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Integration of Gum Arabic in to Geotechnical Materials for Permeability Improvement

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Abstract: **Soil stabilization using eco-friendly materials is gaining attention due to sustainability concerns in geotechnical engineering. This study evaluates the impact of Gum Arabic on the permeability of two subgrade soil samples: greyish sandy gravelly soil (Sample A) and brownish fine-grained clayey soil (Sample B). Laboratory tests were conducted on untreated and treated samples with Gum Arabic dosages ranging from 0.2% to 1.0%. The results indicate a significant reduction in permeability, particularly in Sample A, which exhibited a sharp decline from 8.707 cm/s to 1.369 cm/s at 1.0% dosage. Sample B, with lower initial permeability (2.309 cm/s), showed a more gradual reduction to 1.576 cm/s. The optimal dosage for permeability reduction was determined to be 0.7%, beyond which further improvements were negligible. The findings demonstrate the potential of Gum Arabic as a natural stabilizer for enhancing soil impermeability, making it a viable alternative for subgrade improvement in construction and infrastructure projects.**

***Keywords*: Gum Arabic; Permeability; Soil Stabilization**

INTRODUCTION

In geotechnical engineering, the permeability of soil is a critical factor influencing the stability and durability of civil infrastructure (Vordoagu, 2025). The integrity and durability of civil engineering structures, particularly road pavements, are fundamentally dependent on the properties of the underlying soil, known as the subgrade (Ashioba and Udom, 2023; Verma et al., 2021). The foundation of every civil engineering structure is the soil or the earth (Vordoagu, 2025). A critical parameter influencing subgrade performance is soil permeability, which dictates the movement of water within the soil matrix. Permeability can affect the strength of the foundation by affecting the groundwater flow. An increase in pore water pressure due to reduced permeability could reduce the soil strength (Verma et al., 2021). High permeability can lead to excessive water infiltration, resulting in soil erosion, reduced strength, and compromised structural integrity, compromising the structural stability of pavements, while low permeability may result in poor drainage and water accumulation, adversely affecting structural integrity, leading to structural failures (Firoozi and Firoozi, 2024; Paradelo et al., 2024; Sukur, et al., 2023). Expansive clays, prevalent in many areas, pose significant challenges due to their high shrink-swell potential, which can lead to substantial structural damage if not properly managed (Alsabhan and Hamid, 2025; Karki and Kolay, 2024; Zhao et al., 2024). Low permeability can cause poor drainage, leading to water accumulation and associated issues. Improved permeability can facilitate better water movement, reducing pore water pressure and the likelihood of soil liquefaction under loading conditions. Conversely, excessive permeability may lead to rapid water ingress, undermining soil strength (Firoozi and Firoozi, 2024). Therefore, achieving an optimal balance in soil permeability is essential for the longevity and functionality of infrastructure.

Traditional soil stabilization methods often involve chemical additives like cement or lime to modify soil properties, including permeability (Verma et. al., 2021; Archibong, et. al., 2020; Huang, et. al., 2021). However, these methods can be costly and have environmental drawbacks, prompting the search for sustainable alternatives (Gunarathne, et, al., 2020; Verma, et. al., 2021; Tracy and Novak, 2023; Belaïd, 2022; Mohamad, et. al., 2022; Khaiyum, et. al., 2023). Moreover, the use of synthetic polymers, which are non-biodegradable, raises concerns about long-term soil and groundwater contamination (Bodor, et. al., 2024; Wanner, 2021). These polymers can persist in the environment for extended periods, leading to microplastic pollution and potential harm to ecosystems (Ali, et. al., 2024; Ziani, et. al., 2023). Additionally, in regions where these materials are scarce or costly, there is a pressing need for alternative, sustainable solutions. This has led to the exploration of natural polymers like Gum Arabic, a biopolymer derived from Acacia trees, known for its adhesive properties and environmental compatibility (Soldo, et. al., 2020; Fatehi, et. al., 2021; Rimbarngaye, et. al., 2022; Novoskoltseva, et. al., 2022). Gum Arabic, a natural polysaccharide derived from Acacia trees, has been recognized for its potential in soil stabilization (Murtoff, 2024; Rimbarngaye, et. al., 2022; Prasad, et. al., 2022). It is a natural exudate from Acacia trees, has emerged as a promising soil stabilizer due to its biodegradability and availability in arid and semi-arid regions (Amiri et. al., 2021; Tiamiyu, et. al., 2023). It is highly soluble in water, non-toxic, and readily biodegradable, making it an ideal candidate for sustainable soil stabilization (Prasad, et. al., 2022). Gum Arabic has been extensively utilized in various industries, including food, pharmaceuticals, and cosmetics, due to its emulsifying and stabilizing properties (Razavi, et. al., 2021; Tiamiyu, et. al., 2023; Froelich, et. al., 2023; Muruganantham, et. al., 2022). In recent years, its application has extended to geotechnical engineering, where studies have investigated its potential as a soil stabilizer.

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The integration of Gum Arabic into geotechnical materials presents a sustainable alternative to traditional chemical stabilizers. Its natural origin and biodegradability make it an environmentally friendly option for soil stabilization. Its application in soil stabilization has shown potential in enhancing soil properties, including permeability (Rimbarngaye, et. al., 2022). Recent studies have demonstrated that Gum Arabic can enhance soil strength and stability by increasing cohesion and plasticity, leading to improved compaction and load-bearing capacity. Research indicates that Gum Arabic can enhance soil strength and reduce plasticity, making it a promising candidate for soil stabilization efforts. For instance, a study by Ajagbe et al. (2024) demonstrated that incorporating Gum Arabic into subgrade soils improved compaction and increased the California Bearing Ratio (CBR), indicating enhanced soil strength and stability. However, limited studies have specifically addressed its impact on soil permeability, a gap this research aims to fill. However, while the effects of Gum Arabic on soil strength and compaction have been explored, its specific impact on soil permeability requires further investigation. Understanding how Gum Arabic influences permeability is essential for optimizing its application in geotechnical engineering, particularly in regions where conventional materials are scarce or expensive.

The research focuses on evaluating the impact of Gum Arabic on the permeability of subgrade soils. Experimental investigations involved treating soil samples with varying concentrations of Gum Arabic and conducting standard permeability tests to assess changes in hydraulic conductivity. Complementary tests, such as moisture content determination, specific gravity, Atterberg limits, and compaction characteristics, was performed to provide a holistic understanding of the soil's geotechnical properties post-treatment. By evaluating changes in hydraulic conductivity and associated geotechnical properties, the research seeks to determine the efficacy of Gum Arabic as a natural soil stabilizer for permeability improvement.

METHODOLOGY

Soil Sample Collection

This investigation found and chose appropriate geotechnical materials, (sand and clay (laterite)), which are representative of the normal soil compositions seen in civil engineering projects, were among these elements. Panada (7° 38' 09.191" N 4° 11' 40.510" E), in the Iwo local government of Osun state, and Ebebi (7° 47' 14.402" N 4° 28'25.075" E), in the Egbedore Local Government area, were the two places from which the items were obtained. Prior to treatment, these soils' baseline characteristics were established by characterization. To avoid contamination and moisture loss, the soil samples were collected as disturbed soil samples, securely packed in airtight containers, and then delivered to the lab.

Gum Arabic Preparation

To guarantee its quality and purity, gum Arabic was purchased from reliable vendors. Then, to make a homogenous solution, the Arabic gum was dissolved in water. Gum Arabic was incorporated into the geotechnical materials using this solution, and the concentration was meticulously regulated to guarantee consistent outcomes at various dosages.

Figure 1: Sample of Gum Arabic`

Sample Preparation

To evaluate its effect on consolidation qualities, gum Arabic was combined in different amounts with the chosen geotechnical materials. The Gum Arabic solution and the soil samples were thoroughly homogenized by the mixing process. Following treatment, the samples underwent a battery of mechanical and consolidation tests. To produce stabilized specimens, several amounts of Gum Arabic (0%, 0.2%, 0.4%, 0.7%, 0.8%, and 1% by weight of dry soil) were combined with the soil.

Laboratory Testing

Preliminary tests were carried out on the soil samples to determine the initial characterization of the soil. These tests include moisture content analysis, specific gravity test, plastic limit test, liquid limit test, sieve analysis and compaction. Permeability test was the carried out on the treated and untreated soil samples to determine the effect of dosages on the permeability of the soil

Moisture Content: The moisture content of soil is determined by measuring the loss of weight upon drying a soil sample to a constant weight. The procedure involves weighing a representative soil sample, drying it in an oven at 110 ± 5°C, and reweighing it to calculate the moisture content as a percentage of the dry soil weight. A representative soil sample was collected and immediately placed into a pre-weighed moisture content container. The combined mass of the container and the moist soil was recorded. The container with the moist soil was placed in an oven maintained at 110 ± 5°C and dried for a minimum of 24 hours to ensure complete removal of moisture. After drying, the container was removed from the oven, allowed to cool to room temperature in a desiccator to prevent moisture absorption, and then weighed to determine the mass of the dry soil. The moisture content was then calculated.

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Specific Gravity: Specific gravity is the ratio of the mass of soil solids to the mass of an equal volume of water. The test involves using a water pycnometer to determine the specific gravity of soil particles passing the 4.75-mm (No. 4) sieve. Approximately 50 grams of oven-dried soil passing the No. 4 sieve was obtained. A clean, dry pycnometer was weighed, and its volume was determined by filling it with de-aired, distilled water and recording the mass. The soil sample was placed into the pycnometer, and de-aired, distilled water was added to submerge the soil. A vacuum was applied to remove entrapped air, ensuring full saturation. After temperature equilibration, the pycnometer was filled to its calibrated volume with distilled water, and the total mass was recorded. Then the specific gravity (Gs) was calculated.

Atterberg Limits: The Atterberg limits define the moisture content at which soil transitions between different states of consistency.

i. Liquid Limit

This is the water content at which soil changes from a plastic to a liquid state. The test involves placing soil in a standard cup, cutting a groove, and counting the number of blows required to close the groove over a specified distance. A portion of air-dried soil passing the No. 40 sieve was mixed with distilled water to form a uniform paste. The liquid limit device was inspected to ensure proper functioning, and the drop height of the cup was verified to be 10 mm. The soil paste was placed into the cup of the liquid limit device and leveled. A groove was formed using the standard grooving tool. The cup was repeatedly dropped at a rate of two drops per second until the groove closed over a length of 13 mm. The number of drops required was recorded. The procedure was repeated for at least three additional trials with varying moisture contents to obtain a range of data points. A flow curve was plotted on semi-logarithmic paper, with the number of drops on the logarithmic scale and moisture content on the arithmetic scale. The liquid limit was determined as the moisture content corresponding to 25 drops.

ii. Plastic Limit

This is the water content at which soil begins to exhibit plastic behavior. The test involves rolling soil threads until they crumble at a diameter of 3.2 mm (1/8 inch). A 20-gram sample of soil passing the No. 40 sieve was mixed with distilled water until it became plastic enough to be easily shaped into a ball. A portion of the soil was rolled into a 3 mm diameter thread on a glass plate. If the thread crumbled before reaching 3 mm, the moisture content was determined. The process was repeated until two consecutive moisture content determinations agreed within 0.5%. The plastic limit was taken as the average moisture content at which the soil could just be rolled into threads of 3 mm diameter without crumbling.

Compaction: The compaction test determines the relationship between the moisture content and dry density of soil for a specified compaction energy. The Modified Proctor Test (ASTM D1557) involves compacting soil into a mold using a 4.54 kg (10 lb) hammer dropped from a height of 457 mm (18 inches) in five layers, each receiving 25 blows. The resulting data is used to establish the soil's maximum dry density and optimum moisture content. Approximately 3 kg of air-dried soil passing the No. 4 sieve was mixed with varying amounts of water to prepare samples at different moisture contents. Each soil sample was placed in a standard Proctor mold in three equal layers. Each layer was compacted by dropping a 5.5 lb (2.5 kg) rammer from a height of 12 inches (305 mm) for 25 blows per layer. After compaction, the mass of the mold with the compacted soil was recorded. A sample was taken to determine its moisture content using the procedure described earlier. The process was repeated for additional samples with different moisture contents to establish a range of data points. The dry unit weight was calculated for each sample, and a compaction curve was plotted with moisture content on the x-axis and dry unit weight on the y-axis. The optimum moisture content and maximum dry unit weight were determined from this curve.

Permeability Test: Permeability, or hydraulic conductivity, measures the ease with which water can flow through soil. The Constant Head Test is suitable for coarse-grained soils, while the Falling Head Test is used for fine-grained soils. These tests determine the rate at which water flows through a soil sample under a constant or variable head, respectively. A representative sample of granular soil was selected, ensuring it contained no more than 10% of particles passing the 75-µm (No. 200) sieve, as specified by ASTM D2434. The soil was oven-dried and then compacted into a permeameter mold, maintaining a consistent density to simulate field conditions. The permeameter was assembled with a porous disk or suitable reinforced screen at the bottom to support the soil specimen and prevent particle migration. Manometer outlets were connected to measure the hydraulic head loss over a specified length of the soil sample. De-aired, distilled water was introduced from the bottom upward to saturate the soil specimen, minimizing air entrapment. A constant head reservoir was connected to maintain a steady water level above the soil sample, ensuring a constant hydraulic gradient during testing. Once steady-state flow was established, the quantity of water discharged through the soil specimen was measured over a recorded time interval. The temperature of the effluent water was also recorded to account for viscosity variations. The coefficient of permeability (k) was then calculated.

Table 1: Tests and their respective standards

S/N	Tests	Standards
1.	Moisture Content	ASTM D2216
2.	Specific Gravity	ASTM D854
3.	Atterberg Limit Tests	ASTM D4318.
4.	Compaction Test	ASTM D1557
5.	Sieve Analysis	ASTM D6913
6.	Hydrometer Analysis	ASTM D7928
7.	Permeability Test	ASTM D2434

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RESULTS AND DISCUSSION

Initial Soil Characterization

For the geotechnical characteristics of Samples A and B, the preliminary characterization tests listed in Table 2 offer significant baseline information. These results lay the basis for assessing how they might behave in various engineering scenarios and if stabilization methods are appropriate. A notable discrepancy was found in the samples' average moisture content: Sample A had a low moisture content of 3.80%, suggesting comparatively dry circumstances and little water retention. Sample B, on the other hand, had a much greater average moisture content (19.93%), indicating a considerable capacity for water retention. The consolidation behavior of the samples under applied loading may be considerably impacted by this variance. Measurements of specific gravity showed that Sample A recorded 2.60 and Sample B slightly lower at 2.57%, which are normal values for inorganic soils. These findings imply that the mineralogical compositions of the two samples are comparable, with small variations that might be explained by variations in the proportions of fine and coarse particles. The consistency and behavior of the soil were demonstrated by the Atterberg limits. The plastic limit (PL) was measured at 34.08 and the liquid limit (LL) at 62.00% for Sample B. According to the classification results, Sample B was further classified as organic clay and inorganic silt with high compressibility, which is consistent with its strong plasticity and shrinkage properties. These intrinsic characteristics emphasize the necessity of stabilization in order to improve the geotechnical performance of the soil.

Table 2: Initial Characterization Test

S/N	**Parameters**	**Values**	
		Sample A	Sample B
1.	Average Moisture Content (%)	3.80%	19.93%
2.	Average Specific gravity of Soil Sample	2.60	2.57%
3.	Plastic Limit (%)	-	34.08%
5.	Liquid limit (%)	-	62.00%
6.	Plastic Index of Soil Sample (%)	-	27.92%
7.	Liquidity index (%)	-	0.51%
8.	Consistency Index	-	1.51
9.	Linear Shrinkage (%)	-	7.14%
10.	Classification	-	Inorganic silts of high compressibility and organic clay

Compaction Tests

With consequences for their engineering applications, the compaction properties of soil samples A and B, as indicated by their Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), show notable variations in their capacity to reach maximum compaction under particular moisture conditions.

Sample A, as depicted in Figure 2, has an optimal moisture content (OMC) of 12.60% and a maximum dry density (MDD) of 1915 kg/m³. Its dense particle arrangement and preponderance of coarser particles (sand and gravel) are reflected in its comparatively high MDD. According to earlier analyses, the sample's well-graded character allows for improved packing and interlocking, which raises the compaction capacity. The moisture content at which the soil reaches its maximum density with little pore water interference is indicated by the mild OMC. These attributes imply that Sample A is ideal for structural uses where a high load-bearing capacity is essential, such as subgrade or base material for highways and foundations.
In contrast, Sample B, as depicted in Figure 3, has an Optimum Moisture Content (OMC) of 17% and a Maximum Dry Density (MDD) of 1636 kg/m³. The finer particle size distribution and higher silt and clay content, which prevent the soil from achieving a densely packed structure during compaction, are reflected in the lower MDD. The more water needed to lubricate the fine particles for ideal compaction, the higher the OMC. This also emphasizes the soil's heightened vulnerability to moisture-related problems, such swelling or shrinkage, in a variety of environmental settings. For dependable use in building projects, Sample B might need to be stabilized in order to increase its strength and lessen its sensitivity to moisture.

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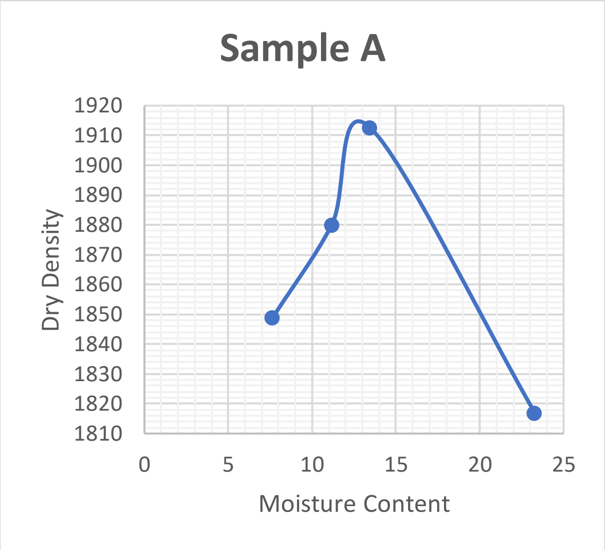

Figure 2: Figure of MDD and OMC for Sample A (PANADA)

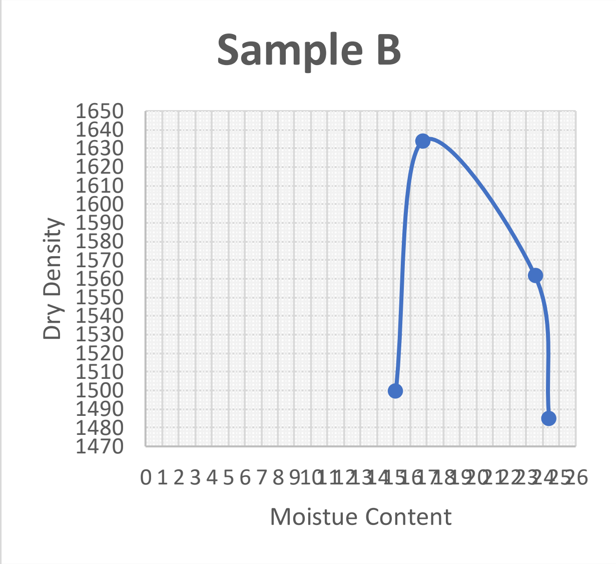

Figure 3: Figure of MDD and OMC for Sample B (EBEDI)

Permeability of Soil Samples

The permeability results for Soil Samples A and B at different treatment dosages, presented in Table 3, illustrate the effect of Gum Arabic stabilization on soil hydraulic conductivity (K). Both samples demonstrate a substantial reduction in permeability with increasing dosages, highlighting the ability of the stabilizer to fill voids and enhance soil sealing.

The untreated permeability of Sample A is 8.707 cm/s**,** reflecting its sandy gravelly nature and coarse-grained structure. The larger particle sizes and high porosity facilitate significant water flow. At a low dosage of 0.2%, permeability reduces sharply to 1.655 cm/s**,** indicating the immediate impact of Gum Arabic on filling void spaces and binding particles. The decline continues steadily, reaching 1.463 cm/s at 0.7%, where stabilization effects are optimized. At higher dosages of 0.8% and 1.0%, permeability stabilizes at 1.369 cm/s**,** showing no further significant improvement. This plateau suggests that Gum Arabic has saturated the void spaces in the soil, achieving maximum sealing capability. Beyond this point, excess stabilizer appears to provide no additional benefit.

The untreated permeability of Sample B is 2.309 cm/s, much lower than Sample A due to its fine-grained clayey composition, which naturally exhibits smaller voids and lower porosity. The introduction of Gum Arabic at 0.2% reduces permeability slightly to 2.125 cm/s**,** with further decreases to 1.784 cm/s at 0.7%. Unlike Sample A, the reduction in Sample B is more gradual, as the finer particles require less treatment to enhance impermeability. Between 0.8% and 1.0%, permeability continues to decrease, with the final value reaching 1.576 cm/s**.** This continued reduction, though minimal, indicates a lesser degree of stabilization saturation compared to Sample A. The remaining differences may be due to Sample B's finer particles interacting more efficiently with Gum Arabic, limiting water flow at moderate doses.

The observed reduction in permeability resulting from Gum Arabic stabilization aligns well with findings from prior investigations, reinforcing its effectiveness as an eco-friendly soil sealing agent. In your study, permeability for the coarse-grained Sample A dropped sharply from 8.707 cm/s to 1.463 cm/s at a 0.7% dosage, and then plateaued at 1.369 cm/s at higher dosages. The finer-grained Sample B exhibited a more gradual reduction, from 2.309 cm/s down to 1.784 cm/s and eventually 1.576 cm/s as dosage increased. These trends are consistent with earlier research on biopolymers, such as Gum Arabic, which similarly demonstrated marked declines in hydraulic conductivity due to pore-filling and particle binding. For example, Sujatha and O'Kelly (2023) reported that a 2% gellan gum additive reduced soil permeability by a factor of 10^5, an enormous decline validating the efficacy of polysaccharide-based treatments. Likewise, changes in water retention and permeability noted in biopolymer-treated soils confirm that such additives, through forming hydrogels or films, significantly enhance soil impermeability (Zhang and Liu, 2023; Deylaghian *et al.*, 2024). Though studies involving xanthan and guar gums likewise document permeability decreases and enhanced soil stability at low concentrations (Deylaghian *et al.*, 2024), this study quantifies this effect using Gum Arabic across both granular and cohesive soil types. The convergence of permeability values around 1.4–1.6 cm/s for both soil types at 0.7% dosage shows a practical threshold where void spaces become sufficiently sealed.

Sample A initially exhibits much higher permeability than Sample B due to its coarser texture and increased void spaces. However, with stabilization, the permeability values of both soils converge to comparable levels, with Sample A achieving 1.369 cm/s and Sample B reaching 1.576 cm/s at 1.0%. The rate of decline is steeper for Sample A, reflecting its greater initial permeability and sensitivity to the stabilization process. Gum Arabic was highly effective in reducing the permeability of both coarse-grained and fine-grained soils, significantly limiting water movement through the soil matrix. While both samples exhibit improved impermeability, Sample A shows a more dramatic reduction due to its initially higher void content. Sample B, with naturally lower permeability, demonstrates consistent but less pronounced declines. The optimal dosage for achieving substantial reductions in permeability while maintaining cost efficiency is 0.7% for both soil types.

Table 3: Permeability of Soil Samples at different treatment dosage

Treatment Dosage	Permeability K (cm/s)	
	Sample A	**Sample B**
0%	8.707	2.309
0.2%	1.655	2.125
0.4%	1.562	1.950
0.7%	1.463	1.784
0.8%	1.369	1.678
1.0%	1.369	1.576

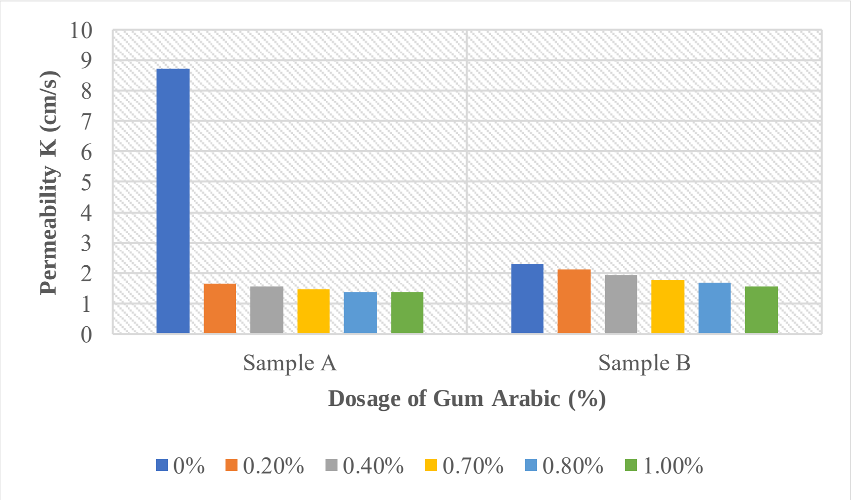

Figure 4: Permeability of Soil Samples

CONCLUSION

In this study, the effects of Gum Arabic doses on the consolidation characteristics of brownish fine-grained clayey soil (Sample B) and greyish sandy gravelly soil (Sample A) were assessed. Permeability was significantly reduced, particularly at lower dosages, with a minimum achieved at 0.7% for both soils, highlighting improved soil sealing properties. Gum Arabic effectively reduced the permeability of the soil, making it a suitable natural stabilizer for civil engineering applications. The optimal dosage was identified as **0.7%,** where both demonstrated peak performance and higher dosages led to decline.

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