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Assessing the Permeability of Bentonite with Sand, Marble Dust, and Fly Ash mixture with and without Effect of Permeate Solution for the Development of Efficient and Cost-Effective Landfill Liner for Sustainable Waste Management and Environmental Preservation

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Abstract

This exploration paper researches the capability of further developing landfill liner materials by integrating varying percentages of bentonite into sand, marble dust, and fly ash mixtures. The study focuses on determining whether these mixtures are suitable for development of landfill liner by examining their permeability properties. Bentonite, a clay known for its high swelling and sealing properties, is added to sand, marble dust, and fly ash at different range from 0% to 40%. The permeability testing is conducted under various electrolyte concentration to simulate diverse environmental conditions that landfill liners may encounter. Three electrolytes, in particular $CaCl_2$ (1N, 1.5N, 2N), NaOH (1, 1.5, 2N), and HCl (1N, 1.5N, 2N), are utilized to investigate the materials' responses to varying pH levels and ionic strengths. The penetrability evaluations aim to provide experiences into the effectiveness of the mixtures in preventing the migration of pollutants/contaminates in landfill sites. The findings of this study are supposed to contribute valuable information to the field of geotechnical engineering, explicitly in the development of landfill liners. The result of this study will offer guidance to engineers and researchers to work on sustainable practises with the focus on waste utilization and cost effective approach on the development of landfill liner material.

Keywords: Permeability, Electrolyte, Sand, Marble dust, Flyash, Bentonite

INTRODUCTION

The global surge in municipal solid waste (MSW) generation, projected to ascend from 2.01 billion tons in 2016 to an expected 3.4 billion tons every year by 2050, pressing environmental challenge [1]. Urbanization, population growth, and improved living standards contribute to this increase, highlighting the need for urgent attention to MSW disposal [2]. With landfilling comprising roughly 95% of worldwide MSW the executives, its monetary feasibility and straightforwardness make it a dominating technique [3]. The management of solid waste become highly crucial because of the expansion of industrial and commercial sectors expand. Hence, it is important to understand for providingsecure landfill practices for sustainable waste management and environmental preservation [4].

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Most of the developed nation currently utilizing as Landfilling one of the preferred and cost-effective disposal method for managing municipal solid waste [5, 6]. In this context, the pivotal role of clay liners in landfill systems is more significant, because of their high containment adsorption capacity and low hydraulic conductivity, they are important because they prevent leachate from entering groundwater [7]. Generally, expansive clays meet the EPA standard for liner materials by exhibiting hydraulic conductivity of $\leq 10^{-7}$ cm/s and shear strength surpassing 200 kPa [8]. This double ability fulfills material prerequisites as well as actually abridges the movement of leachate, accentuating the essential role of clay liners in ensuring the environmental integrity of landfill systems [9, 10].

In a variety of geotechnical applications, marble dust (MD), a byproduct of the marble industry, has demonstrated its value as a valuable geomaterial [11]. Past examinations have investigated the positive effect of MD on improving geotechnical properties in both sandy and expansive clayey soils [12, 13]. Notably, Jain et al. [14] examined that the behavior of marble dust and sand, when amended with bentonite for development of liner material exhibited remarkable similarities considering the geotechnical properties. Additionally, flyash majorly obtained from thermal power plant is imperative to acknowledge because of its notable geotechnical significance [15]. Incorporating fly ash into the assessment extends the scope of our research, aiming to discern its impact alongside marble dust in conjunction with bentonite under conditions reflective of aggressive leachate environments [16]. This study aims to learn more about MD, Flyash, and sand behave when individually amended with bentonite, particularly under aggressive leachate conditions. This thorough investigation expands upon past discoveries as well as advances how might interpret the synergistic impacts of marble dust, sand, and fly ash when amended with bentonite. Such evaluation are important for developing novel and environmentally conscious geotechnical solutions, specially in the context of sustainable waste management and landfill liner design.

Landfill liners get through a range of testing physicochemical and natural powers, influencing the durability of liner materials [17, 18]. Thus, evaluating the chemical compatibility of these materials with varying electrolyte concentrations becomes crucial [18, 19, 20, 21). Various examinations have dug into the viability of bentonite, either in confinement or amended with sand, marble dust and fly ash, when exposed to permeate solution. Various studies, such as Olson and Mesri [22] and Mesri and Olson [23] have contributed significantly on the effect of salt solution on the landfill liner material. Notably, Shirazi et al. [24] and Dutta and Mishra [25] reported, reduction in liquid limit and swelling for bentonites by increasing the salt concentration. Xue et al. [26] extended this exploration to geosynthetic clay liner (GCL) materials, revealing higher hydraulic conductivity values with $CaCl_2$ permeant, followed by $MgCl_2$, KCl, and NaCl permeants. Furthermore, Dutta and Mishra [25] delved into the consolidation properties of bentonites under saturating fluids (NaCl and $CaCl_2$) and a increasing trend in the C_v value is observed. In their comprehensive investigation, Jadda and Bag [19] scrutinized two distinct types of bentonites—monovalent and divalent—within a salt environment. Their findings unveiled a substantial impact on hydraulic conductivity values, revealing a remarkable increase of approximately 76 times for monovalent bentonite in the presence of 1N NaCl electrolyte solution and a corresponding 41-fold increase for 1N $CaCl_2$ electrolyte solution, compared to the baseline values obtained with distilled water [27]. Mulyukov's [28] reported that at aconcentration of 0.1N NaOH, a notable swell in clayey soil could be induced. Despite this significant observation, limited research has delved into the effects of lower concentrations, specifically 0.5 and 1 N, of NaOH on the behavior of liner materials. Such studies suggest that these concentrations decreased the permeability of the landfill liner material, however, very less attempts has been made on the impact of higher concentration of NaOH on the landfill liner material. Similar to salt (NaCl and $CaCl_2$ etc.) and Alkaline (NaOH etc.) concentration, the impact of acidic (HCL) concentration alter the permeability and structural integrity of the landfill liner which impact its long term performance [29]. Previous studies reported that HCL concentration changes the mechanical properties of the liner, impacting their stability and overall performance. Nevertheless, the impact of higher concentrations of $CaCl_2$, NaOH, and HCl on the behavior of liner materials remains unexplored, specially in the context of flyash and marble dust with addition to bentonite for landfill liner. Additionally, there is a notable gap in the published literature concerning the performance assessment of bentonite-marble dust and bentonite-flyash when exposed to various permeate or electrolyte solutions, encompassing low to high concentrations. This research aims to address this gap and assess the viability of bentonite-marble dustand bentonite-flyashblends as an innovative and environmentally friendly liner material for landfill systems.

The present investigation aims to assess the performance of bentonite-marble dust and bentonite-flyash landfill liner as an alternative of bentonite-sand liner subjected to permeate solution (i.e. $CaCl_2$, NaOH and HCl from 1N-2N concentration) to find the optimized mixtures for a landfill liner. The performance of B-MD, B-FA in comparison to B-S mixes on permeate solutions are examined based on the pH, electrical conductivity, compaction characteristics and permeability. The study most focus on to find the sustainable, Cost effective and utilization of waste material as an alternative of sand with bentonite for development of landfill liner.

MATERIAL AND METHODOLOGY

Material

In the present study following materials have been collected and used for the investigation, Shown in Table 1:

Table 1. Materials used in the study and their source.

S.N.	Material	Collected from
1	Bentonite	Bikaner District, Rajasthan
2	Sand	Jagatpura, Near Poornima University, Jaipur, Rajasthan
3	Marble dust	Kishangarh Dist. Ajmer, Rajasthan
4	Fly ash	Kota, Rajasthan
5.	$CaCl_2$, NaOH, HCl	Commercially

Methodology Followed

In the present study different methods are used for analysis of geotechnical properties of materials are presented in Table 2.

Table 2. Geotechnical properties of materials (Sand, Marble Dust, Fly Ash and Bentonite).

Description	Sand	Marble Dust	Bentonite	Flyash	IS-CODE
Sand (4.75-0.075 mm), %	98.00	95.50	6.00	93.50	[30]
Silt (0.075-0.002 mm),%	2.00	4.50	14.00	6.50	[30]
Clay (< 0.002 mm),%	-	-	80.00	-	[30]
Soil Classification as ISC and USCS	SP (Poorly graded sand)	Poorly graded	Clay with high plasticity		
Max. Dry Density (MDD), gm/cc	1.52	1.74	1.14	1.49	[31]
Optimum Water Content (OWC),%	14.76	16.00	48.00	23.12	
pH value	8.35	8.54	7.97	8.81	[32]
EC value (ms/cm)	0.13	0.088	0.281	0.07	
Permeability (cm/s)	0.0045	0.0038	0.004	2.00E-11	[33]

Table 3. Electrolytic concentrations at various normality.

Electrolyte	Molecular Weight	1N	1.5N	2N
	(in gm)	*(in gm per litre)*		
$CaCl_2$	110.98	58.5	166.47	221
NaOH	40	40	60	80
HCl	36.5	36.5	54.75	73

Permeate Solution

In this investigation, we utilized laboratory-prepared permeate solutions consisting of $CaCl_2$, NaOH, and HCl dissolved in distilled water at varying concentrations. The solutions were meticulously prepared, ensuring a molar solution ratio of 1 L to 1 mol of solute for accurate and controlled experimentation, Shown in Table 3.

RESULT AND DISCUSSION

Physicochemical Analysis of B-S, B-MD, B-FA Mixes

The experimental investigation of pH variations in composite materials involving marble dust (MD), sand (S), and fly ash (FA) with different proportions of added bentonite presents valuable insights, particularly for landfill liner applications, reported in Figure 1.

It is observed that the pH values gradually increase at lower percentage of bentonite (0-15%), indicating potential enhancement in the alkalinity. Further Beyond 15% addition of bentonite a substantial rise in pH value is observed. In the context of development of landfill liner, where pH stability is important to prevent leachate contamination, these findings underscore the importance of carefully optimizing bentonite content for achieving desired alkaline conditions and enhancing the overall effectiveness of the liner materials [34].

Electrical Conductivity (EC) of marble dust (MD), sand (S), and fly ash (FA) with varying proportions of added bentonite provides crucial insights, particularly in the context of landfill liner applications, results are depicted in Figure 1. With increasing bentonite content, the EC values exhibit distinct trends. The EC values exhibit a gradual rise at lower concentrations of bentonite (0-15%), reported a potential increase in the electrical conductivity of the composite mixtures. Further addition of 15% of bentonite content, a more pronounced escalation on EC is observed, highlighting the influence of bentonite content on the electrical properties of the materials [35].

Compaction Characterstics Analysis of B-S, B-MD and B-FA Mixes

Maximum Dry Density (MDD) and Optimum Moisture Content (OWC) of marble dust (MD), sand (S), and fly ash (FA) with addition of bentonite content provides essential insights into the potential application of these mixtures in landfill liners, as illustrated in Figure 2.

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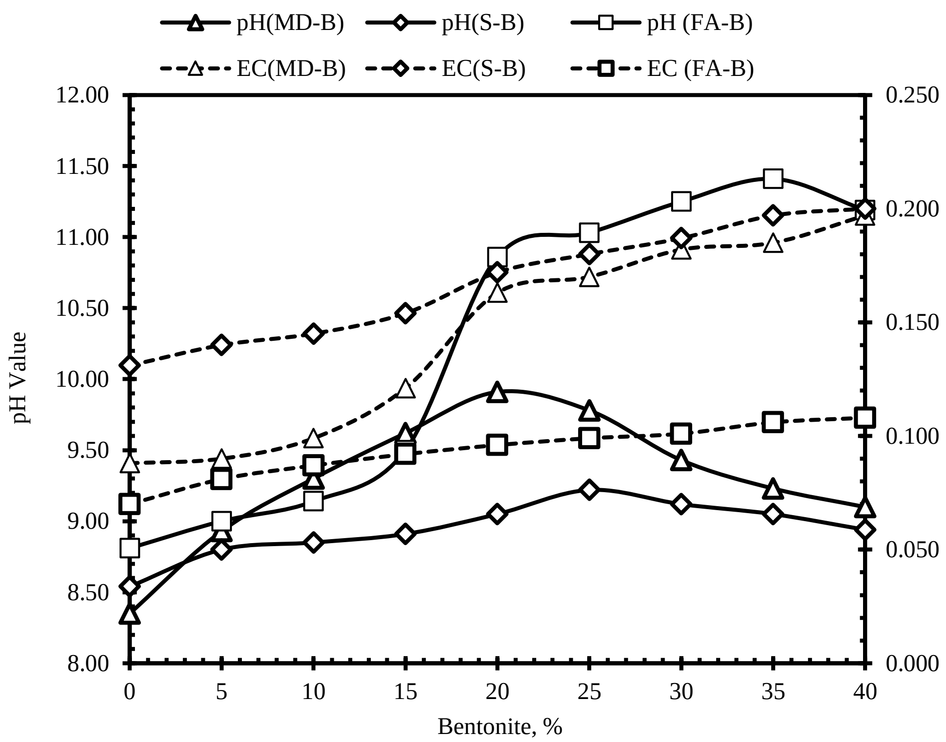

Figure 1. pH and EC value of B-S, B-MD and B-FA mixes.

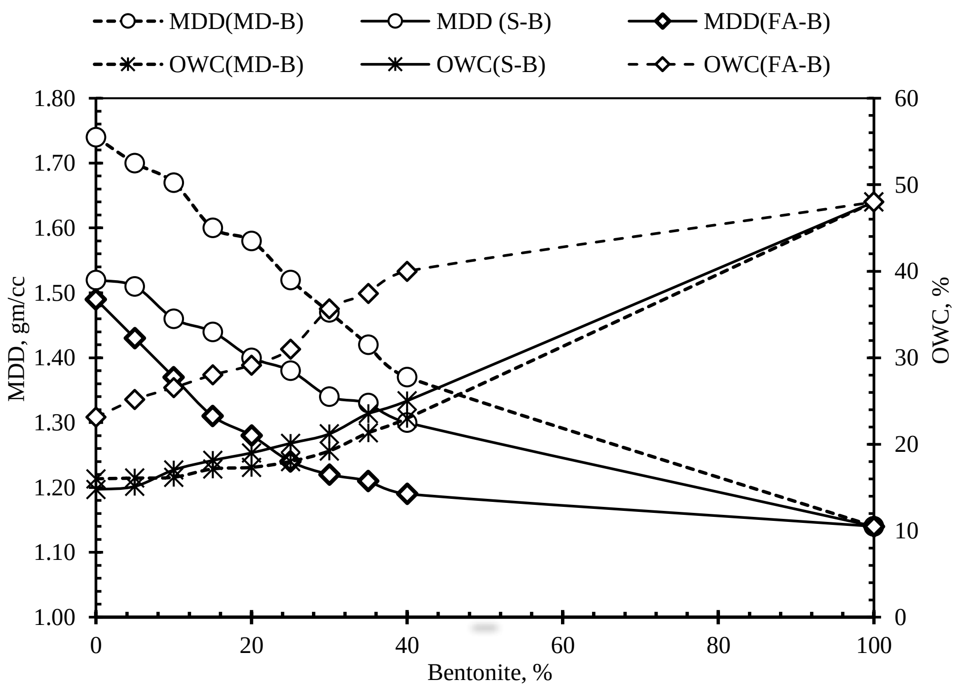

Figure 2. Compaction characteristics of B-S, B-MD and B-FA mixes

It is evident from the trend of MDD that the addition of bentonite led to a consistent reduction in density of MD-B, S-B, and FA-B. This reduction in MDD can be attributed (i) expansive nature of bentonite, (ii) volumetric increase of mixture [36] and (iii) lower dry density of bentonite. Additionally, the optimum water content (OWC) exhibits a declining trend with increasing bentonite content, which suggests the addition of bentonite enhances the moisture resistance of the three mixtures [37].

Further, the decrease in MDD could influence the structural stability of the liner, which require careful consideration of compaction to achieve the required density. Simultaneously, the reduction in OWC indicates the improved resistance to moisture, for preventing leachate infiltration and for ensuring the liners long-term performance [38].

Permeability of B-S, B-MD and B-FA Mixes Without Electrolyte Concentration

Permeability of marble dust (MD), sand (S), and fly ash (FA) with addition of varying percentage of bentonite, is pivotal for evaluating their suitability as landfill liners, is presented in Figure 3. The liner's resistance to fluid flow, particularly leachate, and its ability to prevent environmental contamination are directly influenced by permeability, an important parameter [39]. The obtained permeability values, expressed in terms of the coefficient of permeability (k), reveal the impact of bentonite content on the hydraulic conductivity of the mixtures.

At the baseline (0% bentonite), the permeability values for MD-B, S-B, and FA-B are 3.80E-03, 4.50E-03, and 4.00E-03, respectively. As the bentonite content increases, a notable reduction in permeability is observed across all mixtures. At 40% bentonite, the permeability values for MD-B, S-B, and FA-B decrease to 9.75E-08, 8.10E-08, and 1.23E-07, respectively. The reduction in permeability is particularly significant, indicating enhanced resistance to fluid flow [40].

In the context of landfill liner design, regulatory bodies such as the Environmental Protection Agency (EPA) set stringent standards for permeability i.e. $1x10^{-7}$ cm/s to ensure effective waste containment. The EPA mandates that landfill liners must exhibit low permeability to prevent the migration of contaminants into the surrounding environment [41]. The obtained permeability values, especially at 40% bentonite percentages, align with the EPA's minimum permeability requirements for landfill liners.

The results suggest the efficacy of bentonite as an additive in reducing permeability, making the B-MD and B-FA well-suited for landfill applications as an alternative to B-S. The possibility of meeting or even exceeding the EPA's minimum permeability requirements is suggested by the decrease in permeability, particularly at 40% bentonite [42]. The impermeability accomplished with higher bentonite content improves the materials' capacity to act as a viable barrier against leachate migration [43].

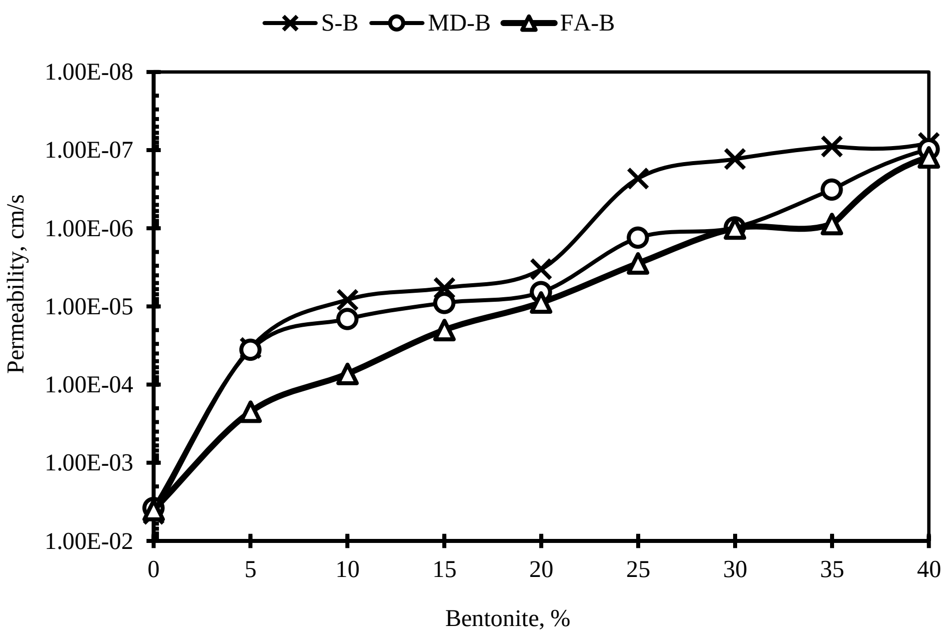

Figure 3. Permeability of B-S, B-MD and B-FA mixes.

A promising or similar trend is obtained on the comparison of permeability reduction in landfill liner materials, incorporating marble dust (MD) and fly ash (FA) as alternatives to sand with added bentonite. Hence, these findings highlights the potential versatility of MD and FA in the development of landfill liner, providing environmentally sustainable and cost effective solutions for achieving reduced permeability and enhanced containment of waste. These result contribute to the development of novel environmentally and sustainable landfill liners, aligning with the EPA's permeability requirements and suggesting the importance of thoughtful material design in landfill liner.

Permeability of B-S,B-MD and B-FA Mixes With Electrolyte Concentration

The permeability performance of B-S (bentonite-sand), B-MD (bentonite-marble dust), and B-FA (bentonite-fly ash), under varying electrolyte concentrations of NaCl, NaOH, and HCl are presented in Figures 4, 5 and 6 respectively. This investigation is important for understanding the role of these mixtures under field condition of salt, alkaline and acidic environment [44]. The findings will help improve the designs of landfill liner systems, ensuring their effectiveness in a different environmental conditions and improving their waste containment performance. Following are the experimental evaluation of different mixtures under varying electrolyte concentration:

Salt Concentration

The permeability of landfill liners comprising sand (S), marble dust (MD), and fly ash (FA) mixed with bentonite (B) under varying $CaCl_2$ concentrations, as shown in Figure 4. The increase in permeability with rising $CaCl_2$ concentration can be attributed to several factors: [i] presence of $CaCl_2$ influences the pore structure, [ii] saline solution interacts and potentially altering the arrangement of particles [45], [iii] alteration facilitates the movement of water through the liner matrix, resulting in higher permeability.

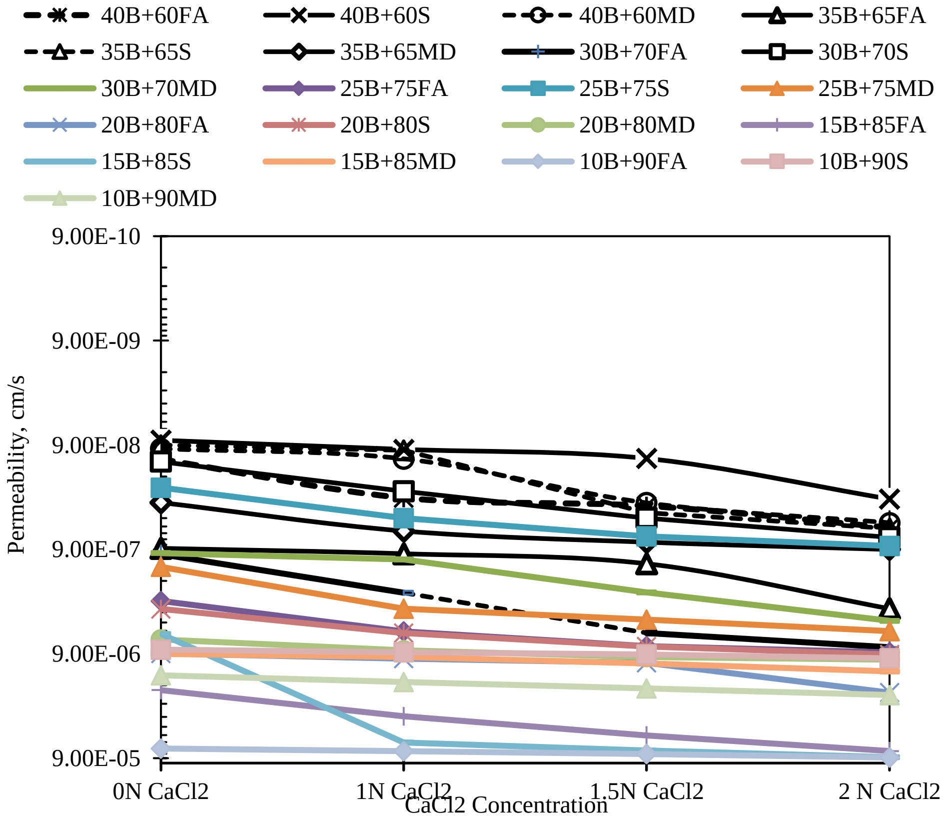

Figure 4. Permeability of B-S, B-MD and B-FA mixes subjected to $CaCl_2$ concentration.

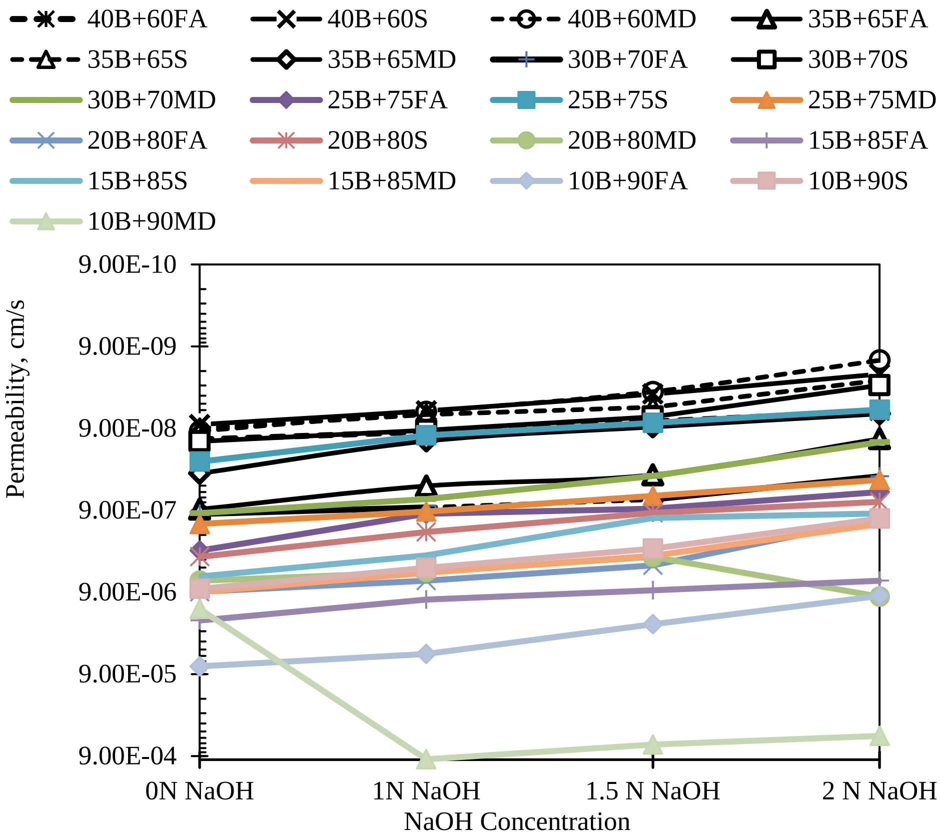

Figure 5. Permeability of B-S, B-MD and B-FA mixes subjected to NaOH concentration.

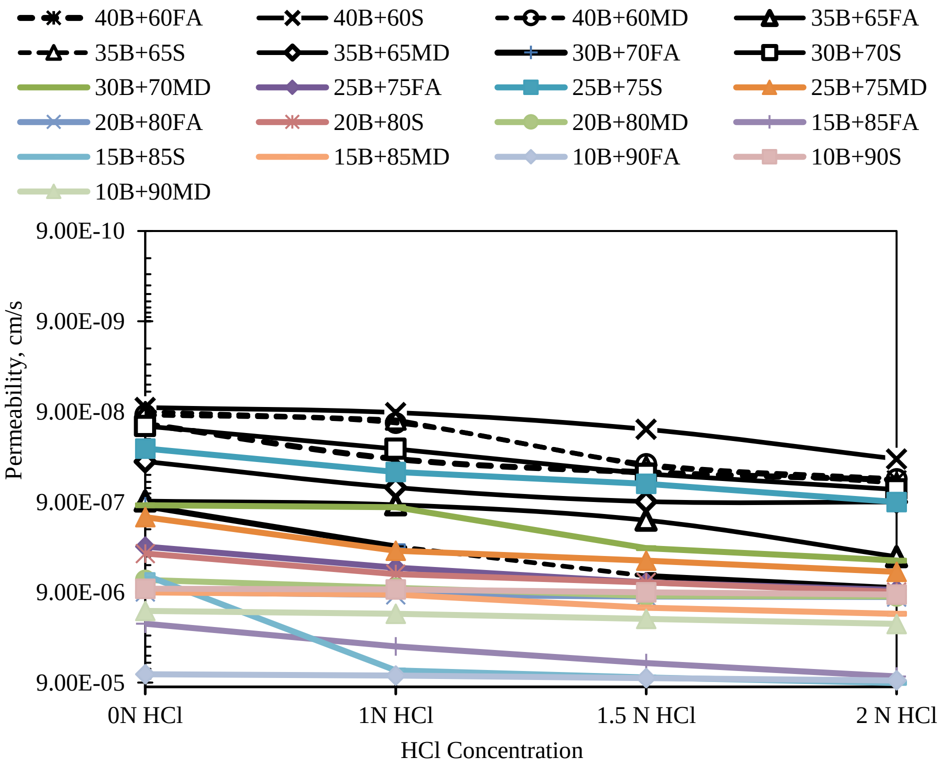

Figure 6. Permeability of B-S, B-MD and B-FA mixes subjected to HCl concentration.

In the case of mix 40B+60S, 40B+60MD, and 35B+65S, the permeability values increaseswith low

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to high concentrations of $CaCl_2$. This negative consequence of this increased permeability, especially in the presence of sand, marble dust, and fly ash, is a compromised ability of the landfill liner to effectively contain and isolate waste contaminants. This could lead to the leaching of harmful substances into the surrounding soil and groundwater, posing environmental risks [46]. Variations in leachate composition are common at field condition where these findings emphasize the need for liner design considering the potential for high $CaCl_2$ concentrations. Geotechnical Engineers and environmental scientists must weigh the trade-offs between the cost-effectiveness of using certain materials and their performance under specific leachate conditions to ensure the long-term efficacy of landfill liners in preventing environmental contamination.

Alkaline Concentration

The permeability of landfill liners comprising sand (S), marble dust (MD), and fly ash (FA) mixed with bentonite (B) under varying NaOH concentrations, as shown in Figure 5.

The reduction in permeability is observed by increasing NaOH concentration that attributed due to various factors: (i) NaOH acts as a pore fluid modifier which alters the physicochemical properties of mixtures [47] (ii) Alkaline nature of NaOH promotes flocculation and particle agglomeration which leads to a denser and more compact mixture. This increased density impedes the movement of water molecules through the liner matrix, resulting in lower permeability values. This reduction in permeability is fruitful for landfill liners, as it improve their ability to effectively contain leachate and reduce the migration of contaminants into the surrounding environment. In field conditions, where leachate composition can vary, hence the obtained resultindicate the importance of considering NaOH concentration in liner design.

Acidic Concentration

The permeability of landfill liners comprising sand (S), marble dust (MD), and fly ash (FA) mixed with bentonite (B) under varying HCL concentrations, as shown in Figure 6.

The observed increase in the permeability of the mixtures with rising HCl concentration can be attributed to various factors: (i) Dissolution of Hydrochloric acid (HCl) with the mixtures which weaken the liner materials [48], (ii) Disruption of the cohesive forces between particles [49]. The increased permeability of the mixtures poses a potential risk of groundwater contamination and environmental harm, undermining the protective function of the landfill liner [50].In field conditions, considering HCl concentration in landfill liner design, engineers and environmental practitioners must take precautions to select liner materials and compositions that resist the adverse effects of acidic conditions, ensuring the long-term integrity and performance of landfill containment systems [17].

CONCLUSION

In the present study the experimental evaluation of B-S, B-MD and B-FA on pH, EC, Compaction Characteristics and Permeability is examined. Based on this, following are the specific conclusions drawn from the present study:

1. This study emphasizes the critical role of precise bentonite optimization, particularly in the 15% to 40% range with sand, marble dust and fly ash, for evaluation of pH and electrical conductivity.
2. The experimental analysis reveals that the incorporation of bentonite in composite materials for landfill liners results in a consistent reduction in Maximum Dry Density (MDD), impacting structural stability. Simultaneously, the declining trend in Optimum Moisture Content (OWC) signifies improved moisture resistance.
3. The permeability of sand, marble dust and flyash get decreased with addition of bentonite content and continuously decreasing by increasing the bentonite content.
4. The permeability results indicate a clear influence of electrolyte concentration ($CaCl_2$, HCl, NaOH) on the effectiveness of landfill liner materials, namely B-S (bentonite with sand), B-MD (bentonite with marble dust), and B-FA (bentonite with fly ash). Under increasing $CaCl_2$ concentrations, a notable rise in permeability is observed, suggesting a compromised performance in preventing leachate migration. Conversely, with the introduction of HCl and

NaOH, the permeability tends to increase and decrease, respectively, emphasizing the sensitivity of these materials to specific electrolytes.

Conflict of Interest

- The authors declare that they have no conflict of interest.
- Data Availability Statement
- My Manuscript has no associated data.

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