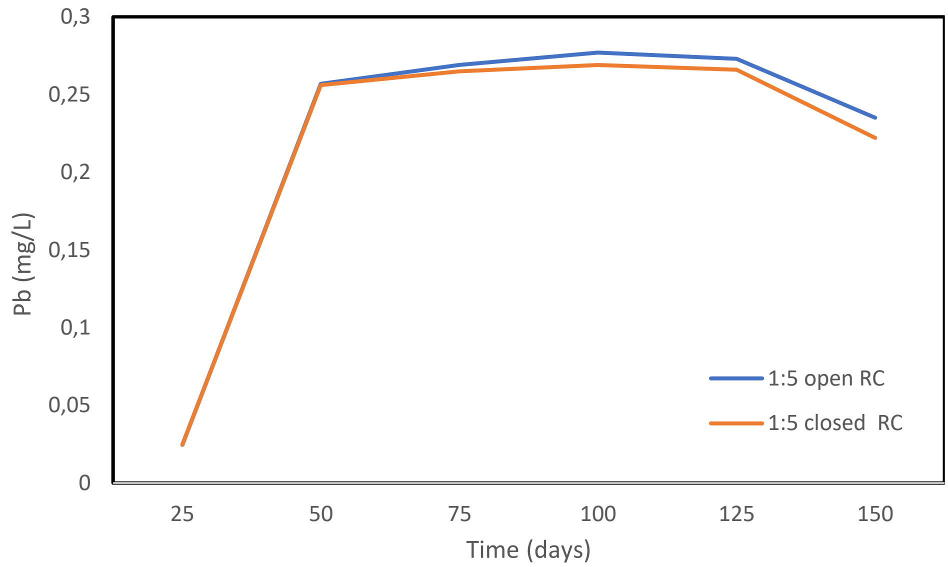


Figure 4.25. Effects of operation mode on Pb over time for NLS-treated clay temporary cover

In Figure 4-26, the concentration of Cd increased slowly as the operation time increased from 25 days to 75 days, whereas the rate of increment became significant between 75 and 100 days. Compared to the collected leachate at 50 days, the concentration of Cd was almost six times higher for the sample collected at 100 days. However, a substantial drop in Cd concentration was recorded after 100 days, such that the concentration of Cd was roughly two times lower for the sample collected at 150 days compared to the sample collected at 100 days.

It is noteworthy that the effects of operation mode on the results became significant and obvious when the operation time exceeded 100 days. The Cd content measured for the closed model was lower than that of the open model, and the level of difference increased from 1.19 times to about 1.6 times as the operation time increased from 125 to 150 days.

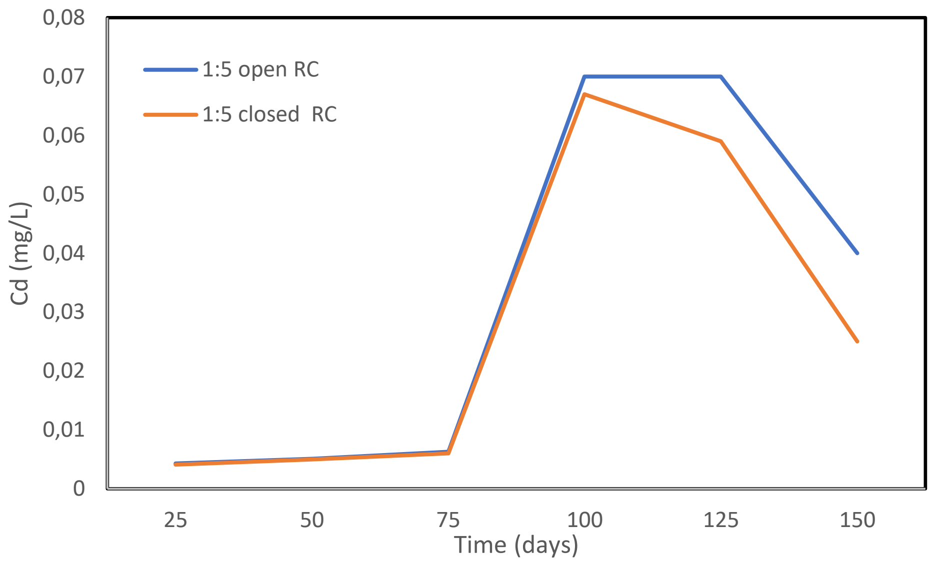


Figure 4.26. Effects of operation mode on Cd over time for NLS-treated clay temporary cover

The variations of Hg concentration resulting from the application of different operation modes are shown in Figure 4-27. Except for the first period (between 25 and 50 days), the results recorded for both models did not exhibit any differences, indicating that both models could adsorb the Hg content relatively similarly. Additionally, there was a significant reduction in Hg concentration between 50 and 75 days of operation, reaching a stable situation by 75 days where no further changes in Hg concentration were measured.

Figure 4-28 indicates that the concentration of as content increased significantly by 10 times between 25 and 50 days from the start of the test. Thereafter, it experienced a substantial decrease by 10.2 times during the period between 125 and 150 days. For operation times between 50 and 125 days, the decrement rates were not significant. Additionally, the results obtained for both operation modes were completely identical in terms of as concentration and changes over time.

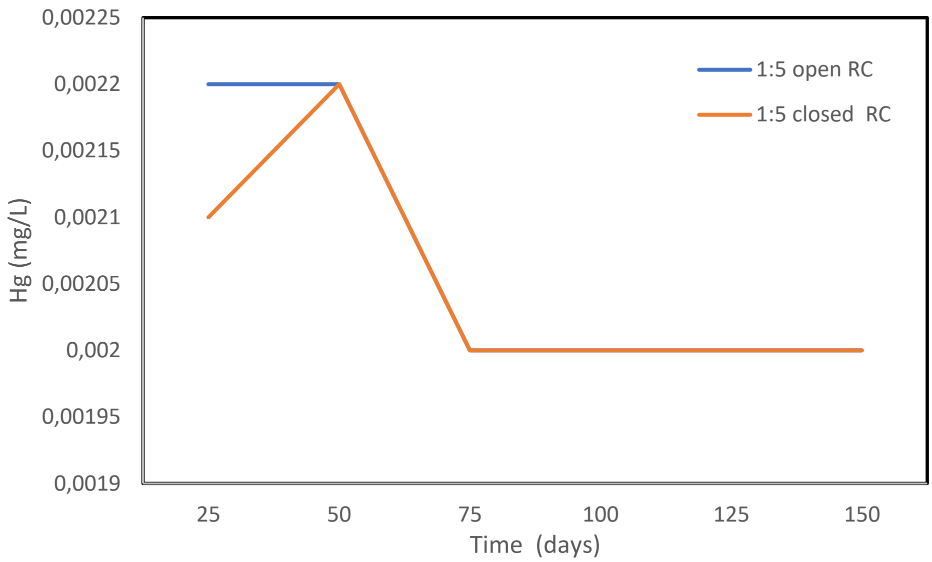


Figure 4.27. Effects of operation mode on Hg over time for NLS-treated clay temporary cover

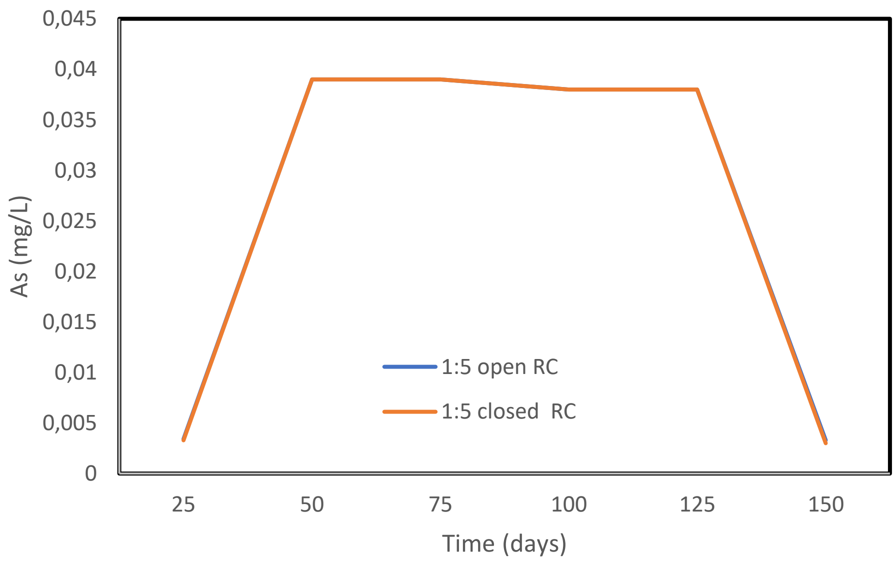


Figure 4.28. Effects of operation mode on As over time for NLS-treated clay temporary cover

The changes in Cr content due to the application of different operation modes are depicted in Figure 4-29. The difference between both modes can be observed for operation times longer than 125 days, where the concentration of Cr for the closed system was lower than that of the open one. Regardless of the operation mode applied in the test, the concentration of Cr increased gradually during the period between 25 and 75 days. Subsequently, it developed significantly between 75 and 100 days.

However, an adverse trend was observed, indicating a decrease in Cr concentration for operation times beyond 100 days.

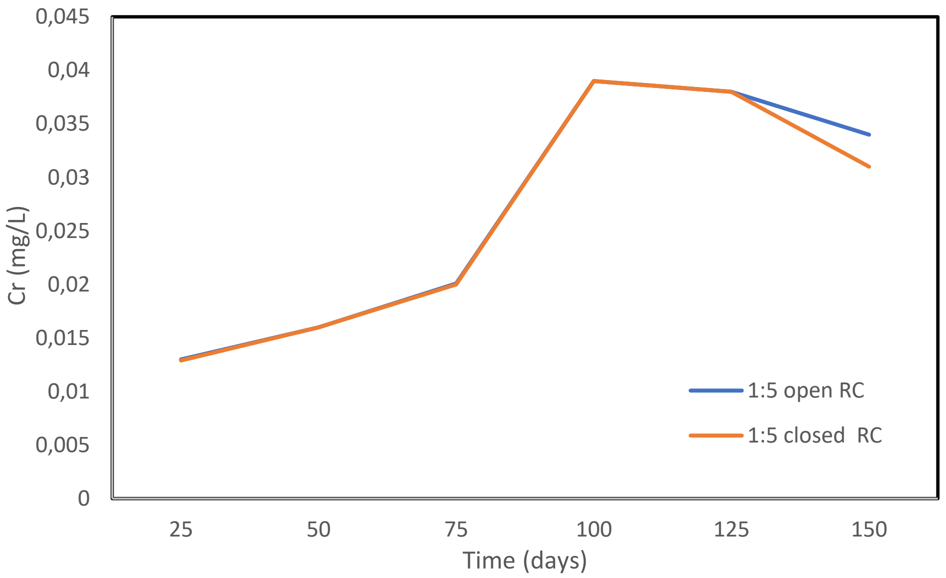


Figure 4.29. Effects of operation mode on Cr over time for NLS-treated clay temporary cover

Figure 4-30 illustrates the effects of operation modes on the concentration of Cu content. A very slight increase in Cu concentration was recorded up to 100 days. However, beyond this specific time, the concentration of Cu content first decreased slightly between 100 and 125 days and then decreased further significantly after 125 days. The concentration of Cu for the closed system was lower than that for the open mode, and the rate of difference between the results of both modes became significant as the operation time increased.

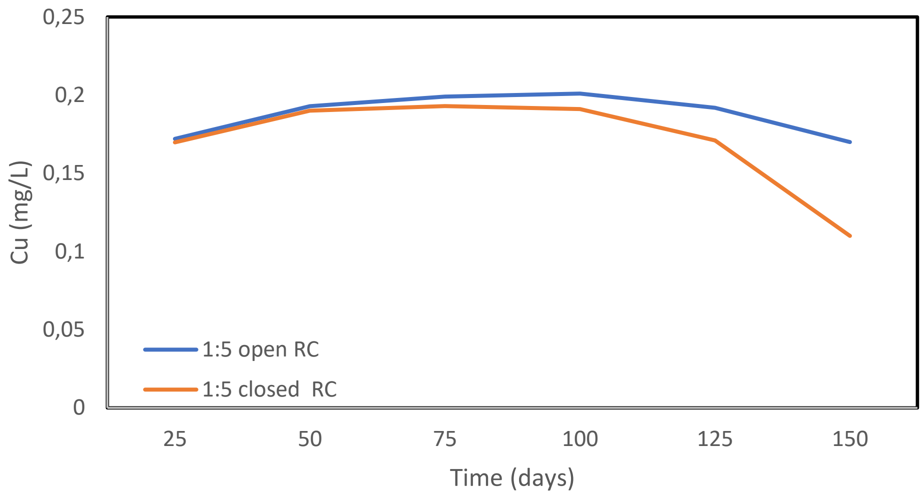


Figure 4.30. Effects of operation mode on Cu over time for NLS-treated clay temporary cover

The changes in Ni content due to the application of different operation modes are displayed in Figure 4-31. Although the closed system yielded a lower Ni concentration compared to the open system, the difference in concentration between the two systems was not significant. For both modes, the Ni concentration increased significantly by 81% up to 100 days, then decreased substantially by 94% between 100 and 125 days. The rate of decrease in Ni concentration slowed down during the period between 125 and 150 days.

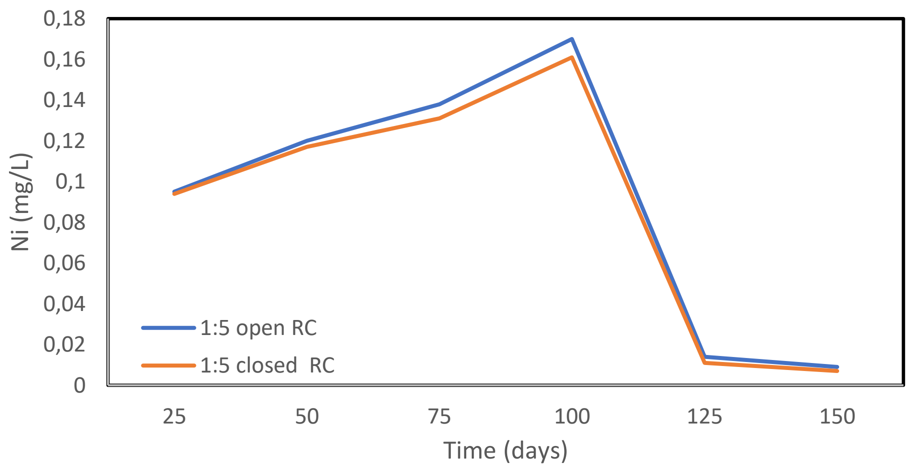


Figure 4.31. Effects of operation mode on Ni over time for NLS-treated clay temporary cover

Figure 4-32 illustrates the effects of operation modes on the concentration of Zn content. There was a slight increase in Zn concentration for up to 100 days, while beyond this time, Zn concentration moderately decreased. The application of the closed system resulted in a lower concentration of Zn content, with the concentration of Zn content in the leachate collected for the closed model being about 19% less than that of the open model.

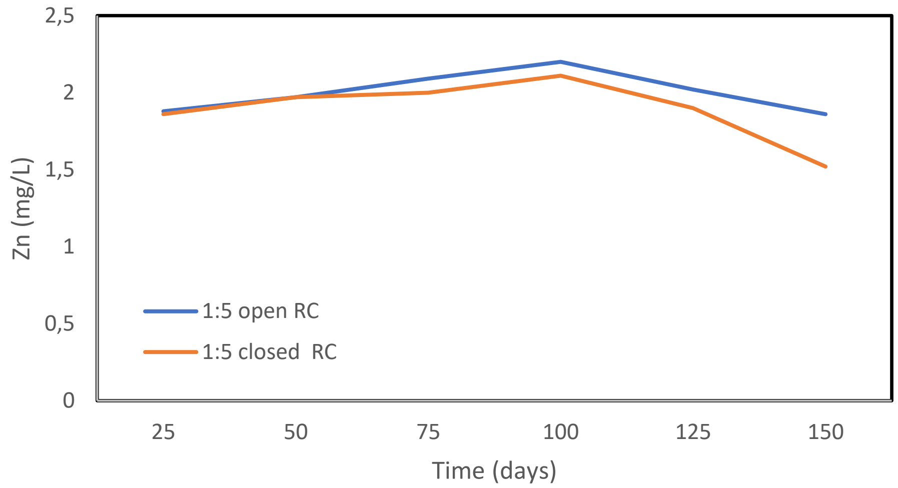


Figure 4.32. Effects of operation mode on Zn over time for NLS-treated clay temporary cover

Figure 4-33 shows the impact of leachate recirculation on the Pb concentration. Irrespective of leachate recirculation, the Pb content rose significantly from 25 to 50 days, then remained relatively constant from 50 to 125 days. Finally, the samples experienced a moderate decrease in Pb concentration from 125 to 150 days. The effects of recirculation on the results became obvious after 50 days, with the amount of Pb in the models subjected to leachate recirculation being higher compared to those with no recirculation.

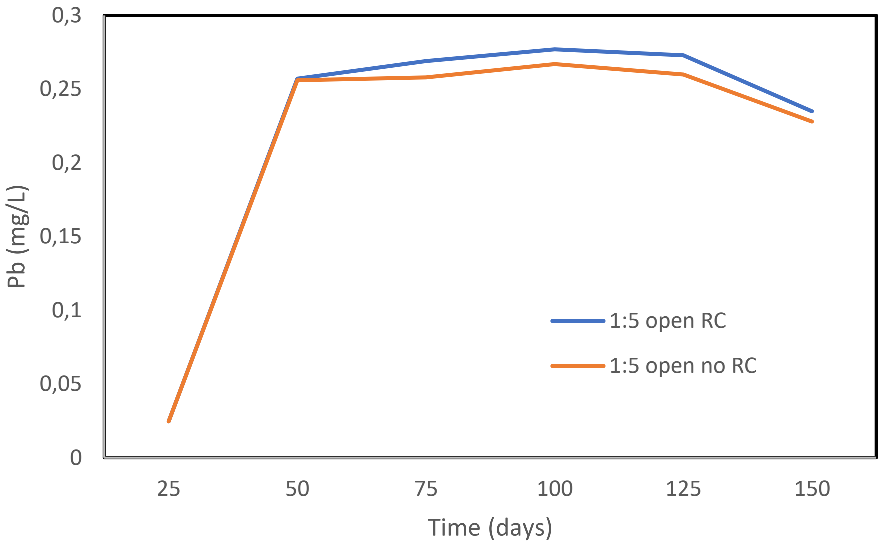


Figure 4.33. Effects of leachate recirculation on Pb over time for NLS-treated clay temporary cover

The considerable impact of leachate recirculation on the concentration of Cd content is illustrated in Figure 4-34. As shown in this figure, the amount of Cd rose slightly from 25 to 75 days, but the increment rate was noticeable from 75 to 100 days. For the samples collected at 125 days, the highest difference in Cd concentration between the models subjected to leachate recirculation and no recirculation was measured, with the Cd concentration being about 1.32 times higher in the leachate recirculation model.

Further investigation focused on the effect of leachate recirculation on the concentration of Hg, as depicted in Figure 4-35. Different results were observed for both models when the operation time was less than 75 days. For operation times longer than 75 days, the Hg concentrations were identical for both models. When the operation time was less than 75 days, the Hg content was recorded to be lower in the no-recirculation model. There was a decreasing trend in Hg content from 50 to 75 days in the recirculation model, whereas the main changes in the no-recirculation model occurred between 25 and 50 days. It should be noted that the no-recirculation model reached stable results 25 days faster than the recirculation model.

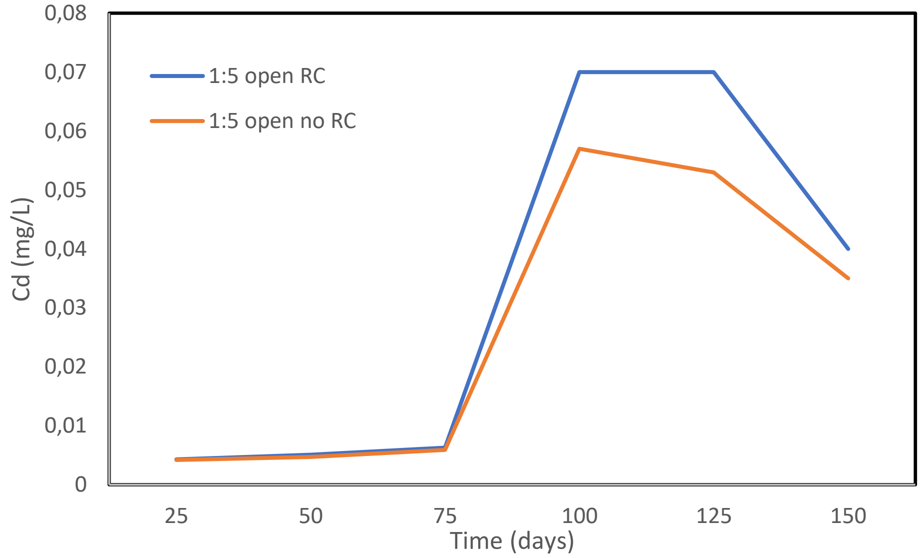


Figure 4.34. Effects of leachate recirculation on Cd over time for NLS-treated clay temporary cover

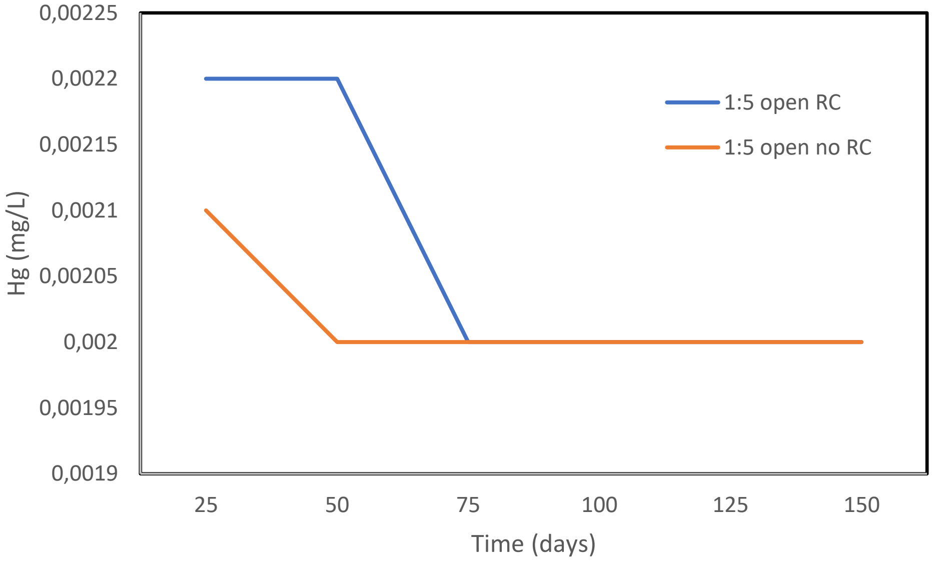


Figure 4.35. Effects of leachate recirculation on Hg over time for NLS-treated clay temporary cover

The experimental results revealed that the general trend for As content changes due to leachate recirculation was similar to that without leachate recirculation. However, for operation times exceeding 100 days, the amount of As content was higher for the model subjected to leachate recirculation. For both models, a substantial reduction in the concentration of As, approximately 11 times, was observed during the operation period between 125 and 150 days.

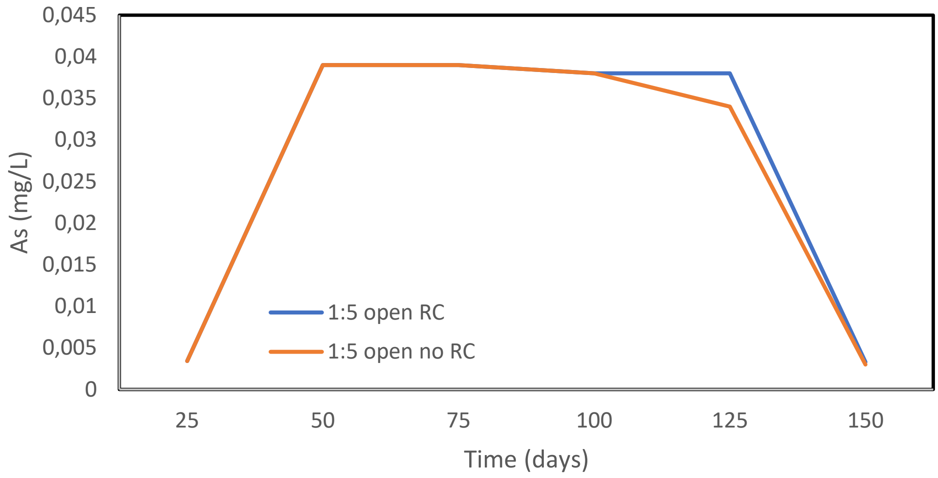


Figure 4.36. Effects of leachate recirculation on As over time for NLS-treated clay temporary cover

Figure 4-37 presents the Cr changes resulting from the application of leachate recirculation in the column model test. There were no obvious changes in the Cr concentration due to applying different procedures for up to 100 days. However, after 100 days, the amount of Cr measured for the model with leachate recirculation was generally higher compared to the model with no recirculation. Additionally, a general increase in Cr content for both models was recorded for up to 100 days, while beyond this time, the Cr concentration showed a gradual decreasing trend.

The effects of leachate recirculation on Cu concentration were further examined, as illustrated in Figure 4-38. Although the trends were similar for both models, including recirculation and no-recirculation, the Cu values measured for the collected leachate from the model that experienced leachate recirculation were higher than those of the model with no recirculation. The longer the operation time, the more significant the difference in Cu content resulting from both models. After 150 days, the Cu content measured for the recirculation model was 1.6 times higher than that of the no-recirculation model.

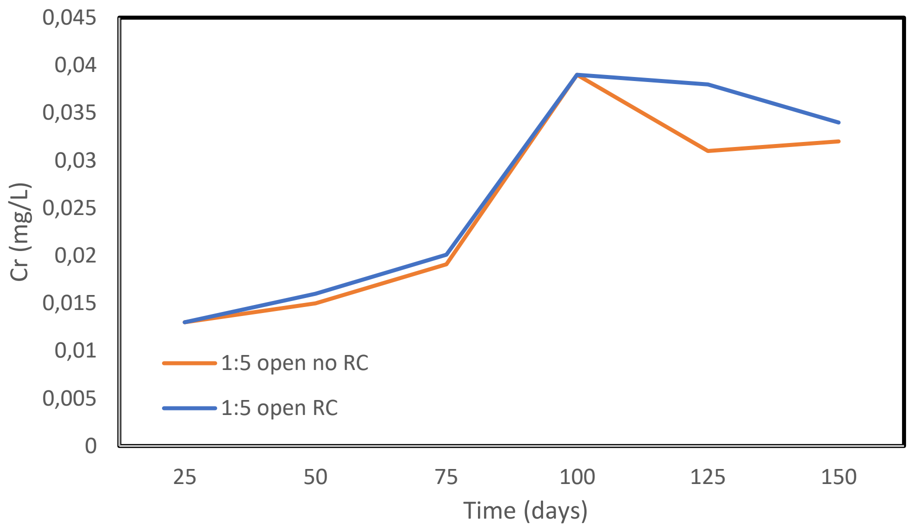


Figure 4.37. Effects of leachate recirculation on Cr over time for NLS-treated clay temporary cover

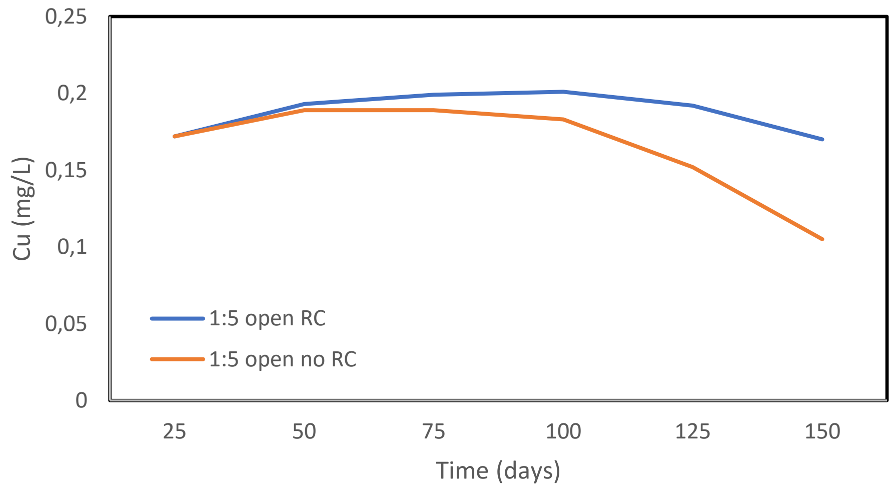


Figure 4.38. Effects of leachate recirculation on Cu over time for NLS-treated clay temporary cover

The results given in Figure 4-39 confirm that leachate recirculation did not notably change the Ni concentration; therefore, the results achieved for both models were almost identical. However, for the Zn concentration, as illustrated in Figure 4-40, the no-recirculation model resulted in lower Zn content.

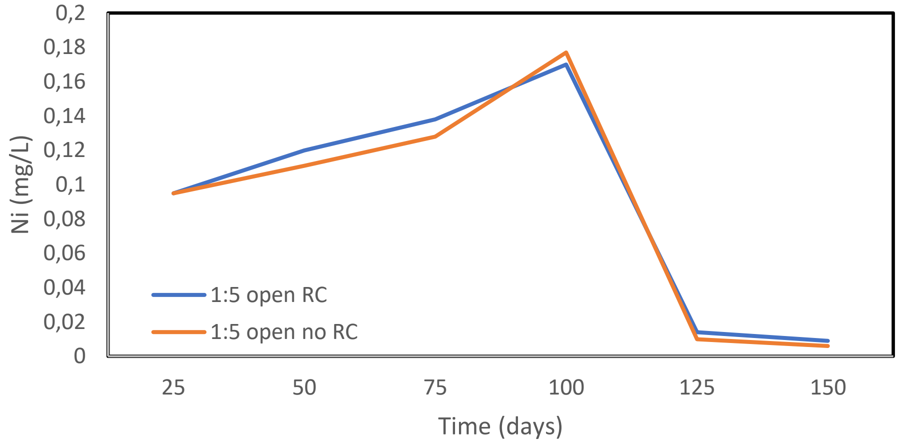


Figure 4.39. Effects of leachate recirculation on Ni over time for NLS-treated clay temporary cover

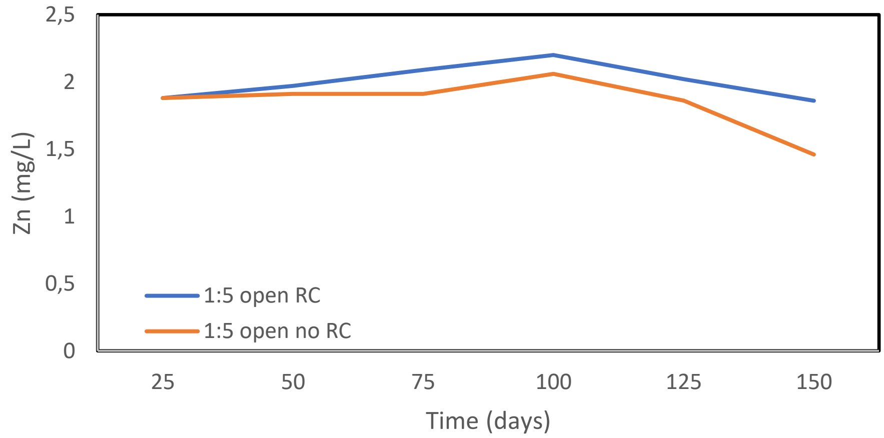


Figure 4.40. Effects of leachate recirculation on Zn over time for NLS-treated clay temporary cover

The effects of temporary cover thickness on the various heavy metal concentrations in landfill systems made of NLS-treated clay temporary cover are presented in Figures 4-41 to 4-48. An overall review of the results confirms that the higher the thickness, the lower the concentration of heavy metals. Although this is a general finding, in some cases, the thickness of the cover did not show significant effects in mitigating and reducing the heavy metal concentration. For example, in the cases of Pb (Figure 4-41), Hg (Figure 4-43), As (Figure 4-44), Cr (Figure 4-45), and Ni (Figure 4-47), there was no substantial difference in the results obtained from various models made of the same NLS-stabilized temporary covers but with different thicknesses. However, a higher temporary cover thickness led to a significant reduction in the amounts of Cd (Figure 4-42), Cu (Figure 4-46), and Zn (Figure 4-48). The results shown in Figure 4-42 verify that the effects of thickness became substantial when the operation time exceeded 100 days. For the samples collected at 150 days, the concentration of Cd reduced by 22% as the thickness of the temporary cover increased by 2.5 times.

Further investigation into the results of Cu, as shown in Figure 4-46, reveals that the increase in thickness started to significantly affect the reduction of Cu concentration after 50 days from the start of the experiment. The difference in results achieved from various models with different temporary cover thicknesses became more pronounced as the operation time increased. At an operation time of 150 days, the concentration of Cu was reduced by approximately 41% when the temporary cover thickness increased by 2.5 times.

Finally, the examination of Zn concentration over time for various temporary cover thicknesses, as depicted in Figure 4-48, indicates that the Zn concentration can increase by up to 35% if the thickness of the temporary cover decreases by 60%.

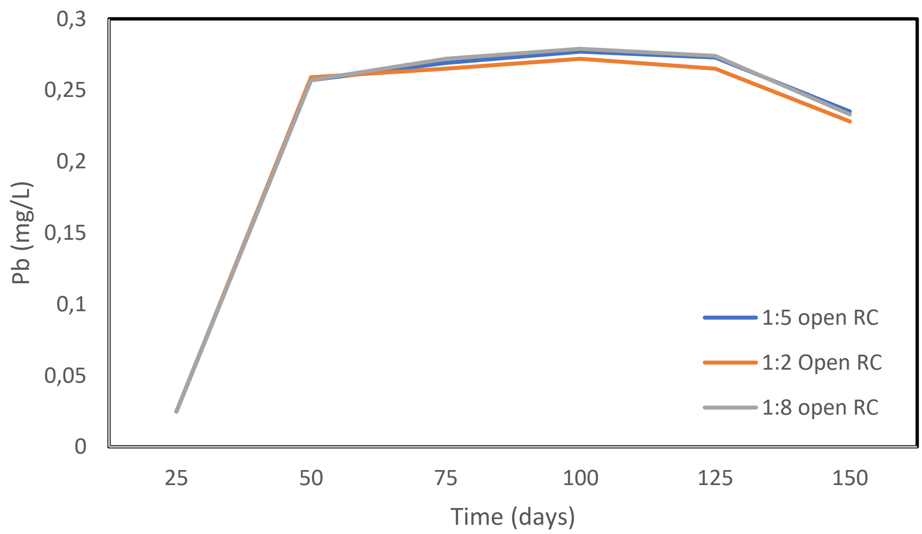


Figure 4.41. Effects of temporary cover thickness on Pb content over time for NLS-treated clay temporary cover

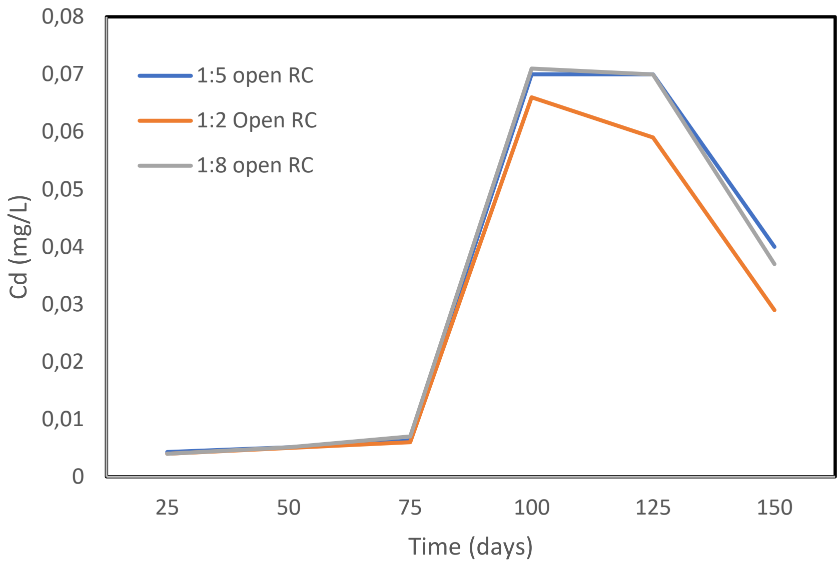


Figure 4.42. Effects of temporary cover thickness on Cd content over time for NLS-treated clay temporary cover

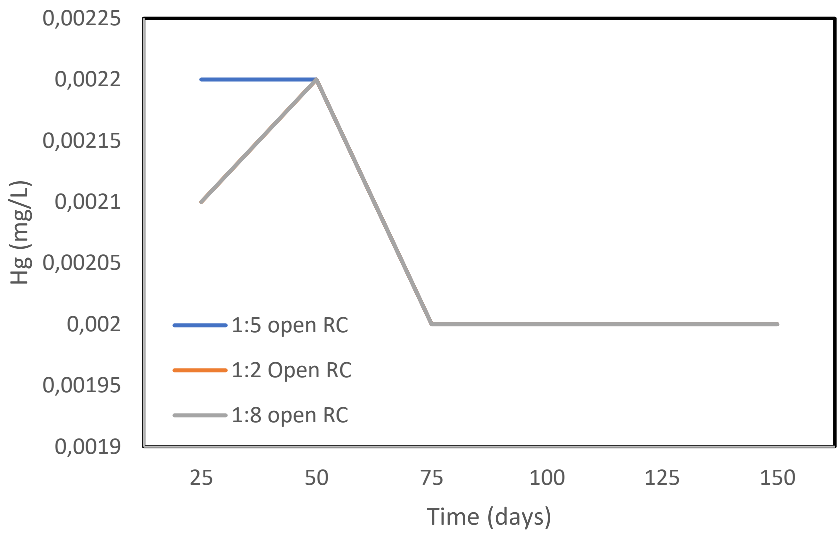


Figure 4.43. Effects of temporary cover thickness on Hg content over time for NLS-treated clay temporary cover

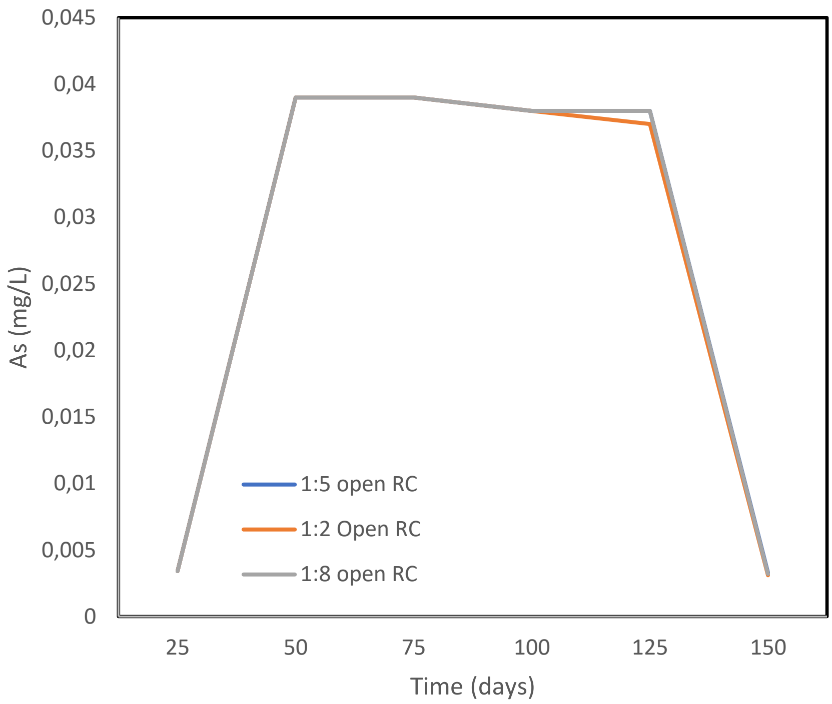


Figure 4.44. Effects of temporary cover thickness on As content over time for NLS-treated clay temporary cover

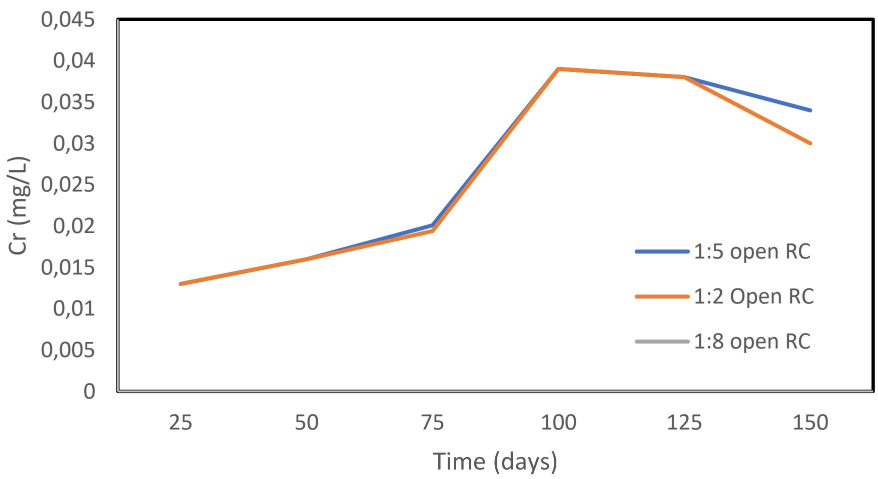


Figure 4.45. Effects of temporary cover thickness on Cr content over time for NLS-treated clay temporary cover

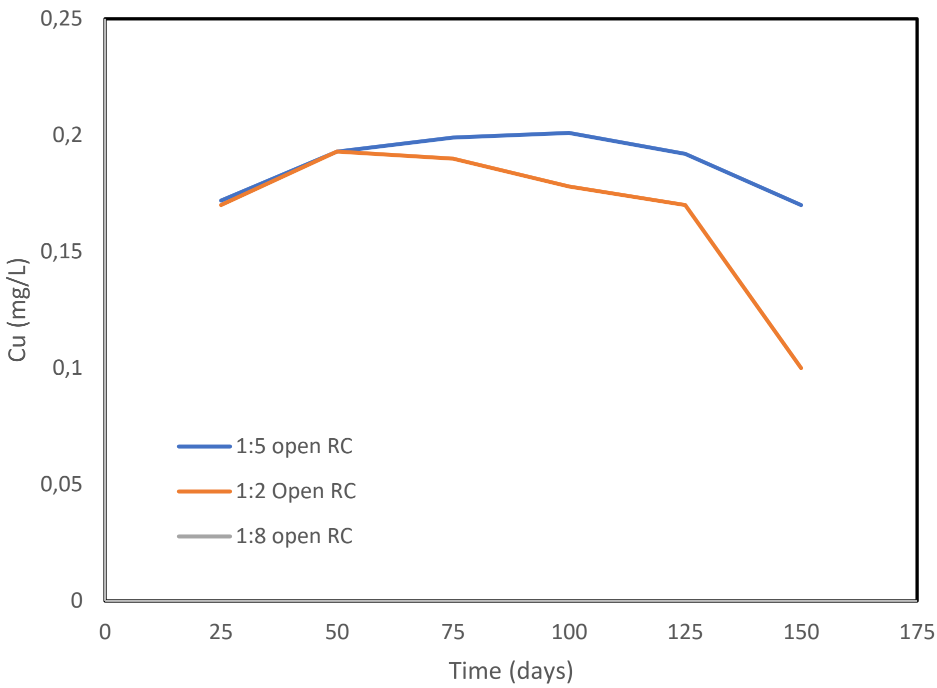


Figure 4.46. Effects of temporary cover thickness on Cu content over time for NLS-treated clay temporary cover

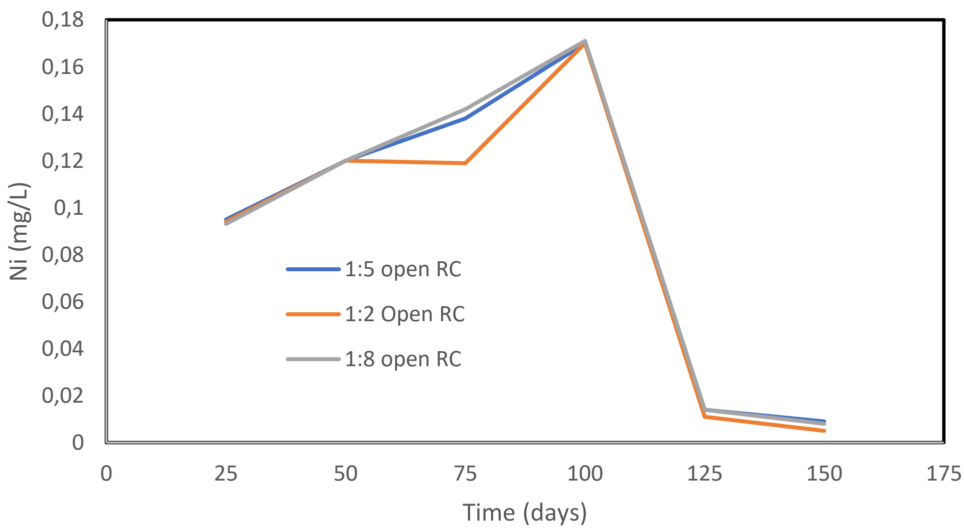


Figure 4.47. Effects of temporary cover thickness on Ni content over time for NLS-treated clay temporary cover

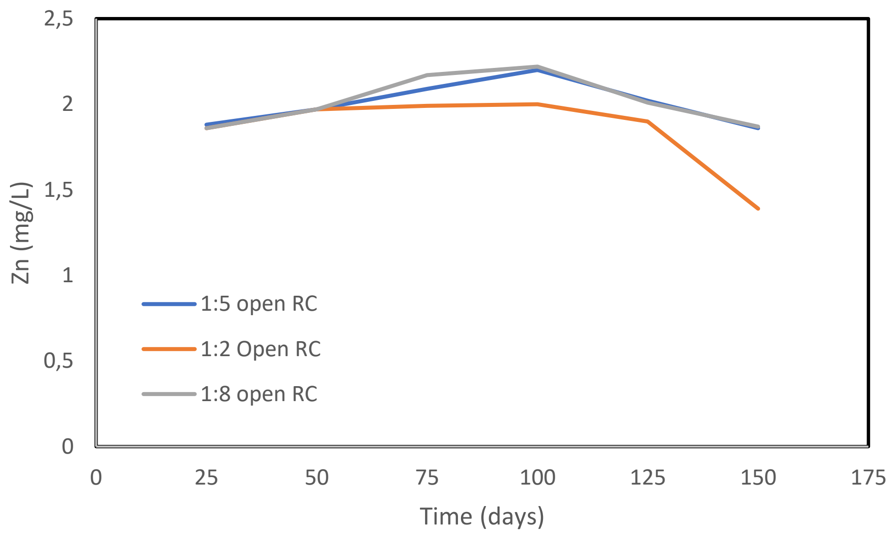


Figure 4.48. Effects of temporary cover thickness on Zn content over time for NLS-treated clay temporary cover

The effects of curing time on the performance of NLS-treated clay temporary cover in terms of mitigating and adsorbing heavy metals in a landfill system are shown in Figures 4-49 to 4-56. It is confirmed that curing time did not show substantial effects on changing the results. Therefore, in the case of controlling heavy metals concentration, 7 days of curing can be considered adequate and optimum.

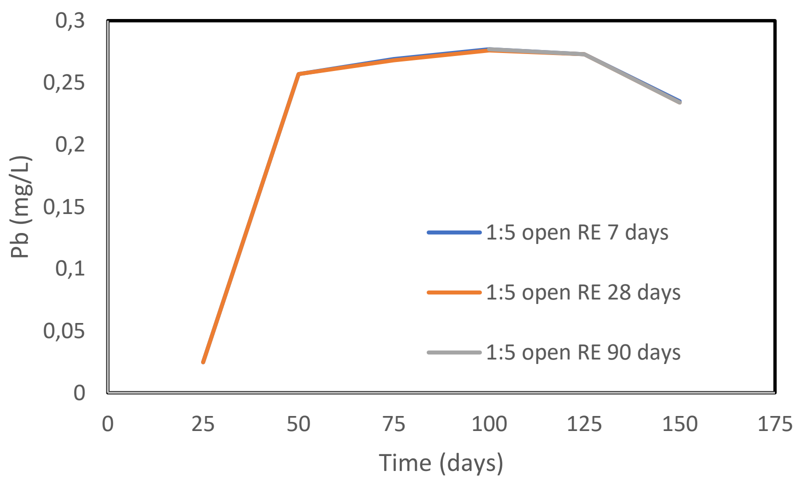


Figure 4.49. Effects of curing time on Pb content over time for NLS-treated clay temporary cover

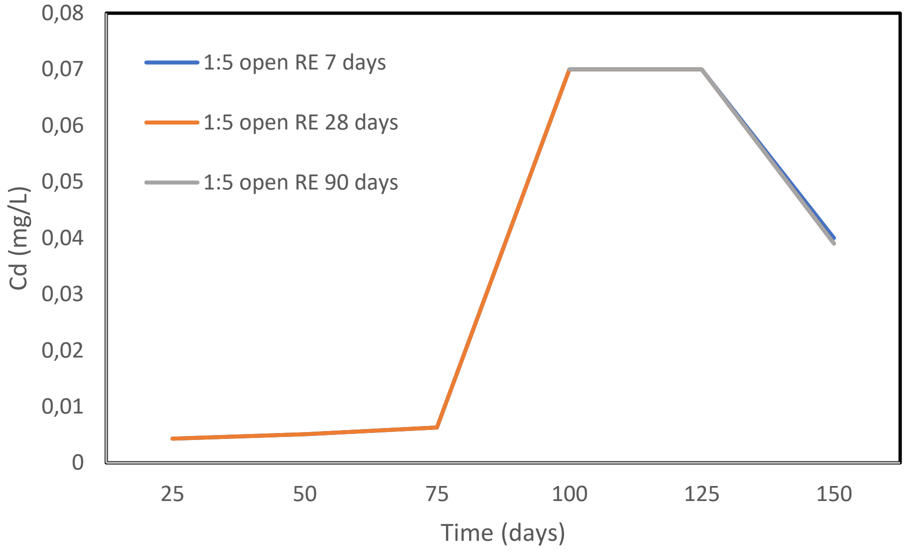


Figure 4. 50. Effects of curing time on Cd content over time for NLS-treated clay temporary cover

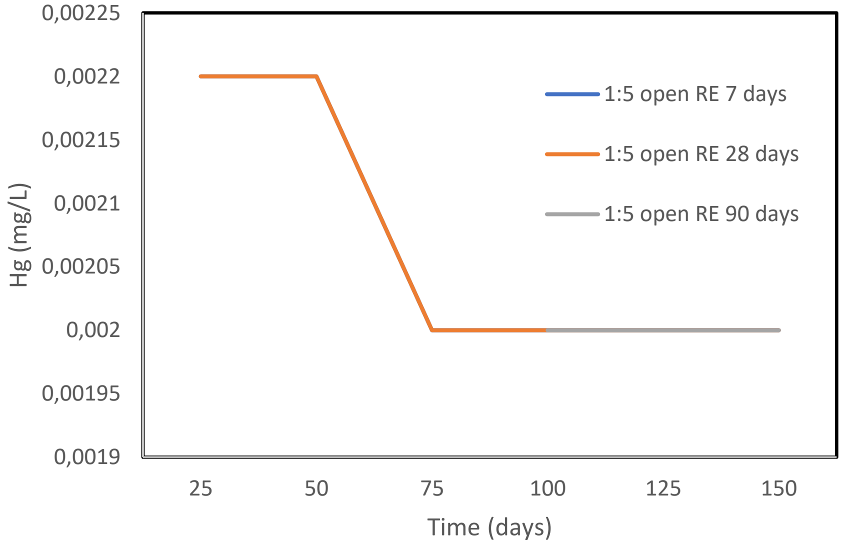


Figure 4.51. Effects of curing time on Hg content over time for NLS-treated clay temporary cover

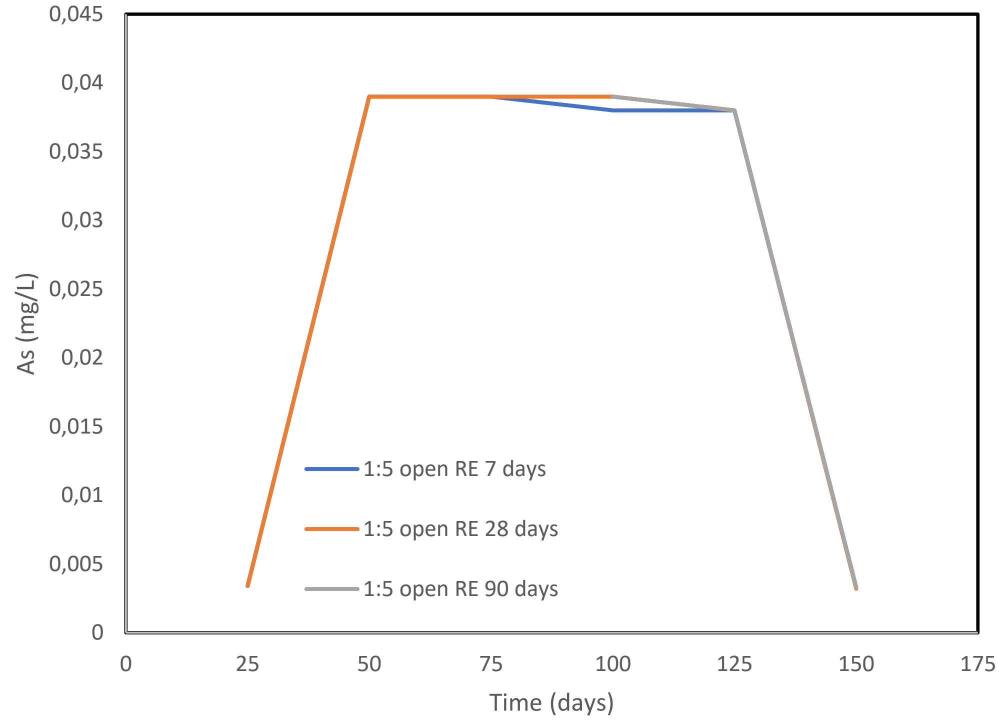


Figure 4.52. Effects of curing time on As content over time for NLS-treated clay temporary cover

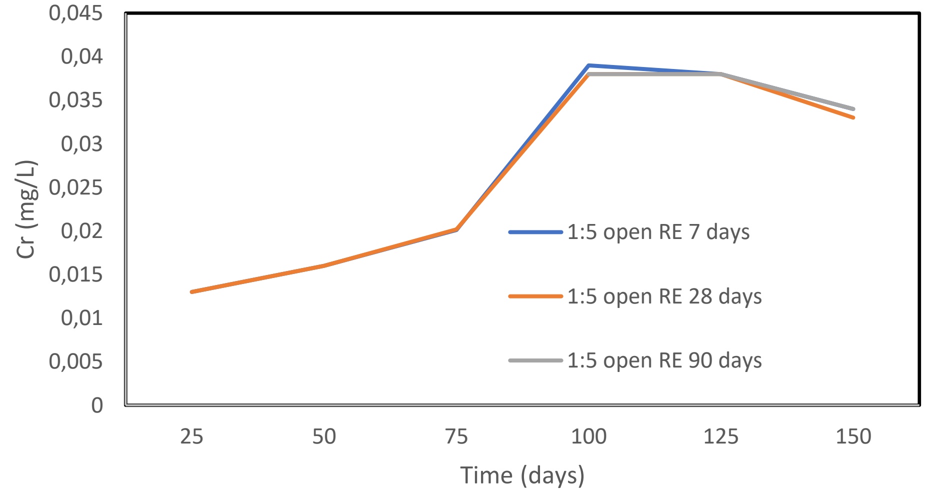


Figure 4.53. Effects of curing time on Cr content over time for NLS-treated clay temporary cover

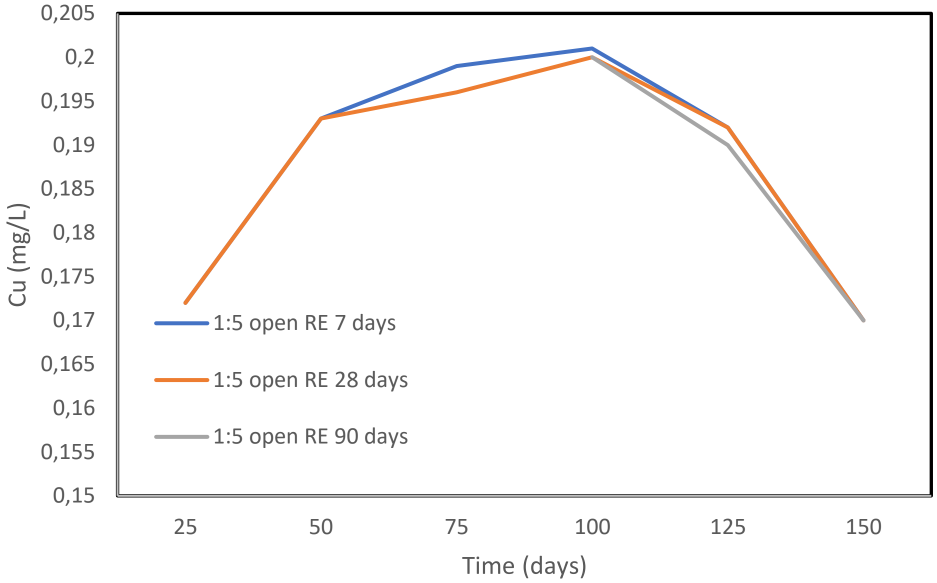


Figure 4.54. Effects of curing time on Cu content over time for NLS-treated clay temporary cover

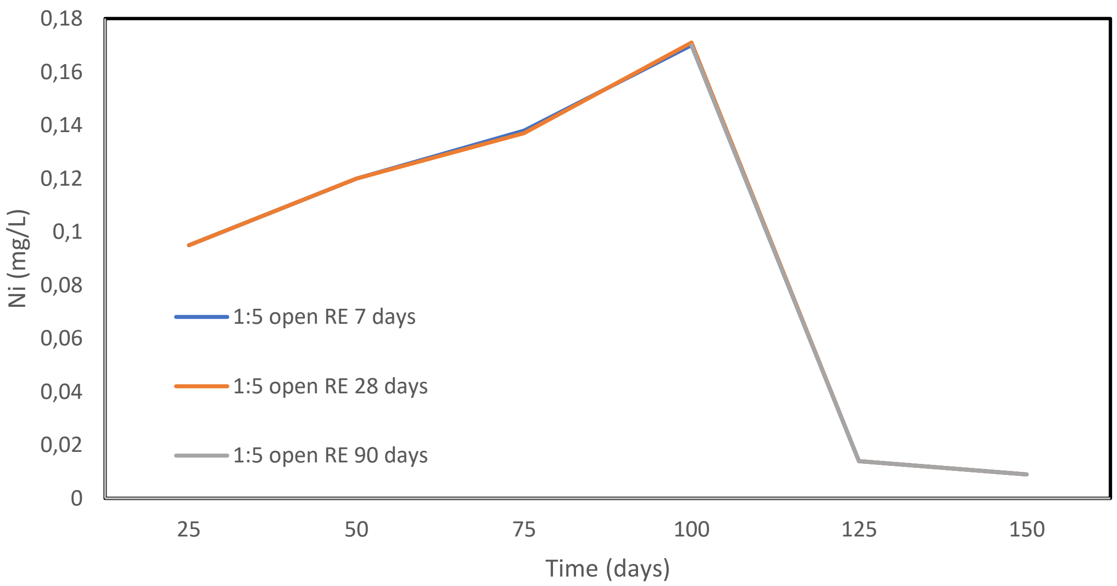


Figure 4.55. Effects of curing time on Ni content over time for NLS-treated clay temporary cover

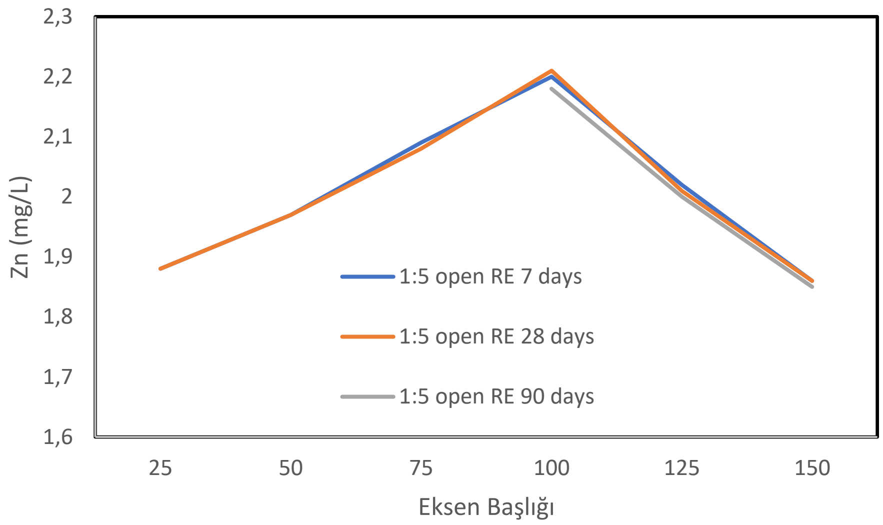


Figure 4.56. Effects of curing time on Zn content over time for NLS-treated clay temporary cover

Figures 4-57 to 4-64 illustrate the effects of material types on the performance of the temporary cover in mitigating and controlling the concentration of heavy metals. Figure 4-57 indicates that the temporary cover made of a mixture of clay and NLS performed better than NLS alone in controlling the Pb concentration for operation periods up to 75 days. However, for operation times longer than 75 days, the model with NLS alone showed better results. For Cd concentration, as shown in Figure 4-58, the results obtained for both models followed the same trend and changes over the operation time. However, less Cd concentration was measured for the model with NLS alone when the operation time exceeded 100 days. At 150 days, the Cd concentration of the model with NLS alone was about 50% less than that of the model with clay and NLS together. These results confirm that using NLS alone can also be considered a suitable material for a temporary cover, provided its performance in terms of strength is verified in future research. Furthermore, it should be noted that no obvious difference was observed between the two models in terms of the amount of Hg, As, and Cr concentrations, as shown in Figures 4-59, 4-60, and 4-61.

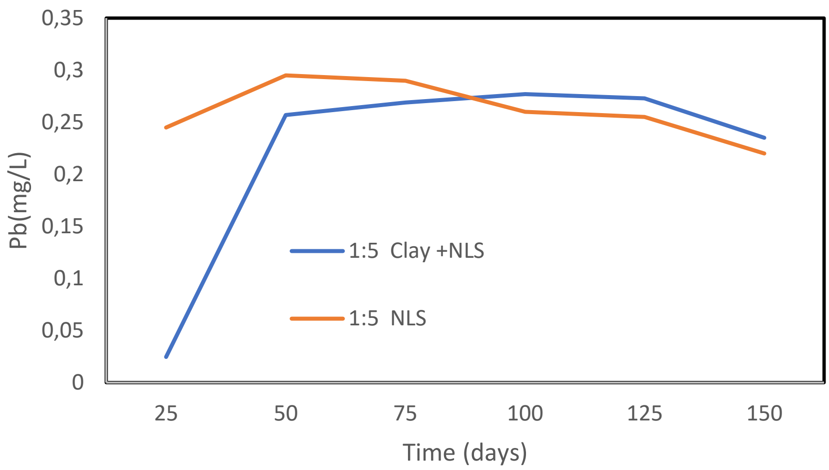


Figure 4.57. Effects of temporary cover material type on Pb content over time

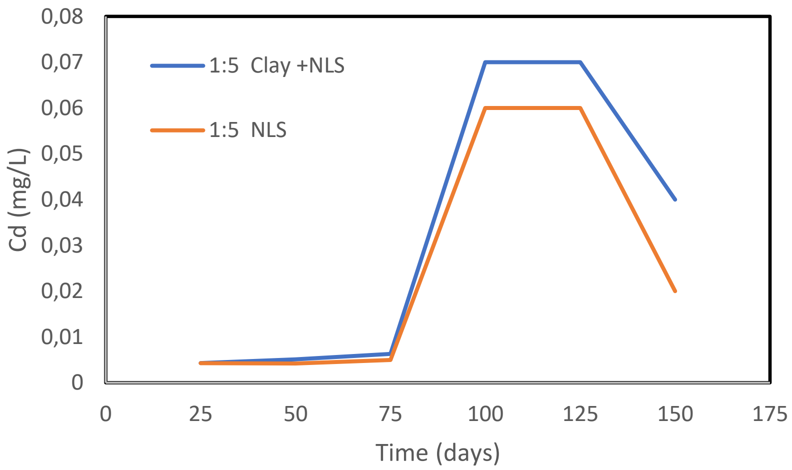


Figure 4.58. Effects of temporary cover material type on Cr content over time

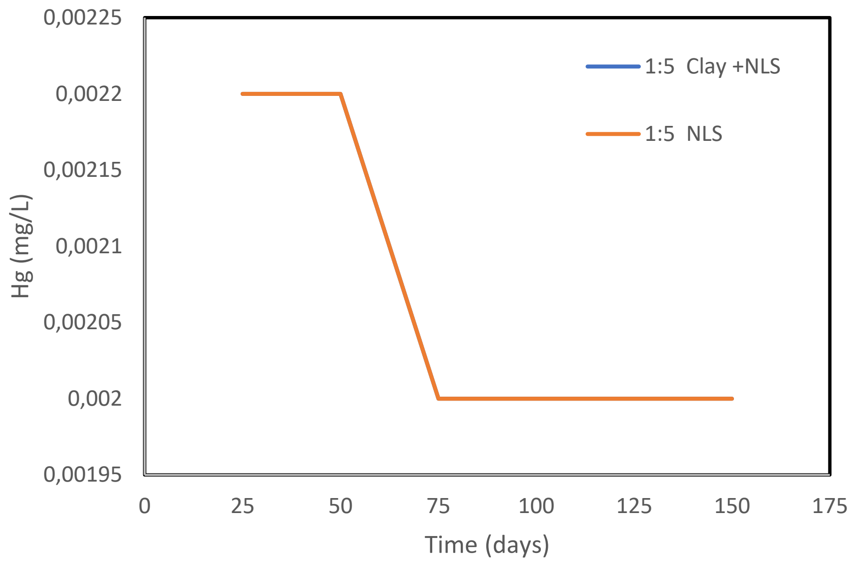


Figure 4.59. Effects of temporary cover material type on Hg content over time

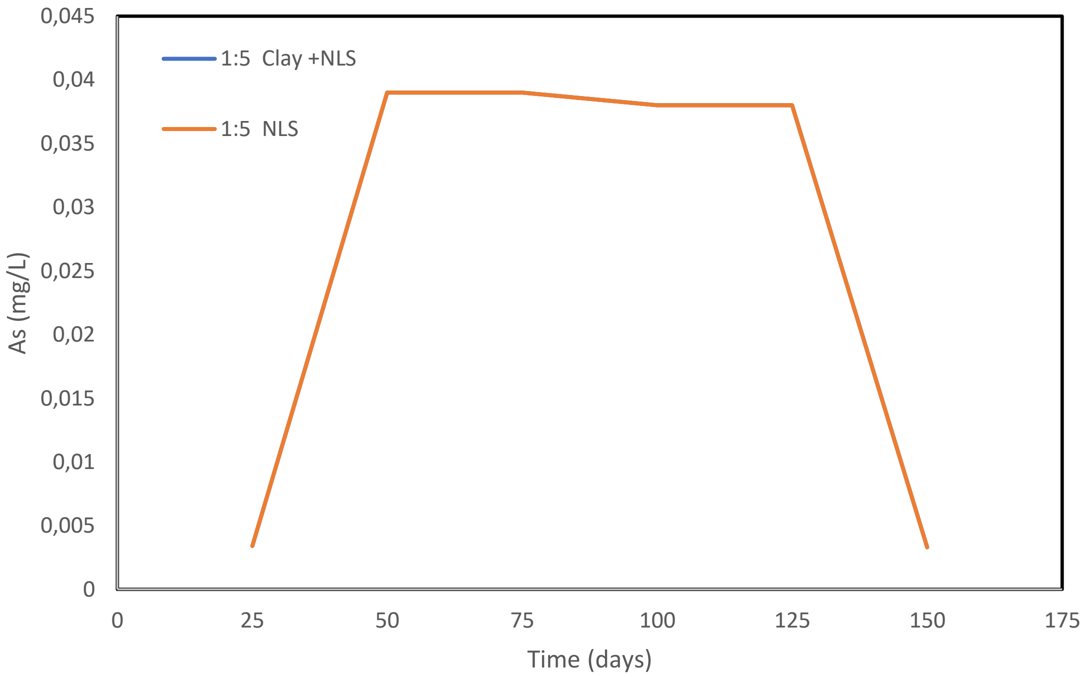


Figure 4.60. Effects of temporary cover material type on As content over time

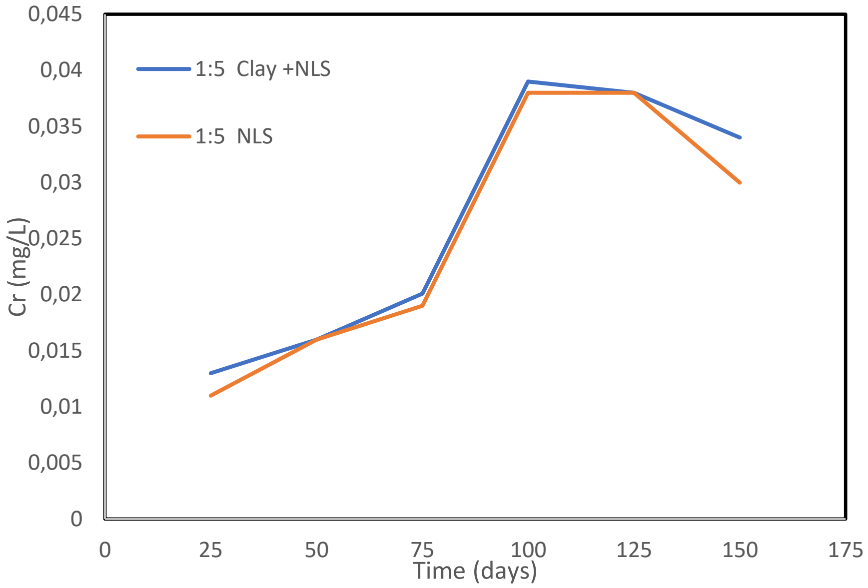


Figure 4.61. Effects of temporary cover material type on Cr content over time

The changes in Cu concentration due to using different materials for temporary cover are depicted in Figure 4-62. It is clear that for all curing operations, the Cu content of the model with NLS alone is lower than that of the model with a mixture of NLS and clay. For example, after 150 days, the Cu concentration in the model with NLS was approximately 41% lower than in the model with the mixture.

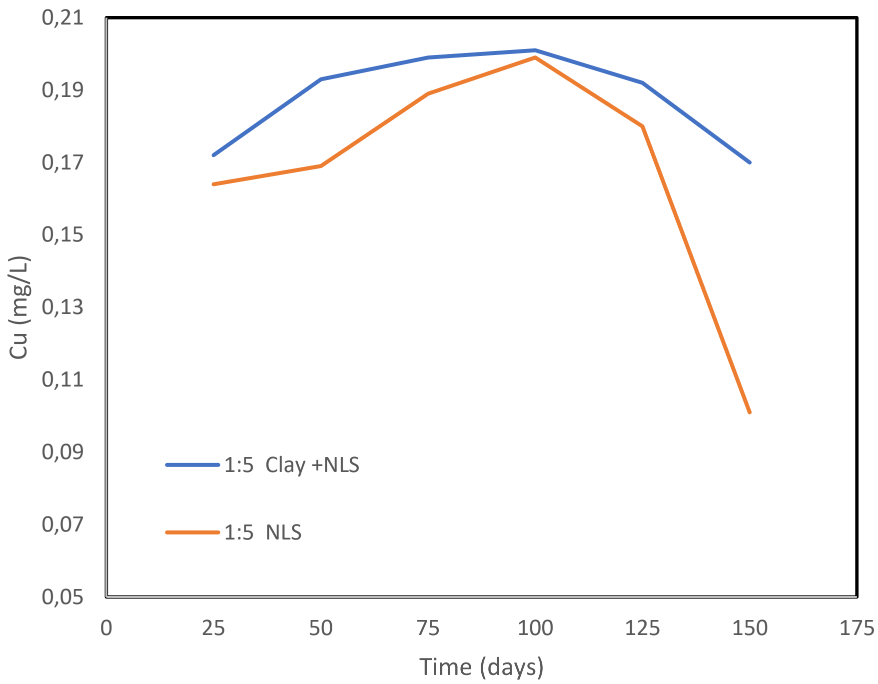


Figure 4.62. Effects of temporary cover material type on Cu content over time

Further investigation focused on the concentration of Ni resulting from using different materials for temporary cover. It was observed that the cover made of NLS alone performed better in terms of mitigating Ni concentration for the first 100 days of operation. For operation times longer than 100 days, the results of both models were very close to each other.

Finally, the results also verified that the model with NLS as a temporary cover performed better than the model with a mixture of clay and NLS in terms of controlling Zn concentration, as shown in Figure 4-63. The effectiveness of NLS became noticeable over longer operation times. For example, the Zn concentration of the model including clay and NLS was about 1.55 times higher than that of the model with NLS alone, demonstrating the efficiency and high capability of NLS to be used as a temporary cover in landfill systems.

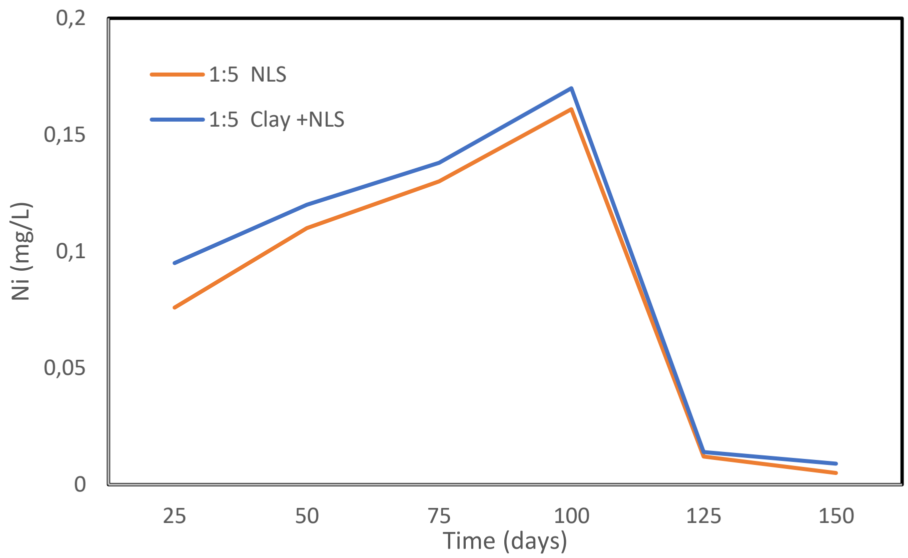


Figure 4.63. Effects of temporary cover material type on Ni content over time

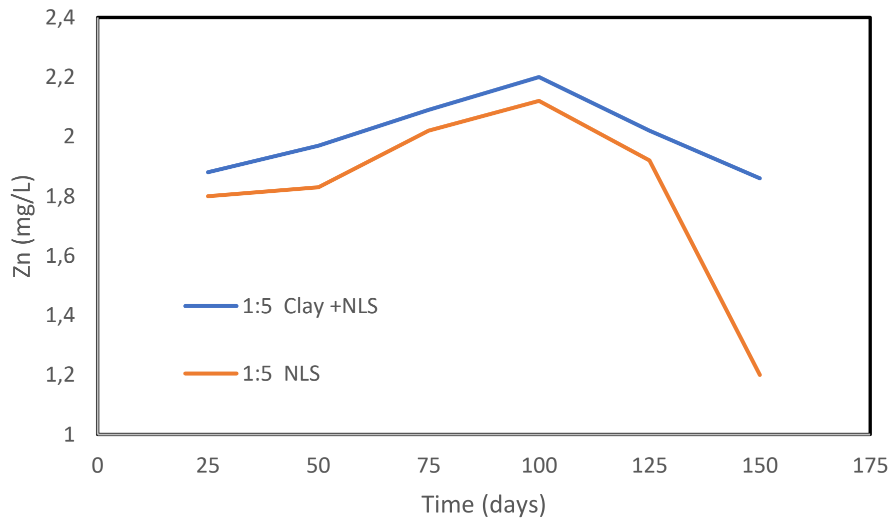


Figure 4.64. Effects of temporary cover material type on Zn content over time

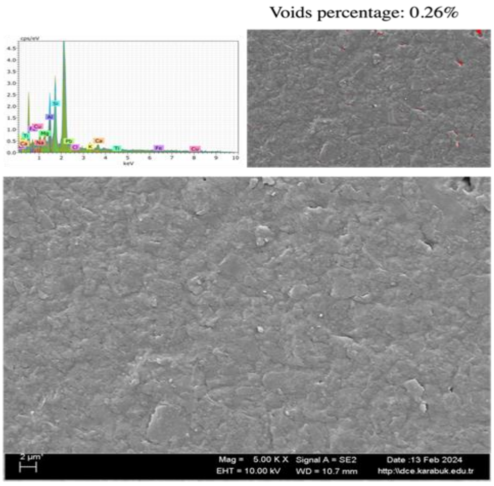
4.4. MICROSTRUCTURAL ANALYSIS

SEM outcomes delve deeply into the microstructural intricacies of CCLs, shedding light on the impacts of leachate exposure and NLS stabilization. Through SEM imaging, alterations in particle arrangement, void distribution, and matrix morphology become evident, providing tangible evidence of leachate's influence on liner integrity and how NLS treatments reshape their microstructure for improved performance.

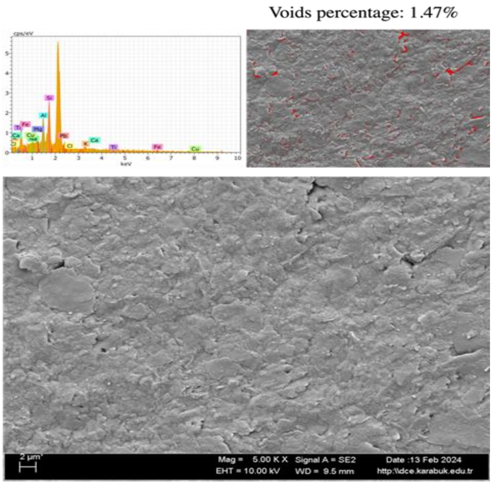
The SEM-EDX test results, depicted in Figs 4-65a-d, verified the mechanical and dynamic test findings, indicating the significant potential of NLS in mitigating the adverse effects of landfill leachate on CCL performance. Due to the influence of leachate on the clayey samples, the percentage of voids increased from 7.06% to 10.17%, indicating an unfavorable rise in the hydraulic conductivity of the samples. Therefore, the presence of leachate not only diminished the strength of CCLs but also augmented the liners' hydraulic conductivity, as evidenced by SEM results revealing a discontinuous matrix with weak particles. However, with the addition of NLS, the void percentage decreased significantly to 1.47% and 0.26% in the case of CCLs mixed with leachate and water, respectively. Hence, NLS acted as a filler, occupying the available voids and enhancing the hydraulic conductivity of the samples. Additionally, the alterations in the microstructure of the samples containing NLS can be attributed to the creation of electrostatic attraction among the clay particles, the development of polymer chains around them, the integration of aggregates, and the formation of denser microstructures, resulting in stronger bonding between clay particles[17].

The FTIR findings furnish valuable insights into the chemical composition and bonding characteristics of both CCLs and NLS-stabilized samples. By pinpointing functional groups and chemical bonds, FTIR spectra delve into the mechanisms driving performance enhancements post-NLS integration. Variations in peak intensities and frequencies elucidate shifts in chemical interactions, such as the formation of polymer chains and the reduction of free hydroxyl groups, significantly bolstering soil strength and reducing deformation.

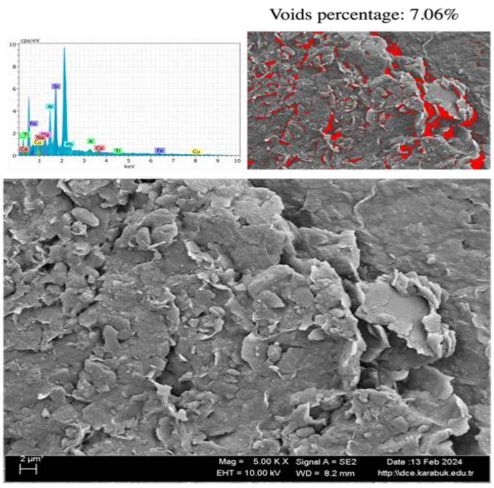
The results of the FTIR test, as shown in Figure 4-65e, demonstrated a significant decrease in the presence of free OH groups, corresponding to the peak at 3624 cm^{-1}, in the NLS-stabilized samples compared to the untreated soil. This reduction in free OH groups contributed to increased soil strength and decreased soil deformation. Moreover, as hydrogen bonding interactions strengthen, the -OH stretching vibration undergoes a downward frequency shift. The vibration bands associated with -OH at 3624, 3377, 1431, 993, and 903 cm-1 experienced a decrease in wave numbers upon the addition of NLS. This shift in peak behavior may be attributed to a decrease in interlayer water content within the soil samples. It suggests that NLS may establish direct bonds with adsorbed cations or coordinate directly with adsorbed moisture [2].



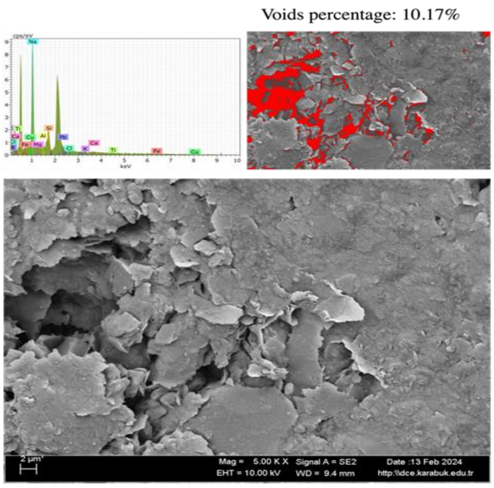
(a) C + W + NLS



(b) C + L + NLS



(c) C + W



(d) C + L

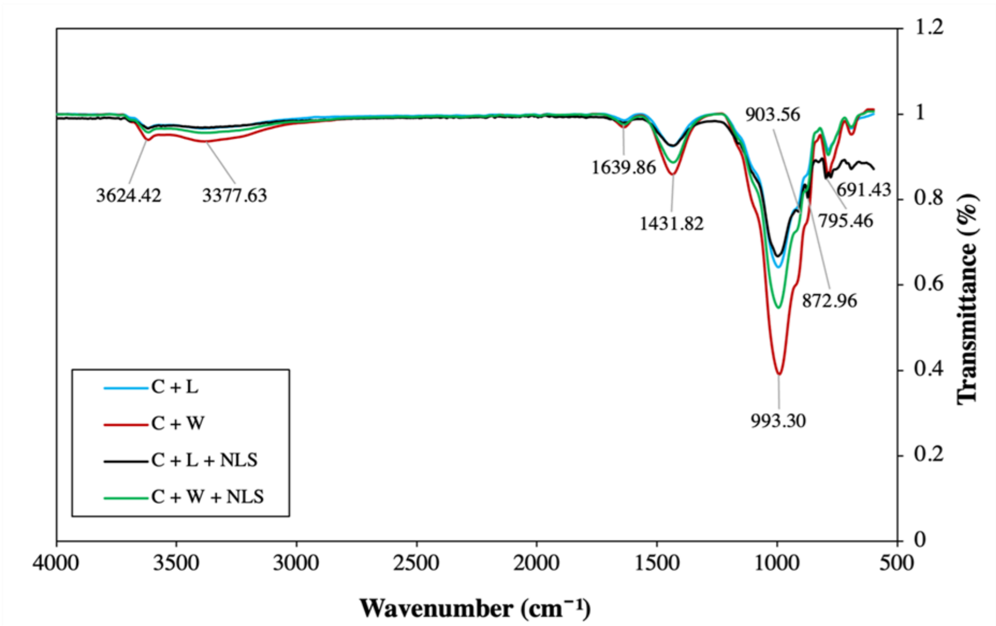


Figure 4.65. SEM-EDX, image processing, and FTIR results of various samples

PART 5

CONCLUSION

5.1. INTRODUCTION

This thesis investigated the innovative potential of sodium lignosulfonate (NLS) in enhancing compacted clay liners (CCLs) against the detrimental impacts of leachates within municipal solid waste (MSW) in landfill structures. The primary aim was to deepen comprehension regarding how NLS can effectively counteract the adverse effects of landfill leachate on CCLs, thereby bolstering the overall performance and lifespan of landfill structures. Through an extensive array of tests and analyses, this study endeavored to assess the efficacy of NLS in augmenting the environmental, mechanical, physical, and dynamic responses of CCLs across diverse conditions. Furthermore, the investigation extends to exploring the feasibility of employing NLS as a temporary cover layer, thereby broadening its utility in waste management practices. Additionally, this project delves into the potential for repurposing and recycling NLS—an industrial byproduct—for novel applications, thus contributing to sustainability initiatives in waste management and resource utilization.

5.2. MAIN FINDINGS

The findings of this study demonstrate that the incorporation of 1% NLS yields significant enhancements in both the micro and macrostructures of CCLs, as corroborated by mechanical, dynamic response, and microstructural analyses. Notably, NLS amplifies the efficacy of conventional CCLs by counteracting the adverse impacts of landfill leachate, resulting in heightened performance across various scenarios. These findings underscore the potential of NLS to stabilize CCLs and mitigate leachate-induced damage, thereby furnishing invaluable insights for the design and construction of future landfill structures. Furthermore, the study unveils promising outcomes regarding the utilization of NLS as a temporary cover layer, indicative of its potential to bolster the properties of both CCLs and cover layers within landfill systems. To conclude, the main findings of this research can be summarized as follows:

1- It was found that leachate penetration and wet conditions could adversely affect the mechanical strength and dynamic response of CCLs, as evidenced by the reduction in UCS and Vs values of the samples resulting from mixing with leachate under dry conditions and/or testing under wet conditions. There was a gradual reduction in both values of the samples due to mixing with leachate and testing in dry condition (DL), followed by mixing with water and submerging in water (WW), mixing with water and submerging in leachate (WL), and finally mixing with leachate and submerging in water (LW).

2- The mechanical strength of the CCL showed significant improvement with the addition of NLS, with the best results observed for the 1% NLS concentration across all curing times. The strength improvement factor for the samples stabilized with the optimum percentage of NLS was measured as 1.83 and 2.12 after 7 and 90 days of curing, respectively.

3- The strength of the sample mixed with leachate, treated with 1% NLS and cured for 90 days was 110% higher than the strength of the untreated sample tested under the same conditions, revealing the good performance of NLS even in the presence of leachate. Therefore, it can be noted that NLS shows high potential in mitigating the adverse effects of leachate on the performance of CCLs.

4- Although applying WCs by both water and leachate resulted in mitigating the strength of CCLs, the NLS-stabilized CCLs exhibited acceptable ranges of strength, with the improvement rate due to NLS addition being at least 50%.

5- The dynamic response of the samples improved significantly due to both NLS stabilization and curing time. In the worst-case scenario (i.e., WCs submerged in leachate), the addition of only 1% NLS resulted in a 20%, 30.5%, and 40%

improvement in the Vs of CCLs with curing time compared to that of the untreated sample.

6- Among various variables, the operation modes and leachate recirculation were found to be very effective in changing the results of heavy metal concentrations in the landfill system, including a temporary cover layer made of a mixture of clay and 1% NLS

7- A higher temporary cover thickness led to a significant reduction in the amounts of Cd, Cu, and Zn.

8- It was confirmed that curing time did not show substantial effects on changing the results of column model tests. Therefore, in the case of controlling heavy metals concentration, 7 days of curing can be considered adequate and optimum.

9- It was found that the model with NLS alone as a temporary cover could perform better in terms of controlling heavy metal concentrations such as Zn, Ni, Cu, and Cd.

5.3. RECOMMENDATIONS FOR FUTURE STUDIES

Drawing from the findings of this study, future research endeavors should prioritize delving deeper into elucidating the mechanisms underlying the beneficial effects of NLS on CCLs and cover layers within landfill systems. This could entail conducting more intricate analyses of the microstructural alterations induced by NLS, alongside investigations into its long-term performance and durability. Furthermore, additional studies could explore potential synergies between NLS and other additives or engineering methodologies to further augment the efficacy of CCL stabilization. Moreover, research endeavors should persist in exploring innovative avenues for recycling and repurposing NLS, thereby fostering sustainable waste management practices. Additionally, future studies could delve into the formulation of guidelines or standards for the utilization of NLS in landfill engineering, facilitating its widespread adoption within the field. Lastly, continual monitoring and evaluation of NLS-treated CCLs in real-world landfill settings would furnish invaluable insights into their long-term performance and efficacy in mitigating environmental risks.

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RESUME

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