T.C.

İSTANBUL KÜLTÜR UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

A METHOD TO DEVELOP LANDFILL LINER MATERIAL USING DESIGN OF EXPERIMENTS METHODOLOGY

Master of Science Thesis

Maheen SHAHZAD

2000001286

Department: Industrial Engineering

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Supervisor: Assist. Prof. Okay IŞIK

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JUNE 2023

ACKNOWLEDGEMENT

I would like to express my gratitude to all those who gave me the possibility to complete this study. I want to thank my advisor, **Assist. Prof. Okay Işık** for providing his expertise, comprehensive guidance and constant supervision and encouragement throughout this study and especially for his confidence in me. Without his support, this research would not have been possible. It is a great honor to work under his supervision.

20-06-2023 Maheen Shahzad

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LIST OF SYMBOLS

F1	RHA
F2	Kapok Fiber
F3	Coconut Fiber
F4	MIW
F5	Fly ash
F6	Limestone
F7	Bentonite
F8	Dry Density
F9	Cement Mixtures
R1	Hydraulic Conductivity
R2	Compressive Strength
R3	Compaction Characteristics
R4	CBR
R5	Compressibility
R6	Shear Strength
x	Factor
y	Response variable

β	Coefficients of linear model
ε	Error term

LIST OF ABBREVIATIONS

AEP	Advanced Endpoint Protection
ANOVA	Analysis of Variance
BBD	Box- Behnken Design
CBR	California Bearing Ratio
CCD	Central Composite Design
CCL	Compacted Clay Liner
DoE	Design of Experiments
FWP	Flexible Wall Permeameter
GCL	Geosynthetic Clay Liner
LAS	Locally Available clayey Soil
MIDUW	Medium Dry Density Unit Weight
MSW	Municipal Soil Waste
OFAT	One Factor at a Time
OMC	Optimum Moisture Content
RHA	Rice Husk Ash
UCS	Unconfined compressive strength
US EPA	United States Environmental Protection Agency

Üniversite	**: İstanbul Kültür Üniversitesi**
Enstitü	**: Lisansüstü Eğitim Enstitüsü**
Anabilim Dalı	**: Endüstri Mühendisliği**
Programı	**: Mühendislik Yönetimi**
Tez Danışmanı	**: Assist. Prof. Okay IŞIK**
Tez Türü ve Tarihi	**: Yüksek Lisans – Haziran 2023**

ÖZET

Deney Tasarımı Metodolojisi Kullanarak Çöp Depolama Alanı Astarı Malzemesi Geliştirme Yöntemi.

MAHEEN SHAHZAD

Bu tez, Deney Tasarımı (DoE) metodolojisini kullanarak çöp depolama alanı astar malzemelerinin geliştirilmesi için bir yöntem sunmaktadır. Çalışma, özellikle depolama alanı astar malzemeleri için kullanılabilecek DoE yöntemlerini belirlemeye odaklanmaktadır. DoE yöntemlerinin astar özelliklerini optimize etmedeki etkinliği değerlendirilmekte ve bu bağlamda DoE kullanmanın potansiyel faydaları değerlendirilmektedir. DoE'nin inşaat malzemesi geliştirmede kullanımını tanıtan sınırlı araştırma olmasına rağmen, bildiğimiz kadarıyla, DoE yöntemlerinin çöp depolama alanı astarlarının geliştirilmesi için uygulanmasını tartışan bir çalışma henüz yayınlanmamıştır. Bu çalışma öncelikle, DoE yöntemlerinin mukavemet ve hidrolik iletkenlik açısından astar performansını iyileştirme potansiyeline sahip olup olmadığını belirlemek için önceki çalışmaları analiz eder. Tez, astar özelliklerini etkileyen faktörlerin belirlenmesi, yanıt değişkenlerinin tanımlanması ve deney tasarımını oluşturarak, DoE metodolojisinin ilk üç aşamasını gerçekleştirmektedir. Sonuç olarak, deney tasarımında merkezi bileşik tasarım (CCD) önerilmektedir. Genel olarak, çalışma, gelecekteki araştırmalar için sistematik bir yaklaşım sunarak, çöp depolama alanı astar malzemelerinin geliştirilmesinde DoE metodolojisinin kullanılmasını önermektedir. Bu araştırma, inşaat malzemelerinin optimize edilmesinde DoE yöntemlerinin anlaşılmasına katkıda bulunmakta ve çöp depolama astar malzeme performansının iyileştirilmesi için potansiyel sunmaktadır.

Anahtar Kelimeler: ….. Astar Malzemesi, Deney Metodolojisi Tasarımı, CCD tasarımı, Optimizasyon.

University	**: İstanbul Kültür University**
Instittute	**: Institute of Graduate Studies**
Department	**: Industrial Engineering**
Program	**: Engineering Management**
Supervisor	**: Assist. Prof.** Okay IŞIK
Degree Awarded and Date	**: MS – June 2023**

ABSTRACT

A Method to Develop Landfill Liner Material Using Design of Experiments Methodology

MAHEEN SHAHZAD

This thesis presents a method for developing landfill liner materials using the Design of Experiments (DoE) methodology. The study focuses on identifying key DoE methods used in construction material development, specifically for landfill liners. The study evaluates the effectiveness of DoE methods in optimizing liner properties and assesses the potential benefits of using DoE in this context. Although limited research exists introducing the use of DoE in construction material development, to the best of our knowledge, a study discussing the application of DoE methods for developing landfill liners has not been published yet. This study analyzes previous studies to determine if DoE methods have the potential to improve liner performance in terms of strength and hydraulic conductivity. It synthesizes findings to evaluate broader implications, such as cost savings, increased efficiency, and improved environmental outcomes. The thesis applies the first four stages of the DoE methodology by identifying factors affecting liner properties, defining response variables, and designing the experiments. Results include a design matrix based on a central composite design (CCD) matrix. Overall, the study recommends using DoE methodology for developing landfill liner materials, providing a systematic approach for future research. This research contributes to understanding DoE methods in optimizing construction materials and offers potential for improved landfill system performance.

Keywords: ….. Liner Material, Design of Experiment Methodology, CCD design, Optimization.

1. INTRODUCTION

1.1. Background

One of the most frightening issues confronting the world is the aggravating waste problem, which threatens public health, pollutes the environment and is a reason why some poor countries are prone to toxicity. Regular trash collection is inaccessible to over 50% of the global population. Annually, 1.3 billion tons of waste is produced worldwide. The situation is anticipated to worsen as the figure is projected to reach 4 billion tons by 2100. (Simmons, 2016)

The annual solid waste generated in Pakistan exceeds 48 million tons and has been growing at a rate of over 2 percent per year. Most of the waste generated from metropolitan cities is estimated to be 77,000 tons per day. Karachi, Pakistan's largest city uses three landfills, while Lahore, the capital of Punjab and second largest city of Pakistan, has three waste disposal sites which are no more than dumps. However, landfills are to be constructed in other cities as well. Solid waste is simply dumped in many parts of cities. In developed countries, solid waste is recycled, incinerated or dumped in landfills. In Pakistan, waste is generally recycled on small scale.

In the municipal solid waste stream, MSW is classified into three distinct categories according to their degradability: degradable, partially degradable, and non-degradable. Wastes decomposed easily by microbes are classified as degradable for example food wastes, fertilizer, garden waste and paper. Partially degradable materials include soft wood, tissues and sanitary residues. Non-degradable wastes are those that cannot go down or degrade for many years. Materials such as plastics, metals, rubber, glass and ceramics are classified as non-degradable (Burnley, 2007)

What should we do about the waste we generate? Waste management generally is a process of treatment, prevention and reusing the waste products in an area. Disposition of heaps of waste lying around in our surroundings is possible by recycling, incineration or landfills. Countries with economical difficulties are developing their industries but have failed to develop appropriate waste disposal systems at an equal pace. This leads to an imbalance between urban expansion and waste management systems. Despite various alternatives, landfilling continues to be the prevailing method for solid waste disposal globally.

Leachate generation is a result of mechanical process and biological decomposition process (aerobic or anaerobic) which change the engineering and physical properties of landfill material hence changing its form. Landfill leachate contains high organic and inorganic pollutant concentration (Stefanakis et al. 2014). The presence of this harmful substance poses a significant risk to the soil and groundwater in the vicinity of the landfill. The chemical makeup of landfill leachate is influenced by factors such as waste composition, climate conditions, and the age and rate of degradation of the solid waste. (Bulc, 2006)

In contemporary landfills, a leachate barrier, commonly known as a landfill liner, is employed to mitigate the environmental consequences associated with landfill leachate. The landfill liner serves as an impermeable barrier designed to prevent the leachate from escaping the landfill system. The main objective of the liner system is to isolate the contents of the landfill from the surrounding environment, thereby safeguarding the soil and groundwater against pollution originating from the landfill.

Landfill liners are categorized into three types: single (also known as simple), composite, or double liners. Single liners are typically made of materials like clay, geosynthetic clay liners, or specialized plastic sheeting known as geomembranes. They are commonly used in landfills to dispose of construction waste such as asphalt, glass, wood, concrete, and bricks. Composite liners combine a geomembrane with a clay liner to effectively restrict leachate migration from the landfill to the subsoil. These composite liners are necessary in municipal solid waste (MSW) landfills. Double liners consist of two single liners, two composite liners, or a combination of a single and a composite liner. In a double-liner system, the leachate is collected above the upper liner, while the lower liner acts as a drainage system for the primary (upper) liner. The lower liner also serves as a leak detection mechanism. Double-liner systems are employed in certain municipal solid waste landfills and all hazardous waste landfills.

Geosynthetic clay liner (GCL) has replaced compacted clay liner (CCL) over the decades. However, CCL are economical as compared to GCL as clay is readily available throughout Pakistan. Compacted clays, for their low hydraulic conductivity and enhanced attenuation capacity are widely used as impermeable liners for landfills.

The migration of leachate is influenced by hydraulic conductivity, a crucial factor in the process. Analysis of past experimental studies reveals that permeability rises with higher concentrations of highly plastic clays. The hydraulic conductivity of clay exhibits a notable increase when permeated with high concentration liquids compared to water permeation. (Anderson et al., 1985)

Compacted clay liners when mixed with suitable proportions of rice husk ash enhance the containment containing characteristics of landfill liners. Rice husk is a by-product from the production of rice. It is richly found in Pakistan being an agricultural country. Burning rice husk as a fuel to generate energy is a significant practice in many rice mills. However, this process generates ash as a waste product, leading to pollution and disposal challenges. Approximately 75% of rice husk ash (RHA) is comprised of organic volatile matter, while the remaining 25% is transformed into ash during the combustion process. (Eberemu et al., 2012)

Despite the waste amount of literature in developing landfill materials, to the best of our knowledge, their main focus is on the evaluation of individual factors or parameters. However, a significant limitation of these studies is their reliance on the traditional "one factor at a time" approach, which fails to capture the complex interactions and synergistic effects that may exist among multiple factors.

Design of Experiments Design of experiment (DoE) is a powerful statistical methodology for identifying important variables and determining their optimal or suitable settings to achieve desired outcomes. DoE can help identify the most important variables. DoE has its origins in agriculture and industrial engineering. One of the key principles of DoE is to control sources of variability in the experimental setup so that the effect of the factors being studied can be accurately estimated. The use of DoE has been shown to lead to improved accuracy, efficiency, and cost-effectiveness in research. Applying DoE to the development of an efficient liner material can lead to significant improvements in performance and cost-effectiveness. By systematically varying the factors that affect liner performance and measuring the resulting effects.

This knowledge can then be used to design and develop a liner material that meets or exceeds the desired performance criteria, while minimizing material and process costs.

1.2. Aims and Objectives

According to the background described previously the main objective of this research is to investigate economical and effective barrier material for municipal solid waste landfills using DoE Methodology and recommend a method for developing suitable liner material.

The specific objectives of this research are to,

- Identify the key DoE methods and techniques that have been applied in the development of construction materials in general, and landfill liner materials specifically. This goal would involve reviewing the literature to identify the specific DoE approaches that have been used in previous studies, such as factorial design, response surface methodology, or Taguchi methods.

- Evaluate the effectiveness of DoE methods in optimizing the properties of landfill liner materials. This goal would involve analyzing the results of previous studies to determine whether the use of DoE methods led to improved performance of landfill liner materials, such as increased strength, durability, or permeability resistance.

- Assess the potential benefits and limitations of using DoE methods for landfill liner material development. This goal would involve synthesizing the findings from multiple studies to evaluate the broader implications of using DoE methods in this context, such as the potential for cost savings, increased efficiency, or improved environmental outcomes, as well as any potential challenges or limitations that have been identified.

- Apply the first four stages of the DoE methodology in the development of a liner material for landfills:
    - Identify the factors that can affect the properties of the liner material: The factors that can affect the properties of the liner material can include the type of material used, the particle size distribution of the material, the compaction pressure, the compaction time, and the moisture content.
    - Define the response variables: The response variables can include the tensile strength, the permeability, the thickness, and the compressibility of the liner material.
    - Design the experiment: Design a set of experiments based on the identified factors and response variables.

1.3. Scope and Structure of thesis

This thesis is organized into 5 chapters.

- Chapter 1 ‘Introduction’ It introduces the background of study including global waste generation, growing solid waste management concern in Pakistan, use of landfills with different landfill liners and introduction to DoE and research objectives of our study.
- Chapter 2 ‘Literature Review’ provides us with detailed literature review. Furthermore, a summary of previously completed similar studies are reviewed and a comparison between them are provided.
- Chapter 3 ‘Methodology’ presents methodology and all the information about each DoE method.
- Chapter 4 ‘Results and discussions’ presents results, and discussion of which methodology can be chosen to develop a liner material depending on the conditions.
- Chapter 5 ‘Conclusion’ is a summary of the research is presented, along with the final findings. Recommendations concerning the implementation and the numerical results are provided, and future recommendations for research are given.

Following this section, Section 2 gives a detailed literature survey

2. LITERATURE REVIEW

US EPA (2004) set the criteria for the natural liner material having low hydraulic conductivity as follows:

1. The soil material should contain 20% fines (particles having size smaller than 0.075 mm).
2. The plasticity index should be more than 10 %.
3. Gravel size particles should not be more than 10%.
4. The soil should be free of particles having size more than 25 mm.

Eberemu et al. (2012) worked on soil-RHA mixtures to decrease the permeability of soil and increase compressive strength, so that it can be used as liner material. Lab tests were performed on clay mixed with up to 16 percentage of RHA. General satisfactory ranges below which the material was appropriate (low hydraulic conductivity <10^{-9} m/s, minimum volumetric shrinkage strain <4% and high compressive strength >200 kN/m^2) were achieved. Outcomes suggested that the suitable percentage mixture was up to 8% RHA treatment, which will decrease the hydraulic conductivity of the liner. He used expansive soils mixed with rice husk ash. Experimental studies were done on the characteristics of low and high plastic soils that were mixed with 0 to 20% RHA with dry soil. Different tests were performed to determine its engineering properties and observe the behaviour. Decreases in the amount of plasticity and shrinkage ratio have shown a decrease in RHA-induced soils that are valuable for difficulties associated with the placement of footpaths on that soil. It has also been noted that the increase in pozzolanic products inside the pore spaces of the soil from the physicochemical changes converts RHA-controlled soils into a mass that has reduced sedation and settlement value. A significant increase in the collision angle and an increment in RHA up to 16% were also detected in direct shear experimenting. It has been concluded that RHA behaviour is a profitable and ecological way to address the difficult soil in developing countries such as Pakistan.

Aziz et al. (2015) used expansive soils mixed with rice husk ash. Experimental studies were done on the characteristics of low and high plastic soils that were mixed with 0 to 20% RHA with dry soil. Different tests were performed to determine its engineering properties and observe the behaviour. Decreases in the amount of plasticity and shrinkage ratio have shown a decrease in

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Bashar et al. (2017) worked on the strength of landfill liner material which was made up of hybrid rice husk with kapok fiber and hybrid rice husk with coconut fiber. A sequence of general experiments to find natural and geotechnical properties such for example the Atterberg limit test (liquid limit, plastic limit), durability tests, strength tests (collapsed head method), leachate features and heavy metal tests are performed on a wide range of composite materials (KC: RH in a ratio of 1: 1and KC: CF in a ratio of 1: 2). The compressive strength of the specimens increased with increasing percentages of kapok fiber and coconut fiber. The maximum compressive strength was observed for the specimen containing 15% kapok fiber and 5% coconut fiber which showed an increase of 68.5% compared to the specimen without fiber. Test outcomes established that the hydraulic transmission of the KC: RH: KF mixture at a ratio of 1: 1: 1 at 7.29 x 10^{-11} m / s was less than 10^{-9} m / s, satisfying the need for landfill liner building materials.

Fattah et al. (2013) worked on clay soils using ash rice in various proportions. The results of experimental studies conducted on three various soils were upgraded by various percentages of ash rice. Samples were collected at various locations in Iraq. Various tests were performed to determine its engineering properties and to evaluate its performance. Tests were performed on clay soil testers varied with different proportions of rice materials such as, plastic limit, liquid limit, shrinkage limit, certain gravitational force, compression, invalid compression tests and composite tests. It was found that the water limit of the three soil samples was reduced by about 11 to 18% with the addition of 9% RHA, while the plastic index reduced by 32 to 80%. Rice husk treatment displayed an overall reduction in the maximum weight of the dry unit and a rise in rice husk percentage to lower values in 9k content. High humidity content is usually increased with an increase in RHA content. There was an increase in the uncompressed compression strength with a rise in the proportions of the rice husks to its size in RHA between (6-8) %. The results showed that the RHA formed pozzolanic compounds with the clay particles, which improved the microstructure of the soil and increased its strength.

Sarkar et al. (2012) worked on the analysis of rice ash in a geotechnical constructor of compacted soils. Various tests were performed to determine the effect. They described the effects of husk ash (RHA) rice on geotechnical structures of stable soil especially strength, performance, density and compression properties. Various tests were performed such as density, Atterberg parameters, free inflammation index, uncompressed compression strength, direct cutting and testing of a combination of different proportions of RHA percentage and real soil samples performed. These experiment outcomes indicate that the soil can be compacted leading to a decrease in dry matter and an increment in moisture content and a decrease in free inflammation and compression due to the addition of RHA and soil. The results showed that the UCS of the specimens increased with increasing curing time, indicating that the strength gain was due to the pozzolanic reaction between the RHA and the soil particles. Alternatively excluded compressive strength (UCS) and ground shear strength can be adjusted with the inclusion of 10% RHA percentage.

Shahzada et al. (2017) worked to consolidate central soil in Pakistan using Marble Industrial waste (MIW) and bagasse ash (BA). Expansive soil is commonly found in arid areas due to the deficiency of moisture in soils and rocks, which is associated with three factors: geology, soil engineering characteristics, and local environmental conditions. The presence of expansive soils is intensified by severe weathering conditions and an arid climate. The volume of expansive soils changes greatly when the moisture content is altered. Various methods are available to stabilize expansive soils, including the addition of rice husk ash, but they have certain limitations. The plasticity index decreased as the content of MIW and BA increased, indicating a decrease in the soil's plasticity. In addition, the maximum dry density and optimum moisture content of the treated soil specimens increased with increasing MIW and BA content. The UCS of the soil specimens also increased with the content of MIW and BA. The maximum UCS was observed in the specimen treated with 15% MIW and 15% BA, which showed a 71% increase compared to the untreated soil specimen. The properties of clayey materials are immediately changed when treated with rice husk ash, resulting in an overall improvement in the mechanical properties of expansive soils.

Gurung et al. (2016) worked on soft clay soil using fly ash and limestone dust. They found that most of the ingredients used for this purpose have been shown to be very active in the development of broad-based engineering structures. He used different laboratory tests like Atterberg limits. Moisture content. Industrial wastes such as brick dust, ceramic dust, fly ash etc. are added to decrease the humidity holding bulk, plasticity to increase stability of soil. The fly ash is a waste of the product from tropical energy plants. It can be hazardous for the environment and for landfills. Therefore, it is better to utilize such types of waste materials as additives for soil stabilization to protect the environment. Here in the Figure 2-1 and Figure 2-2, we can see the relationship between liquid limit and Plasticity index. They are directly proportional to each other. As well the effect of swelling on the no of cycles. They used Atterberg limit tests for these results.

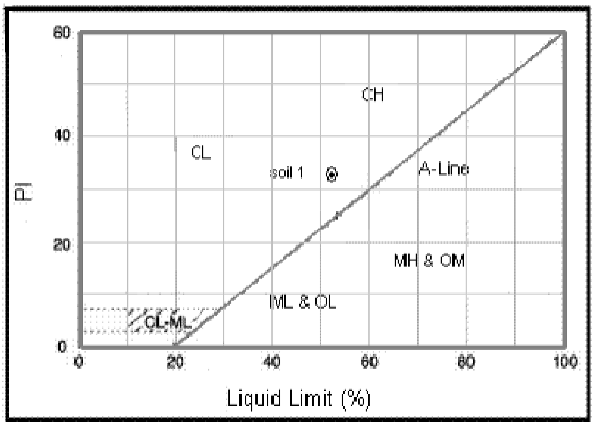

Figure 2-1: Liquid limit vs Plasticity index for soil 1 showing its characteristics according to plasticity chart. (Gurung, 2016)

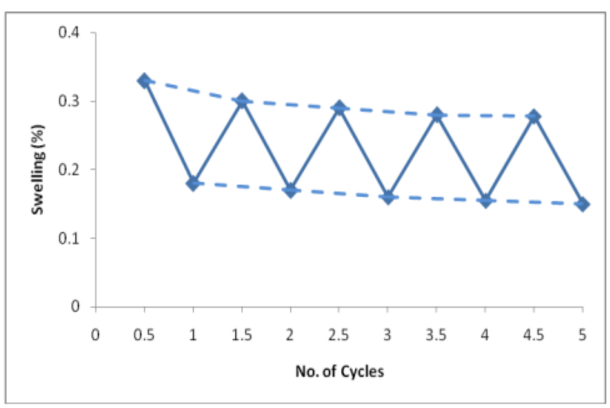

Figure 2-2: Influence of number of cycles on swelling of 15% fly ash and RHA blend under surcharge of 5KPa (Gurung, 2016)

Saadeldin et al. (2017) worked on a research paper which is basically on the hydraulic conductivity of the clay liners. Hydraulic conductivity of the clay of Central and Southern Saskatchewan was investigated and it was found to be 10^{-6} to 10^{-9} cm/s. According to the regulations, field hydraulic conductivity for a soil liner should be ten times more than the hydraulic conductivity found in laboratory from testing of the same soil sample. Flexible wall permeameter (FWP) and Air-entry permeameter (AEP) are used to find the hydraulic conductivity and their results are compared. The results showed that the hydraulic conductivity decreased with increasing saturation time, indicating that the clay till liner became more effective at blocking water flow as it became more saturated. The Figure 2-3 shows the comparison of the consequences of the hydraulic conductivity from the following permeameters and the AEP results were found to be reliable and a comparatively speedy to find the field hydraulic conductivities but it has some restrictions linked with the fixing, period of the experiment and effects of temperature changes with the experiment time

Test ID.	Test type	Dry density (kN/m³)	Result (cm/s)
Test pad	AEP	17.6–18 (avg. 17.8)	1.43×10^{-8}
Remoulded S1	FWP	17.5	6.47×10^{-9}
Remoulded S2			6.13×10^{-9}
Remoulded S3		18	2.06×10^{-9}
Completed liner	AEP	18.2–18.4 (avg. 18.3)	1.09×10^{-9}

Figure 2-3: Hydraulic Conductivity Test Comparison (Saadeldin & Froc, 2017)

Few weeks or maybe longer time is required to execute FWP lab test, but AEP test method is more authentic as it processes the actual accomplished outcomes in the field, and it also required a reduced amount of time than the FWP test.

Sometimes, field calculations of the soil hydraulic conductivity is required to estimate the excellence of the soil liner system. This contrast study gave a useful and quick method to determine the insitu hydraulic conductivity at required time. Through the pre-design, plan and manufacture phases forms oil liners, they can provide useful information of the geotechnical engineers.

Anusree G et al. (2016) worked on silty clay treated with lime and Rice Husk Ash. Various experiments were performed to determine its engineering properties. Various tests were executed to determine its dynamic properties and the difference between the index properties and engineering properties of silty clay when we use moisture of lime and Rice Husk Ash in it as a stabilizer. Many laboratory experiments have been done on clay soil and clay compounds with RHA. Lime was used as the main stabilizer, and RHA used in the installation of 5, 10, 15 and 20% during tests. Specifically, the addition of RHA resulted in an increase in maximum dry density and a decrease in optimum moisture content. The unconfined compressive strength of the silty clay also increased with the addition of RHA, indicating an improvement in the strength properties of the soil. Test results indicate that RHA can be used as an economic stabilizer and Liner material. So, RHA considerably improves soil engineering properties and RHA is also economical so used as liner material.

(Rahman, 1987) worked on clayey soils with RHA and cement mixtures. This research showed the RHA and cement mixtures on engineering properties of clayey soils. Different experiments were performed to determine its engineering properties. Various tests were done for checking the consequence on maximum dry density, UCS and optimum moisture content on soil with suitable percentage of RHA. The addition of RHA and cement resulted in an increase in maximum dry density and a decrease in optimum moisture content, the unconfined compressive strength of the soil also increased with the addition of RHA and cement indicating an improvement in the compaction characteristics and strength properties of the soil. The mixtures were examined after time dated of 7 days and 28 days to monitor the changes in the industrial performance of soil.

Phanikumar et al. (2017) worked on the clay liners. Expansive clays such as montmorilonite and fly ash used for stabilization and used as a liner material. Different tests were performed to determine its engineering properties. When expansive clays were mixed with fly ash and the industrial waste, hydraulic conductivity decreased. Expansive clays also have the ability to swell when it comes into contact with water. The addition of fly ash resulted in a decrease in the swell potential of the clay, indicating that fly ash can be an effective stabilizing agent for controlling the heave potential of expansive clay liners. The objective of this work was to study the heave behavior of the expansive clays which were stabilized with the fly ash by changing different permeating fluids and by changing the percentage of the fly ash in the expansive clays.

Lake et al. (2005) worked on the field case of the 14 years performance. They used compacted Clay Liner (CCL) as a portion of Composite Liner System for leachate lagoon. The clay liner was used in the lower portion of the composite liner system, but the geomembrane showed some defects as it allowed the transfer of leachate between geomembrane and compacted clay liner. Different tests were performed to determine its engineering properties. Investigations showed that the chloride migrated 1.7m into the clay liner, sodium 1.2m and potassium 0.7m approximately. Diffusion and sorption data showed that the geomembrane failed between 0 to 6 years after installation of the liner. The results showed that the biological sludge matter at the base of the lagoon was accountable for the failure of the geomembrane. This study defines the significance of the compacted clay liner with the geomembrane. As the geomembrane failed, compacted clay liner played a vital role in the resistance of the transfer of the leachate and from it we could estimate the failure time of the geomembrane due to the contaminants such as, chloride and sodium.

Rashid et al. (2017) used the locally available soil of various areas of Sri Lanka and its admixtures with 5% and 10% bentonite were used to determine its properties as a natural clay liner underneath solid waste landfill. Different tests were performed on the soil sample including soil plasticity and swell index and permeability tests to know the hydraulic conductivity of the soil sample which defines the behavior of the soil when it is used under landfill to prevent the percolation of the leachate to the subsurface environment. And the value of hydraulic conductivity is also affected by the compaction of the soil and its admixtures used as the liner. As seen in this Figure 2-4, Consolidation pressure has a great effect on the void ratio of the soil sample, as the consolidation pressure increases, the void ratio decreases. As we change the permeant liquid and add some percentage of admixtures, it has a great effect on the void ratio and maximum dry density of the soil as with decreased consolidation pressure, maximum dry density obtained with minimum void ratio due to the minimum swelling effect of the bentonite.

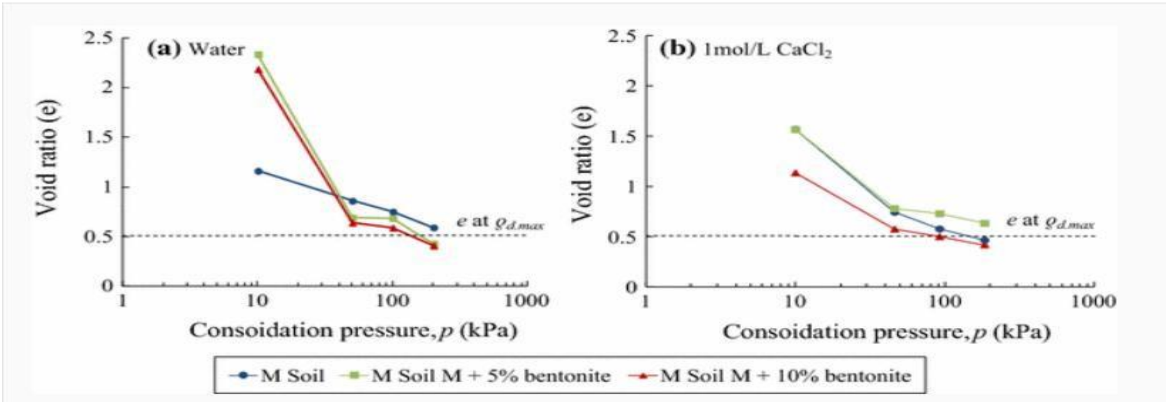

Figure 2-4: Effect of consolidation pressure (p) on void ratio (e) of soil specimen (Rashid, 2017)

He found out that if we increase the percentage of bentonite, liquid limit and swell index and will decrease. As well as we increase the percentage of bentonite and consolidation process, hydraulic conductivity will also decrease. Hydraulic conductivity of soil is affected by the nature of permeant. Finally, With the help of different permeants, consolidation pressure and bentonite percentage, they characterized locally available swelling clay and its bentonite admixtures, for the usage as a landfill liner in MSW landfills in Sri Lanka.

Alhassan et al. (2008) used mixture of soil with 2 to 12% RHA. Different tests were conducted to show the performance of soil and RHA in terms of their engineering properties like unconfined compressive strength tests, CBR tests and compaction tests and other tests. The results showed a reduction in maximum dry density and rise in moisture content with increasing RHA content. The Atterberg limits of the soil samples decreased with increasing RHA content, indicating that the soil became less plastic and more workable. The compaction tests showed that the maximum dry density of the soil samples increased with increasing RHA content, while the optimum moisture content decreased. Their results showed UCS and development in the CBR with increments in the RHA proportion. 6 to 8% RHA was the highest UCS values that were noted, pointing a slight probable of using 6 to 8% RHA for strength development of A-7-6 lateritic soil.

Robert et al. (2009) used fly ash and rice husk ash (RHA) with soil. They used this mixture to advance expansive soil as a structure material, from waste materials and they are economical as well. Expansive soil with different proportions of RHA was used. Different soil characteristics were detected by various soil tests. The strength of the RHA-flash compound has been studied as a layer of decreased inflammation between base suspension and sub-construction. In order to study the value of the research, a cost-effectiveness model was developed that formed the basis for the underlying highway project without strengthening integration. Various tests were performed. The results were similar to the behaviors of uncompressed compression strengths showing that the failure of pressure and pressure enlarged by 106% and 50% correspondingly while from 0 to 25% of fly ash increased. When RHA proportion increased from 0 to 12%, Uncompressed RHA was augmented by 97% while CBR was improved by 47%. Consequently, 12% RHA content and 25% fly ash content is suggested to consolidate the expanded subsoil below. A 15% fly ash content can be selected in combination with RHA by forming a layer of inflammatory reduction due to its optimal performance in laboratory tests. Here in the Figure 2-5, you can see the relationship between RHA and UCS and CBR as well in the form of graph.

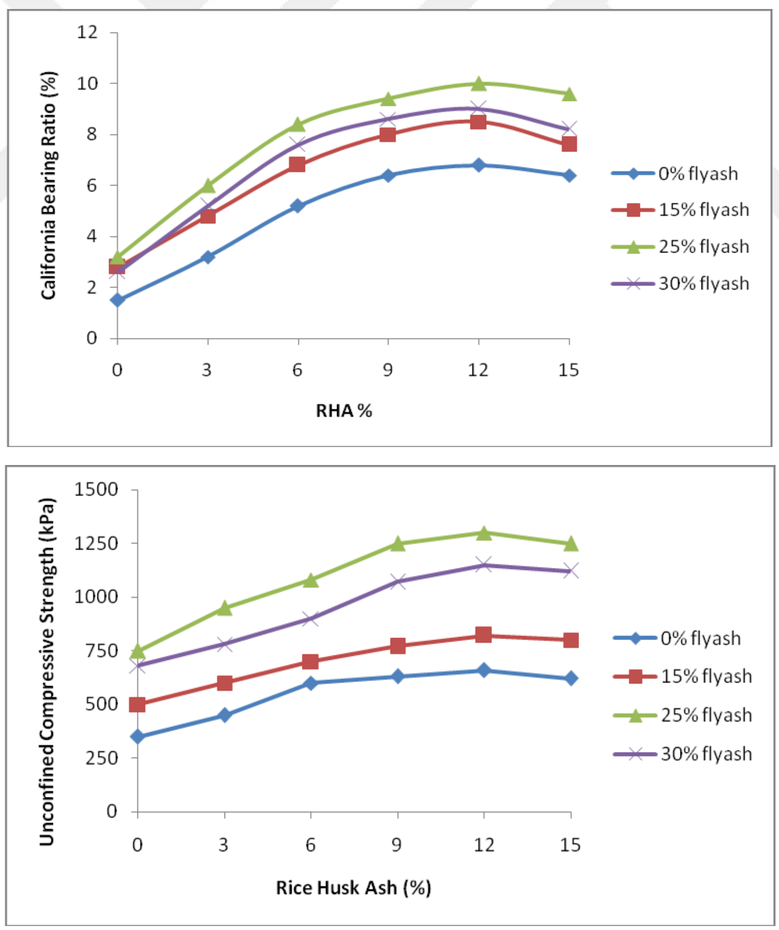

Figure 2-5: Effect or RHA on different engineering properties of soil (Robert, 2009)

Basha et al. (2005) used cement and rice husk ash for stabilization of residual soils is studied. They investigate different engineering properties. The soil samples were stabilized with varying percentages of RHA and cement and subjected to various tests, including compaction, California bearing ratio (CBR), and unconfined compression tests. Different properties such as X-ray diffraction, strength and compaction were estimated by the study. When we add cement and rice hush ash, according to the study the plasticity of the soil decreases. But on the other hand, the combination of cement and RHA causes the maximum dry density to decrease and causes the optimum dry density to increase if we were talking about the term compatibility. In terms of plasticity, compaction and strength features, and budget, concluded adding of 6–8% cement and 10–15% rice husk ash is suggested as a peak amount.

Ashango et al. (2016) work on a wide soil mixture with slag rice husk ash (RHA), and a quick lime as a stabilizer. Geotechnical features, cutting-edge engineering features, and strong stable land structures have been limited. The main mixture is available in the range of 65C + 20SS + 5L + 10RHA65C + 20SS + 5L + 10RHA. Separate tests were performed on the soil with RHA. A randomized controlled trial (UCS) showed that the soil strength of lime and RHA increased by about 45 and 90% in unconfirmed and preserved testers over a 30-day period. The California bearing ratio (CBR) experiment displays that shear strength increases with increasing treatment stages from 7 to 30 days. Various other tests were performed as well. For strength, further experiments of the cyclic triaxial Laboratory were performed under unrestricted conditions to study the vibrant properties of the reinforced soils of various amplitudes and difficulties. The hardness of the hardened soil rises to 58-78% compared to clay soils. This research debated the appropriateness of reinforced underground assets. They found the sand, silt, and clay percentage in particle-size distribution. They found Physical properties i.e., specific gravity, liquid limit, plastic limit, and plasticity index using Atterberg limits test. They used Engineering properties as well for clay and optimum mix. In the Table 2-1, the characteristics and values of clay and optimum mix is stated.

Table 2-1: Properties of the Clay Soil and the Optimum Mix

Tests	**Characteristics**	**Values**	
		Clay	**Optimum Mix**
Particle-size distribution	Sand % (4.75 to 0.075mm)	2	15.18
	Silt% (0.075mm to 0.002)	56	80.35

Tests	Characteristics	Values	
		Clay	Optimum Mix
	Clay %(<0.002mm)	46	4.46
Physical Properties	Specific gravity	2.69	2.609
	Liquid Limit (%)	53	45.1
	Plastic Limit (%)	20	33.97
	Plasticity index (%)	33	11.13
	Shrinkage limit	11	41.5
Engineering Properties	Maximum unit weight (kN/m3)	16.12	15.68
	Optimum moisture content (%)	22	24

Behak et al. (2017) used RHA as a soil stabilizer. Research were done on maintenance by using RHA and lime mixtures that were accompanied in sandy soils. Different tests were conducted. RHA has been used in many ways such as RHA of uncooked rice in ordinary ovens and laboratory heating at measured temperatures has been used. The basic regeneration of RHA was calculated by X-ray analysis and loss in temperature test. The chemical composition of the solvent was the experience of a mixture of soils with different RHA and lime content. Unconfirmed compression (UCS) experiments were performed on soil treated with RHA and lime. The results show an improvement in shear strength across all RHA and lime content and time phases calculated, and all building materials may vary as modified rather than reinforced. Improving RHA sandy soil replaces the final state of social, social and economic recovery. To find the percentage of OMC and percentage of maximum dry unit weight for the admixture of soil with RHA and Lime moisture content the dry density tests were performed. In the Table 2-2, Maximum value of dry density, moisture content was described when we use different proportions of RHA and lime.

Table 2-2: Maximum dry unit weight and OMC of soils and soil-RHA-lime materials.

Soil	RHA (%)	Lime (%)	MIDUW (KN/M3)	OMC (%)
Perez Bustos	0	0	17.4	5.7
	20	10	13	8
Sandstone	2	0	18	5.7
	20	5	11.8	12.4
Villa Passano	2	0	17.4	4.6
	20	5	16.2	10.4
	20	5	13.5	12.4

Soil	RHA (%)	Lime (%)	MIDUW (KN/M3)	OMC (%)
Vergara	0	0	18.1	13.3
	15	3	16.8	14.4
	20	3	15.9	14.9
	20	5	13.8	15

Abdelal et al. (2019) used his research to establish the factors that impact on the compressive strength of Glass Fiber Reinforced Concrete (GFRC). The study used a design of experiments (DoE) full factorial L160A design approach to analyze the compressive strength of GFRC based on four factors: aggregate sand ratio, glass fibers (%), water-to-cement ratio, and cement amount. The authors used the analysis of variance (ANOVA) technique to assess the significance of the main effects of each factor on the compressive strength. The main effect plot showed that the Glass Fiber is the only significant factor effecting the compressive strength of GFRC. He used surface plot and contour plot for interaction effect. The interaction effects showed that the interaction between glass fiber and water-cement ratio had the most substantial effect on the compressive strength of the concrete. Enhancing the amount of glass fiber and reducing the water-cement ratio led to a notable improvement in compressive strength. The interaction effects also showed that the interaction between cement amount and Glass fiber had the most significant effect on compressive strength. As Glass fiber is the most influential factor at a 90% confidence level but still, the presence of a high error percentage indicates the need for further analysis to obtain more precise results. Future work could focus on evaluating compressive strength after 28 days. But the ANOVA table in the paper does not tell us that any factors here have a significance level. There should be more replications, it can help us to signify if there are differences between factor levels. Adding replicants helps us to identify the signify factors. They did not analyze the residual as well and its important assumption that residual is distributed normally for validation of ANOVA table. So, the findings suggest some limitations, and future research could explore ways to enhance the outcomes.

Gao et al. (2022) explores the utilization of entirely recycled fine aggregates in the development of high ductility cementitious composites. The study investigates the impact of various factors including the water-binder ratio (W/B), fiber volume fraction (Vf), recycled fine aggregate-binder ratio (R/B), and fly ash content (FA/B) on the compressive strength, peak tensile stress, and ultimate tensile strain of these high ductility cementitious composites known as R-HDCC (Recycled High Ductility Cementitious Composites).To achieve the desired strength and strain capacity, a mixture design method for R-HDCC was proposed. The study found that increasing W/B led to a significant decrease in compressive strength, while increasing V_f and decreasing W/B improved peak tensile stress. Ultimate tensile strain increased with higher W/B, V_f, and FA/B, but decreased with higher R/B. The suggested approach for mixture design effectively attained the desired levels of compressive strength, peak tensile stress, and ultimate tensile strain in R-HDCC. But there was no mention of which type of mixture design used and how they analyze the data to confirm their findings. So, to check the accuracy of the results, there should be more information.

So, we can conclude that the literature review suggests that various materials have been used to develop liner materials for landfills, including soil, clay, geosynthetic materials, and recycled materials. Soil has been a common choice due to its low cost and availability. However, soil alone may not provide adequate performance for landfill liners, which has led to the development of composite liners using soil, bentonite, and other additives. Research has also explored the use of waste materials, such as fly ash and bottom ash, in composite liners. Geosynthetic materials have also gained popularity due to their high performance and durability, but they are more expensive than traditional materials. Soil-bentonite mixtures have been commonly used as landfill liners due to their low permeability and high durability. Researchers have studied the effects of various additives, such as fly ash, lime, and cement, on the properties of soil-bentonite mixtures. Various laboratory tests have been performed to meet the desired characteristic of liner material. Some studies used DoE to see the effects of different factors on compressive strength on R-HDCC and on GFRC.

Table 2-3 summarizes all the research papers that have been discussed in this part. The table gives us the quick summary of the authors, the setting or sample of their experiments, the methodology they used, and the findings of their cases. The table can help to identify trends and patterns across the studies.

2.1.1 Summary Table

Table 2-3 summarizes our findings regarding the earlier literature discussed above.

Table 2-3: Summary of the literature

Author	Experimental Method	Setting/ Sample	Findings
Eberemu (2011)	OFAT, Hydraulic Conductivity Test, Compressive strength Test, Moisture Content, Volume shrinkage test	Decreasing the permeability of clayey soil with the mixture of RHA.	The findings indicated a correlation between the increase in RHA content and a decrease in the hydraulic conductivity of compacted clay. Notably, the hydraulic conductivity decreased from 4.7 x 10-8 m/s for untreated clay to 1.2 x 10-9s for clay containing 8% RHA. This study proposes that incorporating RHA can be an effective strategy to mitigate the hydraulic conductivity of compacted tropical clay, offering potential applications in areas like landfill liner construction and soil stabilization.
Aziz (2015)	OFAT, UCS, Compaction test, Moisture content, Atterberg Limits	Expansive soil that was mixed with 0 to 20% RHA.	A significant increase in the collision angle and an increment in RHA up to 16% were detected in direct shear experimenting. With an increase in RHA content, there was a noticeable decrease in the plasticity index, suggesting a reduction in the soil's plastic behavior. Moreover, the treated soil specimens exhibited an increase in both the maximum dry density and the optimum moisture content as the RHA content increased.
Bashar (2017)	OFAT, Atterberg limit test (liquid limit, plastic limit), durability tests, strength tests (collapsed head method), leachate features and heavy metal tests	Hybrid rice husk with kapok fiber and hybrid rice husk with coconut fiber.	As the percentages of kapok fiber and coconut fiber increased, the compressive strength of the specimens also demonstrated an improvement. The test results indicated that the hydraulic transmission of the mixture KC: RH: KF, with a ratio of 1:1:1, was measured at 7.29 x 10-11 m/s, which is below 10-9 m/s. This satisfies the requirement for constructing landfill liner materials.

Author	Experimental Method	Setting/ Sample	Findings
Fatteh (2013)	OFAT, Atterberg Limits Test, Compaction Test, CBR, UCS	Clayey soil from Iraq with various properties of rice ash. Enhancing the efficiency of clayey soil with rice ash.	Water limit of the three soil samples was reduced by about 11 to 18% with the addition of 9% RHA, while the plastic index reduced by 32 to 80%. There was an increase in the uncompressed compression strength with an rise in the proportions of the rice husks to its size in RHA between (6-8) %. The results showed that the RHA formed pozzolanic compounds with the clay particles, which improved the microstructure of the soil and increased its strength.
Sarkar (2012)	OFAT, Density, Atterberg parameters, free inflammation index, UCS, direct cutting	Admixture of compacted soil with Rice Husk Ash.	By incorporating a 10% RHA percentage, the UCS and ground shear strength can be modified. The findings revealed that the UCS of the specimens exhibited an increase as the curing time extended, indicating that the strength improvement resulted from the pozzolanic reaction occurring between the RHA and the soil particles.
Shahzada (2017)	OFAT, Atterberg Limits, Compaction Test	Stabilization of expansive soils and rice husk ash.	The swelling of clay minerals is predominantly influenced by three factors: geology, soil engineering characteristics, and local environmental conditions. Arid climates and harsh weathering conditions exacerbate the prevalence of these types of soils. Expansive soils demonstrate significant volume changes when exposed to fluctuations in moisture levels. Additionally, as the MIW (Moisture Index of the Weathering) and BA (Base Additive) content increased, the plasticity index of the soil decreased, indicating a reduction in its plastic behavior. Furthermore, the treated soil specimens exhibited higher values of maximum dry density and optimum moisture content as the MIW and BA content increased.
Gurung (2016)	OFAT, Atterberg Limits, Moisture content and compaction tests	Soft clayey soil, limestone, and fly ash.	Fly ash is incorporated into soil to reduce its moisture retention capacity and enhance its stability by decreasing plasticity. Fly ash is a byproduct of tropical power plants and, if not properly managed, can pose environmental and landfill-related risks. Consequently, it is advisable to utilize such waste materials as additives for soil stabilization, thereby ensuring environmental protection.

Author	Experimental Method	Setting/ Sample	Findings
Saadeldin (2016)	OFAT, FWP, AEP	Clay of Central and Southern Saskatchewan. Useful and quick method to find the hydraulic conductivity.	The findings indicated a decrease in hydraulic conductivity, increasing saturation time, indicating that the clay till liner became more effective at blocking water flow as it became more saturated. Field calculations of the soil hydraulic conductivity is required to estimate the excellence of the soil liner system. This contrast study gave a useful and quick method to determine the in situ hydraulic conductivity at required time.
Anusree G (2016)	OFAT, Atterberg limits test, Specific gravity test, Grain size analysis, Compaction test, CBR, UCS, Direct shear test	Silty clay, Limestone, and rice husk ash.	RHA offers an economical solution for soil stabilization and serves as a suitable material for liners. Notably, the inclusion of RHA led to an increase in maximum dry density and a decrease in optimum moisture content. Additionally, the introduction of RHA resulted in improved unconfined compressive strength of the silty clay, indicating enhanced strength characteristics of the soil. Therefore, RHA significantly enhances the engineering properties of soil and proves to be a cost-effective option for liner materials.
Rahman (1987)	OFAT, Compaction tests, UCS, CBR	Clayey soil, Cement mixtures and Rice Husk ash.	Incorporating RHA and cement into the soil yielded several beneficial effects. These included an increase in maximum dry density and a reduction in optimum moisture content. Furthermore, the introduction of RHA and cement resulted in an improvement in both the compaction characteristics and strength properties of the soil, as indicated by the increased unconfined compressive strength. The performance of the soil mixtures was evaluated at two different time intervals, specifically after 7 days and 28 days, to monitor any changes in industrial performance.
Phanikumar (2016)	OFAT, Atterberg limits test, Specific gravity test, Grain size analysis, Compaction test, Hydraulic Conductivity	Clayey soil montmorillonite and fly ash used for stabilization and used as a liner material.	The combination of fly ash and industrial waste with expansive clays led to a decrease in hydraulic conductivity. Expansive clays have the tendency to expand when exposed to water. However, the introduction of fly ash contributed to a reduction in the swelling potential of the clay, demonstrating that fly ash can serve as an effective stabilizing agent for mitigating the risk of heave in expansive clay liners.

Author	Experimental Method	Setting/ Sample	Findings
Lake (2005)	OFAT, Atterberg limits test, Specific gravity test, Grain size analysis, Compaction test	lay Liner (CCL) as a portion of Composite Liner System for leachate lagoon.	Investigations showed that the chloride migrated 1.7m into the clay liner, sodium 1.2m and potassium 0.7m approximately. Diffusion and sorption data showed that the geomembrane failed between 0 to 6 years after installation of the liner. The study suggests that a CCL can be an effective component of a composite liner system for controlling the permeability of leachate lagoons and preventing contamination of groundwater resources.
Rashid (2017)	OFAT, Soil plasticity, swell index, permeability tests	Locally available soil of various areas of Sri Lanka and its admixtures with 5% and 10% bentonite.	With the help of different permeants, consolidation pressure and bentonite percentage, they characterized locally available swelling clay and its bentonite admixtures, for the usage as a landfill liner in MSW landfills in Sri Lanka.
Alhassan (2008)	OFAT, UCS, CBR, compaction tests	Mixture of soil with RHA of 2 to 12% rice husk ash.	UCS and development in the CBR with increments in the RHA proportion. 6 to 8% RHA was the highest UCS values that were noted, pointing a slight probable of using 6 to 8% RHA for strength development of A-7-6 lateritic soil.
Robert (2009)	OFAT, Compressive strength, CBR, Atterberg limits	Soil with different percentages of fly ash and rice husk ash.	12% RHA content and 25% fly ash content is suggested to consolidate the expanded subsoil. A 15% fly ash content can be selected in combination with RHA by forming a layer of inflammatory reduction due to its optimal performance in laboratory tests.
Basha (2005)	OFAT Compressive strength, durability, CBR, and other engineering properties of soil samples treated with different proportions of rice husk ash and cement.	Soil, Rice Husk ash and cement.	The compaction tests demonstrated that the soil samples exhibited higher maximum dry density as the content of RHA and cement increased, whereas the optimum moisture content decreased. In the CBR tests, the inclusion of RHA and cement in the soil samples notably enhanced their strength and load-bearing capacity. To achieve optimal soil stabilization, it is recommended to add around 6-8% cement and 10-15% rice husk ash, as this combination yielded the best results.

Author	Experimental Method	Setting/ Sample	Findings
Ashango (2016)	OFAT Index properties of soil, Compaction characteristics, CBR, UCS, Swelling characteristics, Shear strength	Mixture of soil with rice husk ash and lime. The main mixture is available in the range of	The hardness of the hardened soil rises to 58-78% compared to clay soils. the soil strength of Lime and RHA increased by about 45 and 90% in unconfirmed and preserved testers over a 30-day period. Based on the results of the compaction tests, it was observed that the maximum dry density of the soil samples exhibited an upward trend with the increasing content of steel slag, RHA, and lime. Conversely, the optimum moisture content experienced a decrease as the aforementioned materials were added to the soil samples.
Behak (2017)	OFAT UCS, Atterberg's limit test	Sandy soil, Rice husk ash, and Lime mixtures	Improvement in shear strength across all RHA and lime content and time phases calculated, and all building materials may vary as modified rather than reinforced. Improving RHA sandy soil replaces the final state of social, social, and economic recovery.
Abdelal (2019)	DoE, full factorial L160A design	Glass Fiber Reinforced Concrete (GFRC)	The percentage of glass fiber content had the most significant effect on the compressive strength of GFRC, followed by the water-cement ratio and the sand-cement ratio. The type of curing method used was found to have a relatively minor effect on compressive strength. The optimal values for each factor were determined, and a regression equation was developed to predict the compressive strength of GFRC based on the input factors.
Gao (2022)	Laboratory tests (Compressive Strength test) DoE, Mixture Design (No specified)	Sample: Water concrete debris, fly ash and recycled pleasant aggregate (R-HDCC). Waste concrete debris with authentic particle grade. Promote the waste recycling, reduce the environmental pollutants, recognize the cleaner manufacturing	The compressive strength of R-HDCC displayed a significant decrease with an increase in the water-binder ratio. On the other hand, the peak tensile stress of R-HDCC experienced a notable improvement with an increase in the fiber volume fraction and a decrease in the water-binder ratio. Furthermore, the ultimate tensile strain of R-HDCC notably increased with the rising water-binder ratio, fiber volume fraction, and fly ash content, while it decreased with an increase in the recycled fine aggregate-binder ratio. However, the specific type of mixture design used and the methodology employed to analyze the data supporting their findings were not mentioned.

2.1.2 Gap Analysis:

Table 2-4 summarizes our findings regarding the selected literature. In most of the studies, the effects of different materials on compaction characteristics, hydraulic conductivity and compressive strength properties were investigated. We can conclude that RHA is the most frequently studied material by researchers. However, all factors included in the experiments were studied with the OFAT (one factor at a time) approach, so it was not possible to discover the interaction effects. The main gap here is the methodology, there is a lack of studies that have used the DoE methodology to study the interactions and higher order effects in developing a landfill liner material. While it can be a powerful tool to optimize the factors to develop a landfill liner material. This table includes the majority of the studies that have worked on liner material.

Table 2-4: Gap analysis

SN	Reference	Factors									Responses						DoE Methodology
		F1	F2	F3	F4	F5	F6	F7	F8	F9	R1	R2	R3	R4	R5	R6	
1	Eberemu (2011)	✓									✓	✓	✓				
2	Aziz (2015)											✓	✓			✓	
3	Bashar (2017)	✓	✓	✓							✓	✓	✓				
4	Fatteh (2013)	✓										✓	✓			✓	
5	Sarkar (2012)	✓										✓	✓			✓	
6	Shahzada (2017)	✓			✓								✓			✓	
7	Gurung (2016)					✓	✓					✓	✓				
8	Saadeldin (2016)								✓		✓		✓				
9	Anusree G (2016)	✓					✓										
10	Rahman (1987)	✓								✓		✓	✓	✓			
11	Phanikumar (2016)					✓							✓		✓		
12	Lake (2005)								✓		✓						
13	Rashid (2017)							✓				✓	✓				
14	Alhassan (2008)	✓										✓		✓			
15	Robert (2009)	✓				✓					✓	✓				✓	
16	Basha (2005)	✓								✓	✓		✓	✓			
17	Ashango (2016)	✓					✓					✓	✓				
18	Behak (2017)	✓								✓		✓		✓			
19	Maheen (2023)	✓								✓	✓	✓	✓				✓

Table Legend			
Factor	**Code**	**Response**	**Code**
RHA	F1	Hydraulic Conductivity	R1
Kapok Fiber	F2	Compressive Strength	R2
Coconut Fiber	F3	Compaction Characteristics	R3
MIW	F4	CBR	R4
Flyash	F5	Compressibility	R5
Limestone	F6	Shear Strength	R6
Bentonite	F7		
Dry Density	F8		
Cement Mixtures	F9		

3. RESEARCH METHODOLOGY

3.1. Introduction

In this section, we discussed thoroughly the design of experiments methodology to understand the effect of different factors on the properties of liner material and which design can be used to achieve the desired liner material.

3.2. Design of Experiment

Design of Experiments (DoE) is a statistical tool that allows for the efficient and systematic exploration of multiple variables and their interactions to determine the optimal conditions for a particular process. To apply the design of experiment methods, there are different steps that can be followed, such as: (Montgomery, 2012)

- Recognition of statement of problem
- Selection of the response variable
- Choice of factors, levels, and ranges
- Choice of experimental design
- Performing the experiment
- Statistical analysis of the data
- Conclusions and recommendations

3.2.1 Recognition of statement of problem

In DoE, recognizing the statement of the problem is crucial to develop an effective experimental plan. Here are some steps that can help in recognizing the statement of the problem.

- Identify the response variable, which is the outcome of interest that the experiment aims to improve or optimize.
- Define the goal of the experiment, such as improving quality, increasing efficiency, reducing costs, or optimizing a process.
- Identify potential sources of variation and the variables that may affect the response variable.
- Determine the factors or variables that are believed to have an effect on the response variable and ensure that all relevant factors are considered.

- Formulate a clear problem statement that defines the research question and experimental objectives, indicating the specific factors that will be studied and how the experiment will be designed to achieve the research objectives.

3.2.2 Selection of the response variable

To select the response variable in DoE, we should first identify the purpose of the experiment and the outcome that will be achieved. Next, we should identify the critical output or performance measure that represents the outcome of interest. The response variable should be relevant to the experiment, measurable, and sensitive to changes in the input variables. Any constraints or limitations that may impact the measurement should be considered, and appropriate measurement tools and techniques should be selected. The response variable should be documented clearly and precisely in the experimental design, including the units of measurement, the method of measurement, and any relevant assumptions or specifications.

3.2.3 Choice of factors, levels, and ranges

To choose factors, levels, and ranges in DoE, we should first identify the independent variables or factors that may impact the response variable. The factors should be relevant to the problem and cover the range of conditions of interest. The levels and ranges of the factors should be selected based on their expected impact on the response variable and should cover the full range of possible values. The number of levels and ranges should be determined based on the experimental design and the resources available. Factors should be chosen so that they can be controlled and manipulated independently of each other. The selection of levels and ranges should be guided by previous research, engineering knowledge, and statistical considerations. The experimental design should ensure that the effects of the factors can be estimated accurately and that the experiment is efficient and effective. The final design should be evaluated to ensure that it is feasible, practical, and meets the goals of the experiment.

3.2.4 Choice of Experimental design

If the first 3 steps are performed effectively, then the choice of the experimental design type would be relatively easy. There is vast amount of design categories for specific purposes. Within the context of this study, hereafter, we briefly summarized major ones. Type of the design is usually dependent on several considerations such as the purpose of the experiment, type of factors and their levels, number of responses and their type (categoric, continuous) or the linear model sought after.

3.2.4.1 Factorial Design

Factorial design methodology is a statistical approach used to study the relationship between multiple input variables and one or more response variables. This methodology involves systematically varying each input variable at different levels and measuring the response. The data obtained from the experiments can be used to build a mathematical model that describes the relationship between the input variables and the response.

3.2.4.1.1 General Factorial Design:

A general factorial design is a type of experimental design in which multiple factors are varied simultaneously to evaluate their individual and combined effects on a response variable. If there are a, b, c, and so on, levels of various factors in a factorial experiment, the general factorial design can be applied. The total number of observations in this case would be the product of the levels of all the factors, and there must be at least two replicates of the complete experiment to determine a sum of squares due to error when all possible interactions are included in the model. In this design, each factor is manipulated at *k* levels, typically labeled as low, medium, and high. The design matrix is constructed such that each row represents a specific combination of factor levels, resulting in a total of 3^k experimental runs.

One advantage of the general factorial design is that it allows researchers to study the effects of multiple factors and their interactions on a response variable in a relatively efficient manner. By varying the levels of the factors, the researcher can obtain a wealth of information about the relationship between the factors and the response variable with a relatively small number of experiments. Additionally, the design allows for the estimation of the effects of each factor on the response variable, as well as the interactions between factors, which can provide insight into the underlying mechanisms that influence the response.

However, the main disadvantage of the general factorial design is that it can become impractical for a large number of factors or levels, as the number of experiments required to fully investigate all possible combinations can quickly become unmanageable. In such cases, alternative experimental designs, such as fractional factorial designs or response surface designs, may be more appropriate.

3.2.4.1.2 2^k Factorial Design:

In this design, each factor is manipulated at two levels, typically labeled as high and low, resulting in four treatment combinations. A general 2^k factorial design is a design that involves k factors, each with two levels i.e., 2^2, 2^3. The levels can be either qualitative or quantitative and are referred to as "low" and "high". The design includes all possible combinations of factor levels, resulting in 2^k treatment combinations or experimental runs. Statistical analysis of the data can be performed using ANOVA or regression analysis. This can help identify which factors and interactions are significant and guide further experimentation or modeling efforts.

The initial step involves determining the effects of factors and assessing their importance by analyzing their magnitudes and signs. This can provide initial information about which factors and interactions might be significant and the direction in which they should be adjusted to improve the response. For the initial model, the full model is typically chosen, including all main effects and interactions, provided that one design point is replicated. In the next step, the analysis of variance is used to test the significance of the main effects and interactions. Then, model refinement involves removing insignificant variables from the full model. Then we check model adequacy and assumptions using residual analysis. Model refinement may occur after residual analysis if the model is inadequate, or assumptions are violated. Finally, graphical analysis is conducted to further analyze the main effects or interactions, such as response surface and contour plots.

To evaluate a 2^k design, researchers typically use ANOVA to determine the main effects of each factor, as well as any interaction effects between the factors.

The model for a 2^2 factorial design with interactions can be represented by the following equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \varepsilon \qquad (3\text{-}1)$$

where y is the response variable, x_1 and x_2 are the two input variables, β_0 is the intercept, β_1 and β_2 are the main effects of x_1 and x_2, β_{12} is the interaction effect of x_1 and x_2, and ε is the error term.

The ANOVA table for a 2^2 factorial design typically includes four sources of variation: the main effect of Factor A, the main effect of Factor B, the interaction effect between Factors A and B, and the residual error. The F-tests associated with each source of variation are used to determine whether the effect is statistically significant, indicating that the factor or interaction has a significant effect on the response variable.

The interpretation of a 2^k factorial design depends on the results of the ANOVA. If the main effect of Factor A is significant, this suggests that changing Factor A has a significant effect on the response variable, regardless of the level of Factor B. If the main effect of Factor B is significant, this suggests that changing Factor B has a significant effect on the response variable, regardless of the level of Factor A. If the interaction effect is significant, this suggests that the effect of changing one factor on the response variable depends on the level of the other factor. Therefore, there is no point in trying to interpret main effects when interaction effect is significant. The ANOVA table also provides the mean square (MS) for each source of variation, which is obtained by dividing the SS by the degrees of freedom (df) for that source. The F-statistic is then calculated as the ratio of the MS for a given source to the error MS, which represents the variation in the response variable that cannot be explained by the factors being studied.

The design is often used for screening experiments, where the aim is to identify important factors and their interactions in a small number of experiments. By screening the most significant factors, we can focus subsequent experimentation and analysis on these factors, rather than wasting resources on factors that have little impact on the response variable. Therefore, the screening step is an important part of the 2^k factorial design methodology as it allows for a more efficient and effective approach to experimentation and analysis. The design can also be used to estimate main effects and interactions, but it assumes that the effects are linear and that there are no higher-order relations between response and factors.

3.2.4.1.3 2^{k-p} Fractional Factorial Design:

The General 2^{k-p} fractional factorial design is a modification of the 2^k factorial design where a subset of the 2^k experimental runs is taken to create a fractional design. The number of runs in the fractional design is typically denoted by 2^{k-p}, where p is the number of generators used to construct the fractional design. The main idea is to reduce the number of experimental runs required while still being able to estimate the main effects and certain number of interaction effects of the factors. The design is created by systematically selecting a subset of the 2^k experimental runs based on certain mathematical criteria, such as the minimum aberration criterion (smallest possible number of confounded two-factor interactions) or the maximum number of clear two-factor interactions criterion. The chosen subset is such that it satisfies the requirement of the fractional factorial design while still allowing for the estimation of the effects of interest. The analysis of the data collected from the 2^{k-p} fractional factorial design is similar to that of the full 2^k factorial design.

3.2.4.2 Response Surface Design:

Response surface is a combination of empirical and statistical techniques that can be very beneficial for examining the relationships between factors and responses; how they interact with each other and to optimize the response of interest. RSM works by building a response surface model that describes the relationship between the process variables and the response variables. The response surface model is then used to predict the optimal settings of the process variables that will yield the desired response.

We first select our response variables, factors, and series of experiments based on our runs. The next step involves fitting a response surface model to the experimental data. The response surface model is a mathematical equation that describes the relationship between the input variables and the response or output variable. The response surface model can be a second-order or higher-order polynomial equation, depending on the complexity of the relationship between the input and output variables. The regression analysis estimates the coefficients of the response surface model that describes the relationship between the process variables and the response variables. The regression analysis also tests the significance of the coefficients and checks for the adequacy of the model fit.

For example, a company wants to optimize the production of a certain chemical product. They have identified two factors that could potentially affect the yield of the product: reaction temperature (x_1) and reaction time (x_2).

So, the yield of chemical process y is a function of the levels of reaction temperature and reaction time.

$$y = f(x_1, x_2) + \varepsilon \qquad (3\text{-}2)$$

Where ε can be the error. The function represented by $f(x_1, x_2)$ is called response surface. We usually represent response surface with the help of graphs. To visualize the shape of the function, we often use surface or contour plots.

Independent factors and its relationship with y are the first thing that we can examine in response surface. Now it depends on the type of relationships between response and the factors we consider, if it's linear, we can use a 1st order Model.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots.. + \beta_k x_k + \varepsilon \qquad (3\text{-}3)$$

If the response exhibits curvature, a higher degree of polynomial is used. Preferably a second order model.

$$\boldsymbol{y = \beta_0 + \sum_{i=1}^{k} \hat{\beta} x_i + \sum_{i=1}^{k} \hat{\beta}_{ii}\, x_i^2 + \sum \sum_{i<j}^{k} \hat{\beta}_{ij}\, x_i x_j + \varepsilon} \qquad (3\text{-}4)$$

The next step is optimization, which involves using the response surface model to identify the optimal values of the input variables that will yield the desired response. RSM works by iteratively refining the response surface model until an optimal set of input variables is identified. The methodology allows for the exploration of the entire design space with a minimum number of experimental runs, and it can optimize multiple response variables simultaneously.

The Method of Steepest Ascent: If we need to gradually increase our response or maximize it, we employ the method of steepest ascent. Conversely, when aiming for minimization, we refer to it as the method of steepest descent. We continue using this method until we no longer observe any further increment or decrement in our response. Once this level is achieved, we are ready to proceed with the 1st order model. In Figure 3-1**,** the path of steepest ascent is depicted.

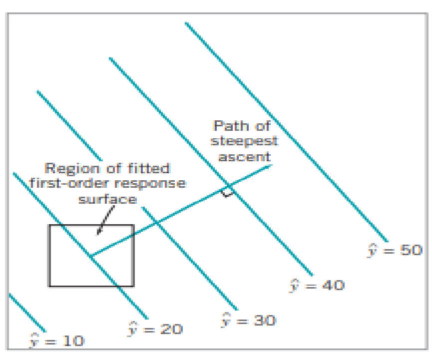

Figure 3-1: Path of steepest ascent

Frequent Designs Used in RSM:

Central composite design (CCD) and Box-Behnken design (BBD) are the most commonly used designs in RSM, as they allow for the estimation of higher-order effects of the input variables and provide a good balance between the number of experimental runs and the accuracy of the model.

3.2.4.2.1 Central Composite Design (CCD):

Central composite design (CCD) is a commonly used experimental design in response surface methodology (RSM) for the optimization of complex processes with multiple variables. CCD allows for the estimation of linear, quadratic, and interactive effects of the input variables on the response variables, making it a powerful tool in RSM. The CCD consists of three types of experimental runs: center points, factorial points, and axial points. Center points are experimental runs that are performed at the center of the design space, and they provide an estimate of the experimental error. Factorial points are experimental runs that are performed at the extremes of the input variables, and they provide estimates of the main effects and the interaction effects. Finally, axial points are experimental runs that are performed at the intermediate values of the input variables, and they provide estimates of the curvature of the response surface.

The experimental runs are conducted according to the CCD design, and the data obtained is used to fit a second-order polynomial model to the response variables. The model can then be used to predict the response variables for any combination of the input variables within the design space.

Once the response surface model is obtained, it can be used to identify the optimal values of the input variables that will produce the desired response.

3.2.4.2.2 Box-Behnken Design (BBD):

Box-Behnken design (BBD) is a commonly used experimental design in response surface methodology (RSM) that is particularly useful when the number of input variables is relatively high. BBD is used to fit a second-order polynomial model to the response variables that can be used to predict the response for any combination of the input variables within the design space.

BBD is a three-level design that focuses on finding optimal settings for continuous variables. It consists of a series of factorial points placed at the center and the midpoint of each side of a hypercube. The design points are chosen to ensure a good estimation of the response surface curvature. BBD strives to achieve orthogonality between the factors to reduce multicollinearity and improve the efficiency of estimating the model coefficients. The design is constructed to minimize the correlation between the main effects and interaction effects. Unlike CCD, BBD does not include axial or cube points. The absence of cube points simplifies the design structure but limits the exploration of the response surface in the extreme factor settings. BBD is designed to be rotatable, meaning that the fitted model coefficients will not change if the experiment is performed at a different orientation or rotation of the design space. This property allows for a more robust analysis and interpretation of the response surface model. BBD provides a more regular and balanced design structure compared to CCD, as it aims to strike a balance between efficiency and simplicity. While BBD does not allow for direct exploration of extreme factor settings like CCD, it offers a more efficient estimation of the response surface curvature.

3.2.4.3 Mixture Design:

Mixture design methodology is a statistical approach that is used to optimize the composition of mixtures by varying the proportion of different components.

The first step in mixture design methodology is to identify the components that make up the mixture and the proportion of each component that will be varied. The components are continuous and the proportions must sum to 100%. Next, an experimental design is chosen to determine the optimal combination of components that will result in the desired properties or performance of the mixture. There are several types of experimental designs that can be used, including simplex lattice, simplex centroid, and simplex axial. During the experimental runs, a set of mixtures are prepared using different proportions of the components, and the properties or performance of each mixture are measured. Once the design points have been selected and the experiment has been conducted, the response variable is measured and used to fit a regression model. The model is then used to identify the optimal mixture proportions for the desired response.

To analyze the results of a mixture experiment, Montgomery suggests using a ternary plot to visualize the proportion of each component in the mixture. The response surface can then be plotted on the same graph to identify the region of the mixture space that corresponds to the desired response.

One of the advantages of mixture design methodology is that it allows for the identification of the optimal combination of components that would not be possible using traditional one-Factor-at-a-time (OFAT) methods. Mixture design methodology takes into account the interactions between the components, allowing for a more accurate prediction of the properties or performance of the mixture.

Design Types

There are several experimental designs commonly used in mixture design methodology. (Jensen, 2016)

3.2.4.3.1 Simplex Lattice Design

The simplex lattice design is a commonly used experimental design in mixture design methodology. It is a regular polygon with vertices at the corners of the simplex, where the number of vertices is determined by the number of components in the mixture. The simplex lattice design is useful for exploring the mixture space and estimating the main effects of the components. To use the simplex lattice design in mixture design, a set of experimental runs are performed where the mixture components are varied according to the design. The response variable is measured for each mixture, and the data are used to estimate the main effects of the mixture components using regression techniques. The main effects of the mixture components can be used to identify the components that have the greatest influence on the response variable. This information can be used to guide the optimization process and identify the optimum mixture composition.

One advantage of the simplex lattice design is that it is easy to visualize and understand, making it a useful tool for communicating the results to stakeholders. It is also easy to generate and does not require specialized software or knowledge. In Figure 3-2, we can see the simplex lattice design with 3 component mixture, labeled as x_1, x_2, and x_3. The total proportion of the components is kept constant at 1. The corners of the simplex represent pure components, i.e., 1 for one component and 0 for the other two components. The other points in the simplex represent various combinations of the three components in different proportions. The lattice points on the edges of the simplex lattice represent the midpoints between two corners of the simplex. The lattice points within the simplex represent the midpoints between three or more corners. These lattice points are used to create the experimental design for mixture experiments.

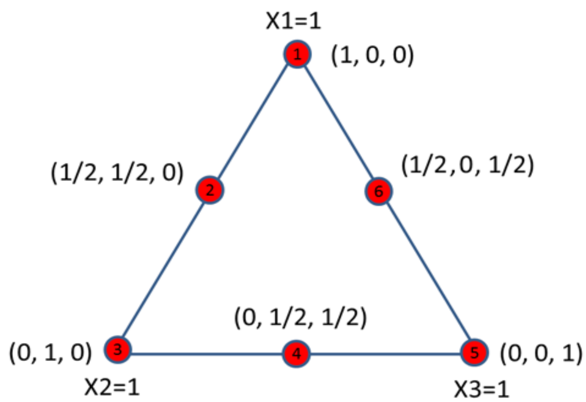

Figure 3-2: Simplex lattice design with 3 factors

3.2.4.3.2 Simplex Centroid Design

Simplex Centroid design is a combination of Simplex Lattice Design and the Centroid Design. In this design, the response variable is measured for each mixture, and the data are used to estimate the main effects and curvature of the response surface using regression techniques.

According to (Jensen, 2016), It involves using a simplex, which is a geometrical shape formed by connecting the vertices of a triangle in n-dimensional space, where n is the number of variables being studied. In this design, a center point is added to the simplex and the experiments are conducted at the vertices and center point. The center point serves as a check on the adequacy of the fitted model and provides an estimate of experimental error.

One advantage of the Simplex Centroid Design is that it is efficient and requires fewer experimental runs compared to other designs. Additionally, it provides a good balance between estimation efficiency and prediction accuracy. In Figure 3-3, A Simplex centroid design for 3-component mixture is shown. The triangle is formed by the three corners representing the three components of the mixture. The design consists of a central point at the center of the triangle and six additional points located at equal distances along each of the six edges of the triangle. The central point is the centroid of the triangle, and the six additional points are the vertices of six equilateral triangles that share a common edge with the central triangle. The distances from the centroid to each of the vertices are equal to the distance from the centroid to each of the midpoints of the edges of the triangle.

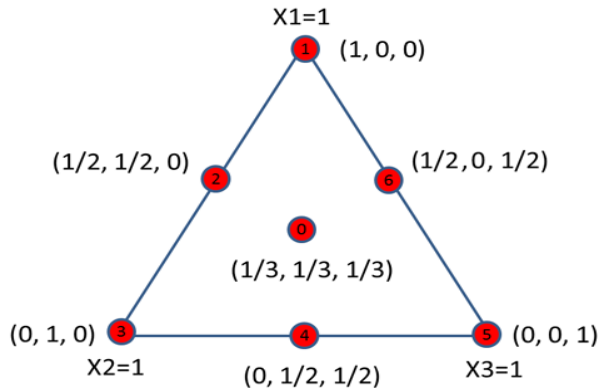

Figure 3-3: Simplex centroid design for 3-component mixture

3.2.4.3.3 Simplex Axial Design

Simplex Axial design is a variation of the Simplex Lattice Design that includes a set of axial points in addition to the vertices of the simplex. The Simplex Axial Design is useful for estimating the second-order effects of the mixture components and for fitting a quadratic response surface model.

The response variable, such as the physical or chemical property of the mixture, is measured for each mixture, and the data are used to estimate the second-order effects of the mixture components and to fit a quadratic response surface model using regression techniques. The second-order effects of the mixture components can be used to identify the interactions between components and the regions of the mixture space that have the greatest impact on the response. The quadratic response surface model can be used to predict the response variable for any combination of mixture components within the design space. (Jensen, 2016)

It provides a good balance between estimation efficiency and prediction accuracy, allowing for better understanding of the curvature of the response surface.

3.2.4.3.4 Mixture Design with Process Variables

Mixture design with process variables is a variation of mixture design methodology that allows for the optimization of a mixture formulation while taking into account the effect of process variables on the response variable. To use mixture design with process variables, a set of experimental runs are performed where both the mixture composition and the process variables are varied according to the design. The response variable is measured for each mixture at each combination of process variables, and the data are used to estimate the effects of both the mixture components and the process variables on the response.

The estimated effects of the mixture components and process variables can be used to identify the optimal mixture composition and process conditions that maximize the desired response. The optimization process typically involves the use of response surface methodology or other statistical techniques to model the relationship between the response variable and the mixture composition and process variables, and to determine the optimal combination of mixture composition and process variables that maximize the response. (Jensen, 2016)

The Table 3-1 below provides a general overview of these types of experiments and their purposes, but there may be situations where a combination of these designs is appropriate. At the end, the choice of experiment design should be based on the specific goals of the experiment and the characteristics of the study being studied.

Table 3-1: Summary table for factorial designs, Response surface methodology and Mixture design

Design type	Design Factors	Purpose	When to use	Advantages
2^k Factorial Design	Multiple categorical or continuous variables	For screening the factors.	If the response has a liner relationship between factors.	Less number of experiments.
Response Surface Methodology (RSM)	Multiple continuous variables	To optimize the response variable by fitting a regression model to the experimental data.	When the goal is to identify optimal factor settings for the response variable, and to explore the relationships between factors and the response variable.	Can optimize response by identifying optimal factor levels.
Mixture Design	Components of a mixture	To determine the optimal proportion of components in a mixture to achieve a desired response.	When the goal is to optimize the response variable by adjusting the proportions of components in a mixture, and to explore the	Reduces the number of experimental runs required to explore

Design type	Design Factors	Purpose	When to use	Advantages
			relationships between components and the response variable.	multiple components.

4. RESULTS AND DISCUSSIONS

Research were done on how to make liner material from different admixtures. Soil with different factors like RHA, lime or coconut fiber are used to make liner material. To the best of our knowledge, in previous studies, authors used experimental methods of developing liner material so there is no proper explanation and the results for the higher order terms and the effects of factors on the contribution of liner materials. So, ignoring higher order terms and interactions can result in an incomplete understanding of the relationships between the factors and the response, potentially leading to suboptimal designs for the liner material. So, we recommend using the DoE methodology to develop liner material.

For instance, Bashar et al. (2017) investigate the potential of using a combination of rice husk and kapok fiber as an alternative liner material in landfill applications. The study involved testing the physical, mechanical, and hydraulic properties of the hybrid material, as well as its ability to reduce the transport of contaminants from landfill leachate. They compared the performance of the hybrid material to a conventional clay liner, which is commonly used in landfill applications. They used a laboratory experimental approach to evaluate the performance of the hybrid rice husk and kapok fiber liner material. They conducted a series of tests to determine the physical, mechanical, and hydraulic properties of the hybrid material, including tests to measure the material's compressibility, permeability, and hydraulic conductivity. In the case of this study, the researchers could have used a DoE approach to vary the composition and proportions of the rice husk and kapok fiber in the hybrid material and measure the resulting physical, mechanical, and hydraulic properties. This could have helped to identify the optimal combination of rice husk and kapok fiber for achieving the desired performance characteristics. There are several advantages to using a DoE approach in this type of study.

- Firstly, it allows for a systematic exploration of the factors that affect the performance of the hybrid material, which can help to identify the most important factors and their optimal settings. This can save time and resources compared to a trial-and-error approach.
- Secondly, a DoE approach allows for a statistical analysis of the results, which can help to quantify the effects of the different factors on the performance of the hybrid material and identify any interactions between the factors. This can provide more robust and reliable results compared to a single-factor-at-a-time approach.

Ignoring higher order terms and its effects may affect the findings of the data. So, the DoE approach would be appropriate.

4.1. Proposed DoE Method to develop a liner material:

By using these different steps, we can propose the DoE method to develop a liner material.

Recognition of statement of problem:

The proper containment of waste in landfills is crucial to prevent environmental contamination and protect human health. One essential component of an effective landfill system is the liner material, which acts as a barrier to prevent the migration of pollutants into the surrounding soil and groundwater. While various landfill liner materials exist, there is a need for the development of innovative materials with improved properties, such as enhanced tensile strength, permeability, and chemical resistance. The development of a liner material with optimized properties using the DoE method is necessary to address the limitations and challenges faced by current liner materials. Existing liner materials often lack the desired combination of properties such as compressive strength, hydraulic conductivity, compaction properties. The absence of a well-defined DoE method specifically designed for the development of liner materials hinders the systematic exploration and optimization of various factors that influence material performance. Without a systematic approach, the development process becomes time-consuming, costly, and less reliable in achieving the desired properties. Therefore, the problem at hand is to develop a liner material using the DoE method, addressing the challenges faced by current materials and optimizing the material's composition and manufacturing process. This includes identifying the critical factors that affect the material's performance, determining their optimal levels, and efficiently utilizing resources to achieve a liner material that exhibits enhanced desired properties. By addressing this problem, we aim to advance the field of liner material development, resulting in improved performance and efficiency in various industrial applications.

Selection of response variable:

According to US EPA (2004) we need low hydraulic conductivity and high compressive strength for our liner material. Compressive strength is a fundamental mechanical property that measures the ability of a liner material to withstand applied compressive forces. A high compressive strength ensures the liner material's stability and load-bearing capacity, providing long-term integrity and structural support. Hydraulic conductivity refers to the ability of a liner material to allow or restrict the flow of fluids, such as water or contaminants, through it. A liner material with low hydraulic conductivity acts as an effective barrier, minimizing the permeability and preventing the passage of fluids through the liner system (leachate). So, we can have these two response variables.

- Compressive strength
- Hydraulic conductivity

Choice of factors, levels, and ranges:

Factors such as soil type, RHA and amount of cement are commonly considered due to their influence on the performance and suitability of the liner material. Different soil types have varying characteristics, including particle size distribution, compaction behavior, permeability, and chemical composition. RHA is often used as an additive in liner materials due to its pozzolanic properties. It can enhance the mechanical strength, durability, and chemical resistance of the liner material. In literature review, while making liner material with RHA, most authors used percentages between 0 -10%. So, we select the relative amount of RHA. Cement is commonly used as a binder in liner material formulations. The amount of cement affects the strength, stiffness, and durability of the material. So, we can see that most authors used soil type and RHA while developing a liner material. So, we can take these factors into account.

- Soil Type: Sandy, Clayey, Silty
- RHA Content: (3.17%), (4%), (8%), (8.82%)
- Cement Amount: Low (10%), Medium (15%), High (20%)

Choice of experimental design:

Using the RSM approach, we would then analyze the data and the model to identify the optimal levels of the factors that would lead to a liner material with the desired properties of high compressive strength, low hydraulic conductivity, and high durability. The RSM approach allows us to model the curvature of the response surface, which can be useful in identifying interactions between the factors and higher order effects that may affect the properties of the liner material. RSM can help us to understand the higher order terms and their interactions by fitting a second-order polynomial equation to the response surface data. This equation includes not only the linear terms of the factors but also the quadratic and interaction terms, which represent the higher order effects. By analyzing the coefficients of these terms, we can determine the significance of each factor and their interactions, as well as identify any curvature or nonlinearity in the response surface. Furthermore, RSM can also generate contour plots and 3D response surface plots to visualize the behavior of the response variables as the factor levels change. These plots can help us to identify the optimal combination of factor levels that result in the desired response variables. So, by optimizing the levels of the factors using RSM, we can develop a liner material that meets specific requirements with improved accuracy and efficiency.

The Table 4-1 below provides us the summary of factors, level ranges, response variables for propsed doe method to develop a liner material.

Table 4-1: Summary table for the propsed DoE method to develp a liner material

Factors	Level Ranges	Response Variable	DoE method
Soil Type	Sandy, Clayey, Silty	Compressive strength	Response surface design
RHA content	(3.17%), (4%), (8%), (8.82%)	Hydraulic conductivity	
Cement amount	Low (10%), Medium (15%), High (20%)		

Table **4-**2 shows design matrix that allows for easy interpretation and analysis of the experimental results by providing a structured representation of the experimental factors and their corresponding coded levels.

Table 4-2: CCD Matrix design (Coded) for proposed DoE method to develop a liner material.

No of experiment	RHA Content	Cement Amount	Soil Type
1	-1	-1	Sandy
2	1	-1	Sandy
3	-1	1	Sandy
4	1	1	Sandy
5	-1.414	0	Sandy
6	1.414	0	Sandy
7	0	-1.414	Sandy
8	0	1.414	Sandy
9	0	0	Sandy

No of experiment	RHA Content	Cement Amount	Soil Type
10	0	0	Sandy
11	0	0	Sandy
12	0	0	Sandy
13	0	0	Sandy
14	-1	-1	Clayey
15	1	-1	Clayey
16	-1	1	Clayey
17	1	1	Clayey
18	-1.414	0	Clayey
19	1.414	0	Clayey
20	0	-1.414	Clayey
21	0	1.414	Clayey
22	0	0	Clayey
23	0	0	Clayey
24	0	0	Clayey
25	0	0	Clayey
26	0	0	Clayey
27	-1	-1	Silty
28	1	-1	Silty
29	-1	1	Silty
30	1	1	Silty
31	-1.414	0	Silty
32	1.414	0	Silty
33	0	-1.414	Silty
34	0	1.414	Silty
35	0	0	Silty
36	0	0	Silty
37	0	0	Silty
38	0	0	Silty
39	0	0	Silty

In the above matrix, -1 and +1 represent low and high levels of each factor, respectively. The values -1.414 and +1.414 represent the alpha levels or the distance from the center point to the factorial points.

4.2. For the possible future studies:

Fit a response surface model: After conducting the actual experiments, we can use the data in our CCD design matrix to fit a regression model that relates the factors (soil type, RHA content, and cement amount) to the response variables (compressive strength and hydraulic conductivity). The regression model will help us model the relationship between the factors and the responses.

Optimization Model: We can Define the optimization objective based on our specific requirements. Since we want to maximize compressive strength and minimize hydraulic conductivity. The function should consider the trade-off between the two response variables. We can set constraints on the factor levels within their respective ranges (e.g., 3.17% to 8.12% for RHA content and for cement content 10% to 20%). We can formulate the optimization problem accordingly. For example.

$$\min z = f_1(x_1, x_2)$$

S.T.

$$f_2(x_1, x_2) \geq 200\ kPa$$

$$x_1, x_2 \geq 0$$

Where f_1 and f_2 represent linear functions for hydraulic conductivity and compressive strength obtained by the experiments.

Optimization Method: We can use gradient-based optimization methods such as steepest ascent or descent that we discussed earlier. Software tools (Minitab, Design Expert) are available that help practitioners with both experimental design and optimization.

5. CONCLUSION

The conclusion and recommendation concisely summarize the benefits of employing the DoE methodology to develop a liner material, highlight the achieved outcomes, and the envisions for future advances in the field as follows:

- DoE methodology has significant potentials to enhance the qualities of landfill liner material.
- DoE allows researchers to systematically evaluate and optimize multiple factors simultaneously, leading to the identification of the most significant factors and their interactions.
- Different types of DoE methods, such as Response Surface Methodology (RSM) and Mixture Design, can capture both linear and non-linear relationships between factors and responses, as well as account for interactions and higher-order terms.
- DoE leads to the identification of a material with improved properties and performance, reducing the environmental impact and increasing the safety of hazardous waste disposal.
- We implemented the first four stages of using doe methodology. For future studies, it is fine to implement the remaining three stages by using actual laboratory experiments to develop a liner material.
- We strongly recommend using DoE methodology for similar types of improvements and new product development studies.

Future studies should focus on the implementation of DoE methodology for the development of other materials with complex compositions and properties.

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