Innovations

Performance Evaluation of Stabilized Soils Using Recycled Glass Powder and Polyethylene Terephthalate for Urban Pavement Applications

Temitope Ogundairo,* David Olukanni, Isaac Akinwumi

Department of Civil Engineering, Covenant University, Ota, Ogun State, Nigeria

Corresponding Author: **Temitope Ogundairo**

Abstract

This geotechnical study delves into sustainable soil stabilization methods for urban pavement construction in Ota, Ogun State, Nigeria. It compares conventional cement-based approach with innovative geopolymer-based techniques, employing recycled glass powder, polyethylene terephthalate with alkaline activator (NaOH). The Laboratory experiments assess mechanical and geotechnical properties, including Atterberg Limits, compaction test and permeability tests for the samples (Control, CBS, PBS and PABS). The result of the atterberg limit shows 23, 35, 28, and 29; 46.83, 53.33, 51.69 and 49.09; 23.83, 18.33, 23.69 and 20.09 for the PL, LL and PI of the samples respectively. For the compaction test, PBS and CBS has 15.0% and 13.0% in their Moisture content and 1.722 and 1.790 dry unit weight (Mg/m^3) respectively. For PABS, the 4 samples was prepared with PET+ RGP of 5%, 10%, 15%, and 20%. In the result obtained for PABS, the Moisture content increased as the proportion increases (14.5%-14.8%) leading to a corresponding decrease in the dry unit weight (1.7Mg/m^3 - 1.677Mg/m^3). For the soil permeability test, the geopolymer-based stabilized soil (PABS) shows a low permeability coefficient (2.46x10^{-7} m/s) which according to British Standard BS:1377-5:1990(1998b), for subgrade soils in road pavements, the maximum permeability of 1x10^{-6} m/s or lower is typically recommended to ensure the long-term durability and stability of the pavement structure. A lower permeability helps the soil withstand moisture infiltration and maintain its strength and stability over time. The study highlights the dual benefits—improved soil properties and sustainable waste management. The research focuses on the potential of waste materials in addressing challenges in waste management and enhancing pavement construction practices, contributing to sustainable urban development in regions grappling with these issues.

1. 0 Introduction

Infrastructure development in rapidly growing urban areas demands innovative and sustainable solutions to address both engineering and environmental challenges (Sata and Chindaprasirt, 2020). Ota, situated in Ogun State, Nigeria, is no exception to this paradigm shift. As the demand for robust pavement systems intensifies, there is a crucial need for geotechnical assessments that not only enhance structural performance but also contribute to sustainable practices (Ojuri, 2016). This study embarks on an integrated geotechnical assessment, focusing on soil properties in Ota, to explore novel approaches to pavement construction. In particular, the research delves into the performance of geopolymer-based stabilized soils in comparison to conventional cement-based stabilization, with the potential to transform waste materials into valuable resources.

The choice of soil stabilization methods is pivotal in ensuring the durability and longevity of pavements (Kamaruddin *et al.,* 2017) Traditionally, Portland Limestone Cement (PLC) has been a standard stabilizing agent. However, the environmental implications and the rising concern for sustainable construction practices necessitate a reevaluation of alternative materials (Bilondi *et al.,* 2018). This study introduces a novel approach by employing recycled glass powder (RGP) derived from waste glasses, combined with Polyethylene Terephthalate (PET) and an alkaline activator (NaOH/Sodium Hydroxide), to form a geopolymer-based stabilization (PABS). Such an approach not only aims for engineering efficiency but also aligns with the urgent need for effective waste management practices in regions like Ota, Ogun State, Nigeria.

Beyond its technical contributions, this research holds a significant social and environmental dimension. Nigeria, like many other developing nations, grapples with inadequate waste management infrastructure, leading to environmental degradation (Williams and Serati, 2020). The geopolymer-based stabilization method investigated in this study presents a dual benefit – providing a sustainable solution for pavement construction while simultaneously addressing the challenge of waste management. The outcomes of this research stand to underscore the importance of responsible waste utilization and management in fostering sustainable development in urban areas like Ota.

The geotechnical assessment conducted in this study involves the comparison of three soil conditions: the control, representing the natural clay soil; cement-based stabilization (CBS) using Portland Limestone Cement; and geopolymer-based stabilization (PABS) employing recycled glass powder, polyethylene terephthalate, and an alkaline activator. The performance evaluation of these stabilized soils encompasses a range of geotechnical tests, including permeability, compaction, and Atterberg Limits. Through this comprehensive analysis, the research aims to contribute valuable insights into the engineering properties and sustainable application of these soil stabilization techniques.

Furthermore, the study specifically addresses the context of pavement works, recognizing the critical role of stabilized soils in achieving durable and resilient road infrastructure. Pavements are vital components of urban development, and the choice of stabilization method significantly influences their performance under varying loads and environmental conditions (Singh and Iyer, 2020). By considering the unique conditions of Ota, Nigeria, this research aims to provide context-specific recommendations for pavement design and construction, fostering an approach that aligns with the region's geotechnical and environmental characteristics.

In conclusion, this integrated geotechnical assessment represents a pioneering effort to bridge the gap between conventional practices and sustainable innovations in soil stabilization. The exploration of geopolymer-based stabilization using recycled materials not only expands the horizon of viable construction methods but also advocates for responsible waste management. The findings from this research hold the potential to influence urban development practices, providing a roadmap for sustainable infrastructure development in Ota, Ogun State, Nigeria, and serving as a model for regions facing similar challenges in waste management and pavement construction.

2.0 Materials and Methods

2.1 Soil Samples

The natural clay soil sample used in the study was collected from Arobieye region, Iju Ota, adjacent to River Atuwara, Ogun State, South-western Nigeria (latitude 6°66'041.4 "N and longitude 3°14'511.6 "E), to represent the control condition. The study utilized Portland Limestone Cement (PLC) (Dangote Cement 42.5R) for cement-based stabilization (CBS) as it meets the guidelines of BS EN 197-1 CEM II/A-LL 42.5R standards. The polyethylene terephthalate (Waste Plastic Bottles) was obtained from Covenant University, Ota, Ogun State, Nigeria. The waste plastic bottles were washed, dried and shredded into powder (Recycled Glass Powder), and an alkaline activator for geopolymer-based stabilization (PABS).

2.2 Laboratory Equipment

1. Casagrande cup for Atterberg Limits testing.
2. Permeameter for soil permeability testing.
3. Proctor compaction apparatus for compaction tests.
4. Sieves, Hand trowel
5. Weighing scales and measuring instruments for accurate material quantities.

2.3 Soil Characterization

The soil was prepared and characterized following British Standard BS 1377: Part 1: 1990 guidelines. The soil specimens underwent sieving to achieve the desired particle size distribution, coupled with compaction techniques outlined in British Standard BS 1377: Part 4: 1990.

2.4 Waste Glass Processing

After the collection and cleaning of the waste glass, specifically glass bottles, the glass preconditioning included milling to significantly reduce particle size, resulting in a finely powdered material measuring 75μm. The finely powdered material was subsequently employed as a precursor in synthesising the alkali-activated binder substance. The finely powdered glass material was blended with an alkaline sodium hydroxide solution during the binder production process. The combination of these components initiated a chemical reaction that bound the glass particles, resulting in a robust and stable material that functioned as a binding agent within the soil.

2.5 Stabilization Procedures

For cement-based stabilization (CBS), the soil samples were mixed with the appropriate amount of Portland Limestone Cement (42.5g) and water, following standard procedures. For geopolymer-based stabilization (PABS), the mixture was prepared by incorporating the recycled glass powder, polyethylene terephthalate, and an alkaline activator (NaOH, 2M). The concentration of sodium hydroxide within the solution was calculated using molar values following established laboratory procedures from Green and Southard (2019). The mixing process was further facilitated using a hand towel to ensure even mixing within the pan. Subsequently, the blending procedure lasted 15 minutes, a timeframe aligning with the method reported by Bilondi et al., (2018). The proportions were adjusted based on laboratory trials for optimal stabilization (5%, 10%, 15%, and 20% RGP for the compaction testing). The laboratory trials was conducted to determine the optimal proportions of stabilizing agents for both CBS and PABS by assessing the mechanical properties and stability of the stabilized soils.

2.6 Atterberg Limits Testing

Atterberg Limits testing was performed using the Casagrande apparatus to determine the Liquid Limit and Plastic Limit of the control soil, as well as soils stabilized with PLC and PABS. The behaviour analysis of the clayey soil modified with polyethylene terephthalate and waste glass geopolymer involved evaluating its liquid limit (WL) and plastic limit (WP) using the Casagrande apparatus, following the procedural guidelines established in BS 1377-2:1990, 1998a.

2.7 Compaction Testing

Modified Proctor compaction tests was carried out to assess the compaction characteristics of the control soil, PLC-stabilized soil (CBS), and geopolymer-stabilized soil (PABS) at varying moisture contents as outlined by Jaber *et al.,* (2021). This test allows for greater compaction effort to be applied to the soil sample, resulting in denser and stronger soil.

2.8 Soil Permeability Testing

The experiment evaluated the coefficient of permeability of the control soil and the stabilized soils (CBS and PABS) under different conditions, providing insights into their drainage characteristics using the Falling Head Test procedure. This involved arranging the soil sample within the cylindrical mould using a filter disc setup and employing a vertical standpipe for controlled water flow measurements. The resulting permeability coefficient was a critical indicator of the soil's permeability characteristics under the conditions explored.

2.9 Statistical Analysis

Statistical analysis tool (SPSS v27) was applied to compare the performance of the control soil, CBS, and PABS. The results were present in tables and figures.

3.0 Results and Discussion

Table 1: Physical and geotechnical properties of the natural soil

Characteristion	Properties	Value / Description
Gradation / Classification	Gravel (>2.00 mm), %	Nil
	Sand (2.00 mm-0.075 mm), %	24.3
	Silt (0.075 mm- 0.002 mm), %	36.4
	Clay (<0.002 mm), %	39.3
	AASHTO Soil Classification System	A-7-6(14)
	Unified Soil Classification System	CH- Lean Clay

	Colour	Light Grey
	Natural Moisture Content (%)	13.8
	Liquid Limit (%)	46.83
	Plastic Limit (%)	23.0
	Plasticity Index (%)	23.83
	Linear Shrinkage (%)	19.39
	Maximum Dry Unit weight (kN/m ^{3})	17.22
	Permeability (k $_{avg}$ (m/s))	1.84 x10^{-6}m/s
Physical	Optimum Moisture Content (%)	**15**
	Unsoaked CBR (%)	**6.2**
Strength	Soaked CBR (%)	2.7
	UCS (kN/m^2) remoulded sample	152.9
	Consolidation: Cc. (Compression Index)	0.2002

Table 1 shows the physical and geotechnical properties of the natural soil. According to the table the UCS value is 152.9, the compression index is 0.2002 and the CBR values are 6.2 and 2.7 for soaked and unsoaked respectively.

Table 2: Specifications and Physical Properties of waste plastic

Properties	**Values/ Description**
Plastic Type	Polyethylene Terephthalate (PET) Bottles
Size	0.06 mm, 1.18 mm, 2.36 mm, 4.75 mm and 6.3 mm
Specific Gravity	1.14 1.26 1.25 1.20 1.16
Colour	white and light blue
Moisture Content (%)	11.95
Density	0.953 g/cm^3
Melting point **(°C)**	150
Young's modulus (MPa)	2965
Tensile strength (MPa)	250

Table 2 presents the specifications and physical properties of waste plastic with the tensile strength of 250, melting point of 150 and density of 0.953g/cm^3.

Table 3: Physical Properties of PLC

Property	Test result
Standard Consistency (%)	32.6
Specific gravity	3.09
Initial setting time (min)	75
Final setting time (min)	280
Specific Gravity	3.0

Table 3 shows the physical properties of the Portland Limestone Cement utilized (Dangote Cement, 42.5R).

Table 4: Soil Permeability Testing

SAMPLES	Permeability Coefficient
CONTROL	1.44×10^{-6} m/s
CBS	2.88×10^{-7} m/s
PABS	2.46×10^{-7} m/s

Table 4 shows the soil permeability results of the studied samples. The permeability coefficient, often denoted as "k," is a crucial parameter in soil permeability testing and plays a significant role in the design and construction of road pavements. The result shows that the soil treated with PET + RGP and alkaline activator had the best of the performance with 2.46×10^{-7} m/s following a decrease from 1.44×10^{-6} m/s to 2.88×10^{-7} m/s of CBS. The permeability coefficient is fundamental in drainage design, in determining the drainage characteristics of soil beneath road pavements (Cherian and Siddiqua, 2019). It signifies how easily water can flow through the soil, which is critical for preventing water accumulation beneath the pavement layers. Efficient drainage as reported in the result will help in maintaining the structural integrity of the pavement by reducing the risk of subgrade saturation and subsequent failure as also demonstrated by Dungca *et al.*, 2019.

In regions where frost heave is a concern, a low permeability coefficient is desirable (Dungca et al., 2019). The Geopolymer-based stabilized soil had a better performance in comparison to cement-based stabilized soil that has K to be 2.88×10^{-7} m/s with the Control sample having 1.44×10^{-6} m/s. A higher permeability allows water to infiltrate the subgrade, which can subsequently freeze and lead to heave during thawing. A well-draining subgrade minimizes the risk of frost-related pavement damage which is in accordance to Rai *et al.,* 2021. The permeability of the subgrade soil affects its stability under traffic loads (Rai *et al.,* 2021) A high permeability may lead to reduced soil cohesion and increased susceptibility to erosion, potentially compromising the stability of the subgrade. Conversely, a low permeability helps maintain soil strength and stability.

In accordance with British Standard BS:1377-5:1990(1998b), no specific range is specified for permeability, but recommends that the appropriate permeability range should be determined based on the specific application and context. However, for subgrade soils in road pavements, a maximum permeability of $1x10^{-6}$ m/s or lower is typically recommended to ensure the long-term durability and stability of the pavement structure. Achieving a lower permeability helps the soil withstand moisture infiltration and maintain its strength and stability over time (British Standard BS:1377-5:1990(1998b). Therefore, the study's results support the importance of permeability in evaluating stabilising agents for subgrade soils in road pavements as also reported by Abdila *et al.,* 2021.

The permeability coefficient is crucial for controlling the subsurface moisture content. Excessive water in the subgrade can weaken the pavement structure over time, leading to rutting, cracking, and other distresses (Abdila *et al.*, 2021). By understanding the permeability of soils, engineers can design effective drainage systems to regulate moisture levels. Proper drainage, facilitated by an appropriate permeability coefficient, contributes to the longevity of road pavements. Effective water management minimizes the impact of environmental factors, such as water-induced erosion and freeze-thaw cycles, which can accelerate pavement deterioration.

Understanding the soil permeability is crucial for assessing the potential environmental impact of road construction. High permeability may lead to faster infiltration of pollutants into the underlying groundwater, emphasizing the need for proper environmental management practices. The results shows that the soil treated with PET + RGP and alkaline activator (2M) has the lowest permeability with the normal soil having the highest reflecting the durability and stability of the pavement structure.

Table 5: Compaction Test of the Test Samples

Sample	Moisture Content (%)	Dry Unit Weight (Mg/m^3)
1. PBS	15.0	1.722
2. CBS	13.0	1.790
3. PABS (5P5R2A)	14.5	1.70
4. PABS (5P10R2A)	14.6	1.695
5. PABS (5P15R2A)	14.7	1.680
6. PABS (5P20R2A)	14.8	1.677

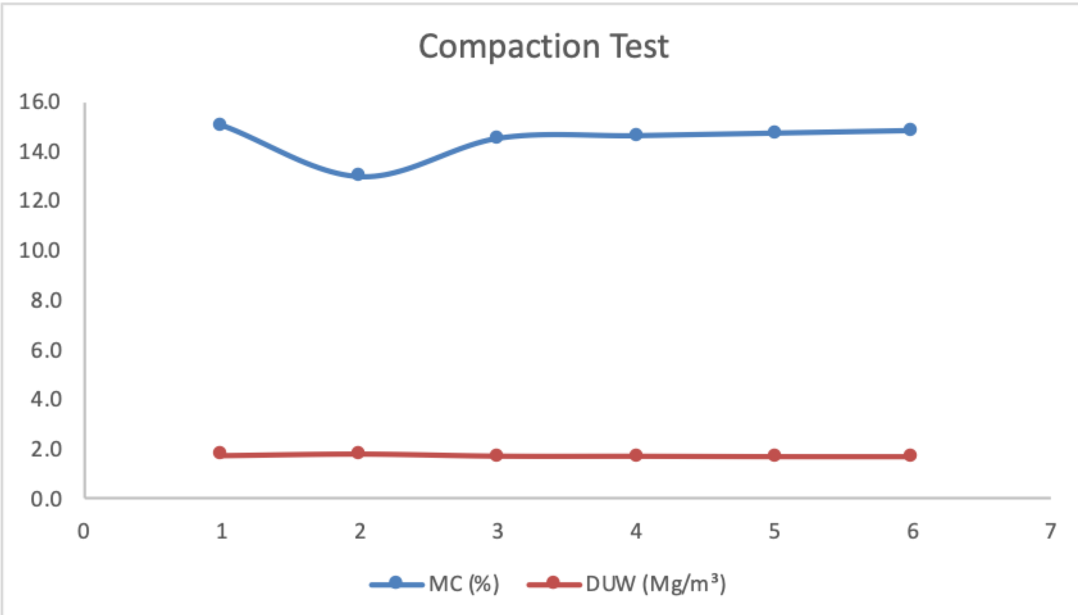

Figure 1: **Compaction Test of the Studied Sample**

Table 5 and Figure 1 shows the compaction test results of the samples for their moisture content (%) and the dry unit weight (Mg/m^3). PBS and CBS has 15.0 and 13.0, 1.722 and 1.790 respectively. According to Wang*et al.,* (2016), compaction tests, specifically the Modified Proctor (ASTM D1557), is vital in geotechnical engineering for evaluating the compaction characteristics of soils. Testing involves determining the relationship between moisture content and dry unit weight, offering valuable insights into soil behavior as reported by Zhang *et al.,* 2018. For the sample treated with PET+ RGP + Alkaline Activator (2M), four samples were considered i.e those treated with 5%, 10%, 15% and 20% respectively. The result shows an increase in the Moisture Content (14.5%-14.8%) and a Corresponding decrease in the dry unit weight of 1.7Mg/m^3 - 1.677Mg/m^3 which corresponds with Gardete *et al.,* (2019). This shows that as the percentage of RGP increases, the Moisture Content increases and the dry unit weight decreased correspondingly. This helps identify the optimal moisture content for a given soil. The moisture content corresponding to the maximum dry unit weight signifies the point at which the soil is compacted most efficiently. This information is crucial for achieving the desired soil density during construction. The maximum dry unit weight achieved during compaction represents the highest density the soil can attain under specific moisture conditions. According to the result obtained, the Engineers use this parameter to assess the structural integrity and load-bearing capacity of compacted soil layers within road embankments, foundations, and other civil engineering structures which corresponds with Hassan *et al.,* 2021.

The Compaction tests assist in establishing appropriate construction control measures as reported by Gardete *et al.,* 2019. By comparing in-place densities with laboratory-determined maximum dry unit weights, engineers can ensure that the compacted soil in the field meets specified engineering requirements. According to the results, the PABS is a very good stabilized soil to be used as alternative to the cement-based soil as they can easily worked on, and cost-analyis ratio is reduced. The compaction test, in conjunction with soil classification, aids in characterizing soil types based on their compaction behavior (Gardete *et al.,* 2019). Different soil types respond differently to compaction efforts, and understanding this variation is crucial for designing and constructing stable structures as reported by Zhang *et al.,* 2018).

In pavement design, achieving a specified level of compaction is critical for ensuring the durability and stability of the pavement structure. The compaction test helps engineers determine the moisture content and dry unit weight necessary for optimal performance. The result shows that the samples possess the moisture content and dry unit weight that's necessary for optimal performance. The compacted soils form the foundation for many structures and uderstanding the compaction characteristics aids in designing foundations with appropriate bearing capacities, minimizing settlement risks, and ensuring the stability of structures.

Table 6: Atterberg Limit Test

S/N		Control	CBS	PBS	PABS
Trial 1	Moisture content	41	45	45	43
	No. of blows	29	30	29	29
Trial 2	Moisture content	50	55	53	52
	No. of blows	23	24	24	23
Trial 3	Moisture content	58	65	60	60
	No. of blows	17	18	18	18
	Plastic Limit (%)	23	35	28	29
	Liquid Limit (%)	46.83	53.33	51.69	49.09
	Plastic Index (%)	23.83	18.33	23.69	20.09

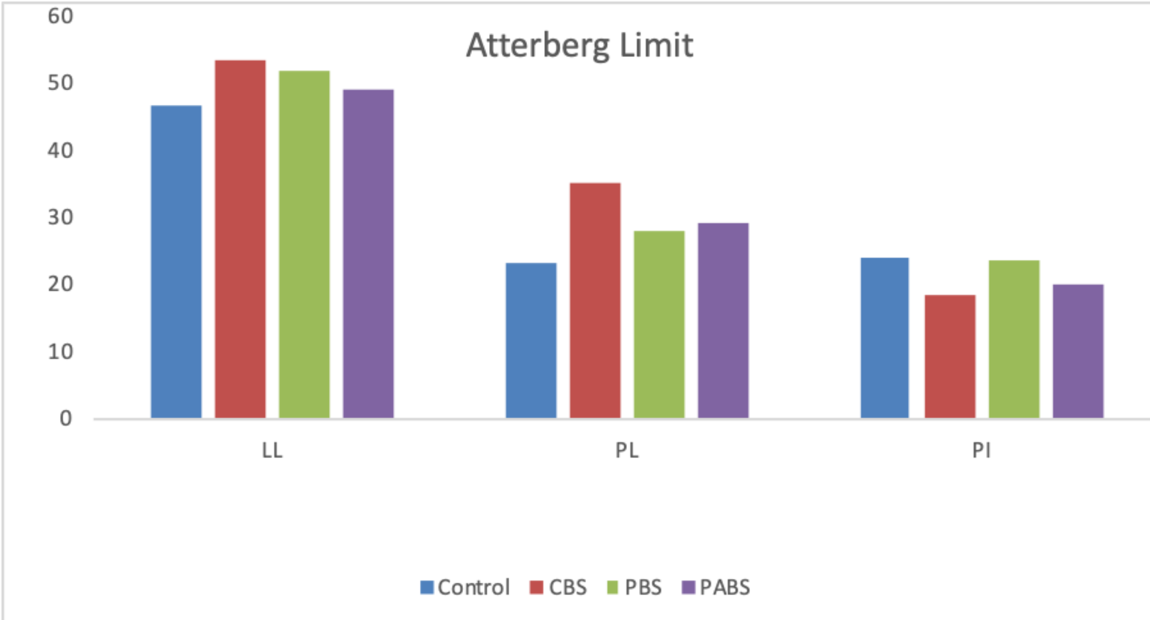

Figure 2: Atterberg Limit Test of the Studied Samples

The result presented in Table 6 and Figure 2 shows the atterberg limit of the studied samples; control soil, cement-based stabilized soil (CBS), PET stabilized soil (PBS) and PET+RGP stabilized soil (PABS) after three trials and subjection to varying number of blows. The Atterberg Limits Test is a crucial component in geotechnical engineering, particularly in the field of civil engineering (FMWH, 2013). The test assesses the physical properties of fine-grained soils, helping engineers and geotechnical professionals understand the soil's behavior and make informed decisions in construction projects. The ALT categorizes soils into different states based on their moisture content. The three primary limits determined by the test are the liquid limit, plastic limit, and shrinkage limit (Das, 2021). This classification aids in understanding soil behavior, including its plasticity and potential for volumetric changes. The results shows CBS to have the highest in terms of Plastic Limit and liquid limit with 35 and 53.33 respectively with the Control having the lowest with 23 and 46.83. The PET+RGP stabilized soil has the PL, LL and PI of 29, 49.09 and 20.09.

Plasticity is a crucial property in civil engineering, especially in the design and construction of earthworks and foundations (Das, 2021). According to Ikeagwuani and Nwonu, 2019, the ALT provides information about plasticity index, which indicates the range of moisture content over which the soil exhibits plastic behavior. This is essential for designing and constructing structures with cohesive soils. The test results are integral in foundation design, as they influence decisions regarding soil compaction and settlement. Engineers use the Atterberg Limits to assess the compressibility and expansiveness of soils, helping ensure stable foundations for structures (Barman and Dash, 2022). The plastic index of the samples are 23.83, 18.33, 23.69 and 20.09. Control and PBS are likely to have high plasticity and cohesion. While CBS and PABS are likely to have moderate plasticity and cohesion An increase in PI reflects an increase in the range of moisture content over which the soil exhibits plastic behavior. This could suggest higher potential for volumetric changes, both in terms of swelling and shrinking. Soils with higher plasticity indices may pose challenges in construction due to their expansive and contractive tendencies. While decrease in Plasticity Index (PI) indicates a reduction in the range of moisture content over which the soil exhibits plastic behavior. This may imply improved stability and reduced susceptibility to volumetric changes (Ikeagwuani and Nwonu, 2019)

The liquid limit for the samples are; 46.83, 53.33, 51.69, 49.09 while the Plastic Limit (PL) are 23, 35, 28, 29 for Control, CBS, PBS and PABS respectively. For increase in PL, it means that the soil requires more water to exhibit plastic behavior. This may indicate an increase in the soil's cohesion and plasticity. Soils with higher plastic limits are generally more moldable and may have increased strength while a decrease in PL indicates that the soil exhibits plastic behavior at lower moisture contents (Das, 2021). This may result in reduced workability and increased susceptibility to cracking. Soils with lower plastic limits are generally less moldable.

An increase was noticed according across the sample except for CBS that has the highest for PL, and LL with low PI. Increase in Liquid Limit (LL) indicates an increase in the moisture content at which the soil transitions from a plastic to a liquid state. This suggests that the soil becomes more susceptible to flow and deformation under stress. Decrease in LL suggests a reduction in the moisture content at which the soil behaves as a liquid. This may indicate improved workability but can also imply a decrease in the soil's ability to retain water and may impact its cohesion. The soil stabilized with PET and RGP shows a good performance base on the results obtained.

Conclusion

The study offers valuable insights into sustainable soil stabilization methods, comparing conventional cement-based and innovative geopolymer-based approaches. The utilization of recycled glass powder, polyethylene terephthalate with alkaline activator (NaOH), and construction and demolition waste presents an eco-friendly alternative for urban pavement construction. The Atterberg Limit results indicate varying plasticity and liquidity characteristics among the samples, with promising trends in geopolymer-based stabilization. Notably, the geopolymer-based stabilized soil (PABS) exhibits favorable compaction characteristics with moisture content and dry unit weight meeting desirable standards.

Furthermore, the permeability test results for PABS showcase a low permeability coefficient, aligning with recommended standards for subgrade soils in road pavements. This underscores the potential of geopolymer-based stabilization to enhance the durability and stability of pavement structures by minimizing moisture infiltration. The study emphasizes the dual benefits of improved soil properties and sustainable waste management practices, particularly in regions grappling with waste challenges. The research sheds light on the promising role of waste materials in addressing both geotechnical engineering needs and environmental concerns, contributing to the advancement of sustainable urban development practices.

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