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Experimental Study of Use of Waste Glass for Sustainable Stabilization of Highway Foundation Soils

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Abstract

Recycling waste glass for subgrade soil improvement not only contributes to the development of sustainable and resilient highways but also mitigates the environmental impact of the vast quantities of glass generated daily. This study examines the potential of using waste glass to enhance the geotechnical properties of soil intended for highway subgrade applications. Soil sample was obtained from a borrow pit in Oyun, Southwestern Nigeria, where lateritic soils are quarried for construction purposes. The mineralogical and geochemical properties of the natural soil were analyzed using X-ray diffraction (XRD) and X-ray fluorescence (XRF). Pulverized waste glass underwent grain size distribution analysis, and the soil samples were mixed with waste glass in proportions of 0.5%, 1%, 1.5%, and 2% by weight. The impact of waste glass powder addition on Atterberg limits, linear shrinkage, compaction parameters, swell potential, and both soaked and unsoaked California Bearing Ratio (CBR) was investigated. The aging effect on the CBR of the stabilized samples was assessed by repeating the soaked CBR tests after 7, 14, and 21 days. Results indicated that the liquid limit, plastic limit, plasticity index, linear shrinkage, swell potential, and of the stabilized soils decreased with increasing glass content. Conversely, the maximum dry density and both soaked and unsoaked CBR values increased, while the optimum moisture content decreased with higher glass content. The stabilized soils maintained their strength even after 21 days of soaking. Waste glass, even at a 0.5% inclusion by weight, acts as an effective cementing agent, improving soil properties for highway foundations.

***Keywords**: Waste glass recycling, Soil stabilization, Highway subgrade, Geotechnical properties, Sustainable construction, Lateritic soil.*

Introduction

It is a common knowledge that waste recycling is one of the most efficient means of sustainable waste management because of its numerous advantages. It helps to conserve natural resources, saves energy, reduces green house gas emission, saves cost, saves landfill space and reduces pollution(Gonçalves *et al.*, 2022; Harrison *et al.*, 2020).Glass is a non - biodegradable waste generated in large quantity globally due to its numerous applications. It contains abundant amorphous silicon and calcium, and has high reactivity (Tang *et al.*, 2020).Statistics has shown that glass waste constitute a significant amount of world's waste, eighty percent of which are glass containers (Bilgen, 2020). According to a report by UNEP 2024, only 21 % of global annual glass production is currently being recycled leaving the rest to constitute environmental nuisance and occupy landfill space. This deficit in the amount of glass waste generated and the amount recycled is huge. There is, therefore, need for research into innovative ways of recycling glass for more efficient solid waste management.

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The possibility of using waste glass in construction does not only provide a more efficient means of solid waste management, but it also contributes to sustainable development via resilient and green infrastructure. Previous research on the applications of waste glass in construction has explored its use as partial replacement for natural aggregates in concrete and asphalt admixtures, supplementary cementitious material, and lightweight fill materials (Mohajerani *et al.*, 2017; Sharma and Sharma, 2018; Vishnu *et al.*, 2019). Waste glass has also been used as additives in soil improvement(Bilgen, 2020; Blayi *et al.*, 2020; Jesús *et al.*, 2020; Niyomukiza *et al.*, 2023), however limited work has been done the improvement of highway subgrade soils using glass waste.

The performance of highway pavements is determined to a large extent by the quality of it's underlying soils(Nik Daud *et al.*, 2019; Owoyemi *et al.*, 2022). Stable highway pavements are indispensable infrastructure for transportation of goods and services necessary for economic sustainability and growth. To achieve highway pavements that are stable and durable enough to cope with traffic demands, strong subgrade is requisite. Subgrades in their natural state often do not provide the required support necessary for achieving this performance(Little, 2009; Owoyemi, 2021), hence the need for stabilization. While additives such as lime and cement are commonly used to improve subgrade strength and durability, utilization of glass waste for subgrade stabilization will provide a cheap and environmentally friendly alternative. Previous research as shown that pozzolanic additives such as waste glass could improve subgrade strength(Abdulazeez *et al.*, 2020; Kalakada *et al.*, 2020; Li *et al.*, 2022; Prashant, 2019). Incorporation of pozzolans into soil significantly influences its properties, particularly in terms of strength, compressibility, and overall stability(Blayi *et al.*, 2020; Hossain and Mol, 2011; Onyelowe *et al.*, 2021; Sutarno and Mohamad, 2023). This enhancement is attributed to the formation of additional cementitious compounds that bind soil particles together more effectively when used for stabilization(Safehian and Rajabi, 2018).

Ibrahim *et al.* (2019) stabilized a highly plastic soil with glass powder using proportions ranging between 6% and 27% by dry weight of soil. They reported an improvement in Atterberg limits, maximum dry density, optimum moisture content, unconfined compressive strength, consolidation, and swelling characteristics of the stabilized soil. Blayi *et al.* (2020) utilized glass powder (2.5 – 25%) in their work and reported decrease in Atterberg limits, OMC and free swell. In the same vein, CBR, MDD and unconfined compressive strength increased. Jalal *et al.* (2022)used glass powder in proportions ranging between 6% and 22% by dry weight of soil. They reported 80% decrease in plasticity, slight increase in maximum dry density (MDD) and decreased optimum moisture content(OMC), Six - fold increment in California Bearing Ratio(CBR) and decreased compressibility. It is noteworthy, however, that the percentages of glass powder used for soil stabilization in these works have often been greater than 2%. This work hereby, seeks to investigate the effect of this additive on important geotechnical properties of foundation soils even at relatively lower concentrations. If found effective, the use of glass waste for soil stabilization at relatively lower concentrations will enhance its applicability in field operations and further establish its potency as a versatile additive for soil stabilization.

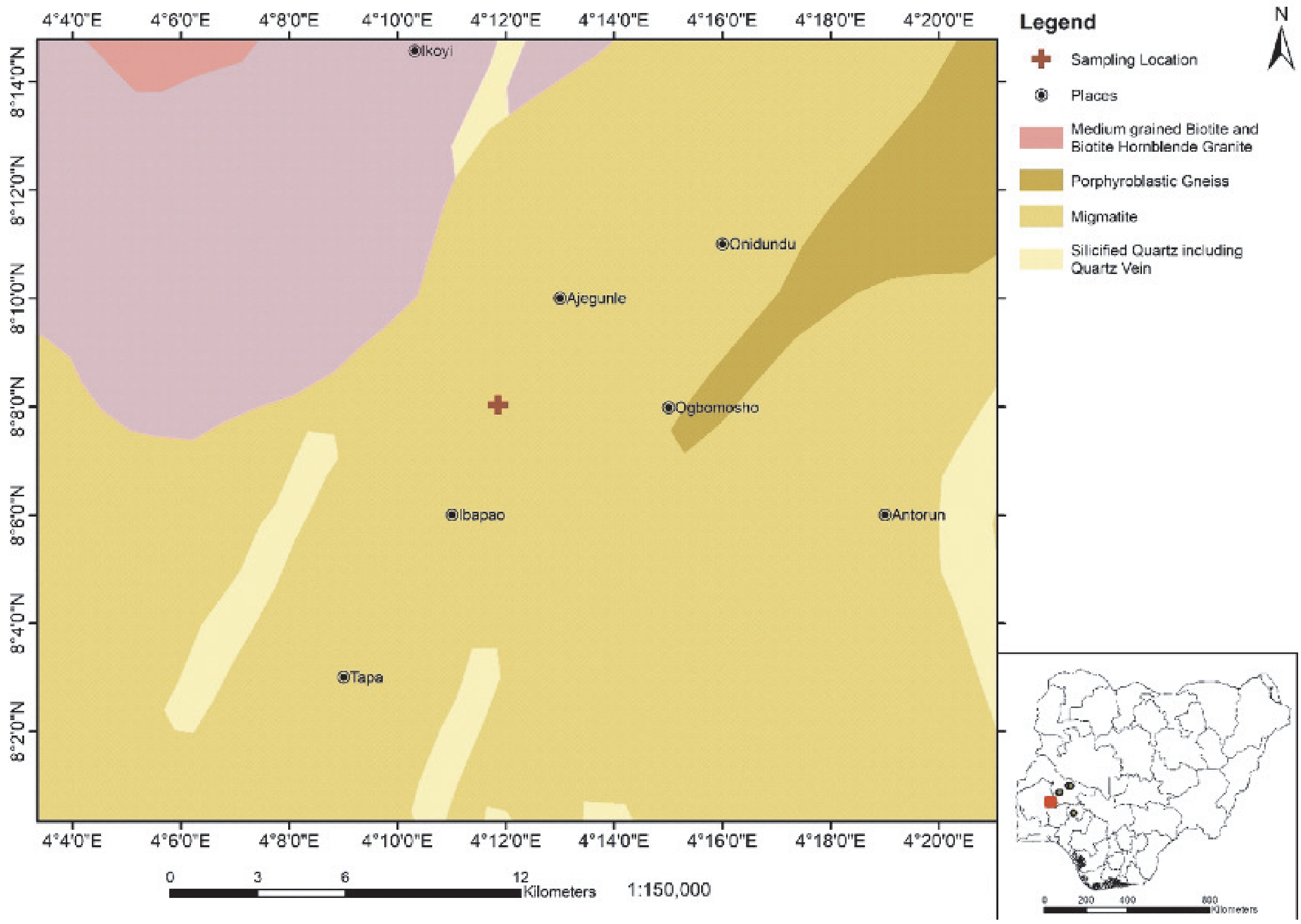

Fig. 1: Geologic map of the sampling site

During geological site investigation for the construction of highway pavements, recommendations that involve change of route might not be feasible while haulage of materials for replacement of poor subgrade soils is not economical. It, therefore, becomes imperative to modify the *in-situ*soil, and soils found in the vicinity of proposed highway routs for use as subgrade and subbase. Hence the need for continuous effort towards sustainable stabilization of highway foundation soils. This work investigates the effectiveness of waste glass derived from crushing containers for subgrade improvement. The results of this experimental research will provide reference data which will serve as guide for highway engineers for sustainable stabilization of highway foundation soils. The soil used for the experimental study was taken from an active burrow pit where soils were being quarried for highway construction. Figure 1 shows the geologic map of the sampling site, and its underlying geology in Oyun, Southwestern Nigeria.

Materials and Method

Properties of the natural soil

Table 1 presents the geotechnical properties of the studied soil. The soil classifies as A-6 (2), rating as fair to poor subgrade material under the American Association of State Highway Transportation Official (AASHTO) classification system. It is rich in silt and clay sized particles with free swell of21.8% indicating a low degree of expansion(Rao *et al.*, 2014). As shown in Table 1 and Figure 2, the dominant minerals in the soil are kaolinite(36%),mica (28%)and quartz (20%) with some goethite and k-felspar. The engineering property of the soils would be largely dictated by the kaolinite and mica content in it. The dominant elements in their oxide forms are silica (SiO_2), aluminium oxide (AI_2O_3) and iron oxide(Fe_2O_3) in order of their abundance.

Glass

The glass used was sourced from waste glass containers previously used for soft drink packaging. The bottles were pulverized using a laboratory mill and the grain size distribution of the resulting powder was determined by sieve analysis using the procedure outlined in British Standard (1990). The result shows that the glass consist of 92% sand sized fragment and 8% fines (particles less than 75 µm). The pulverized glass has grading characteristic like that of a uniformly graded sand as shown in figure 3. Soft drink glasses are typically made of soda = lime glass and they consist of 70-75% silica, 12-15% sodium oxide , 5- 12% calcium oxide and 0 – 5%of combination of magnesium and aluminium oxide(Bilgen, 2020; Ezra *et al.*, 2024; Shelby, 2020).

Table 1: Geotechnical and mineralogical properties of the soil

Geotechnical property	Value
Liquid limit (%)	40.6
Plastic limit (%)	22.5
Plasticity index (%)	18.7
Linear shrinkage (%)	7.4
Soil fraction <2mm (%)	94.6
Soil fraction <423 µm (%)	68
Soil fraction <75 µm (%)	47.8
Gravel size fraction(%)	5.4
Sand size fraction (%)	46.8
Silt size fraction (%)	30.8
Clay size fraction (%)	17
AASHTO classification	A-6(2)
Free swell (%)	21.8
Unsoaked CBR (%)	30
Soaked CBR_7days (%)	12
Soaked CBR_14 days (%)	8
Soaked CBR_21 days (%)	2
MDD_St (g/cm^3)	1.75
OMC_St (%)	11.9
MDD_Md(g/cm^3)	1.78
OMC_Md (%)	11
Mineralogy	Weight (%)
Kaolinite	36
Mica	28
Quartz	20
K-feldspar	8
Goethite	8

***St** (Standard Proctor), **Md** (Modified Proctor)

Methods

The soil sample collected was air – dried in the laboratory until changes in weight ceased. Two batches of laboratory tests were conducted to study the properties of the soil in its modified and unmodified form. Firstly, samples of the unmodified soil were analysed for their mineralogical, geochemical and geotechnical characteristics. The mineralogy and geochemistry were determined using x-ray diffraction (XRD) and x-ray fluorescence (XRF) method respectively. XRD analyses was completed using a PANalytical Empyrean while Highscore was used for interpretation alongside the data base of the International Centre for Diffraction Data (ICDD-

Table 2: Major, minor and trace elements in the soil

Major elements	Weight (%)	Trace elements	Weight (ppm)
SiO_2	50.3	Sc	24
TiO_2	1.1	B	56
Al_2O_3	24.57	Cr	6
Fe_2O_3	10.05	Co	43
MgO	0.23	Ni	17
MnO	0.03	Cu	26
CaO	0.15	Zn	101
Na_2O	0.05	As	12
K_2O	2.97	Rb	151
P_2O_5	0.07	Sr	108
LOI	8.91	Y	52
Total	98.43	Zr	658
		Nb	40
		Ba	1031
		Pb	5
		Th	17
		U	3

PDF2®) of 2021.All elements, except Na_2O, were analysed on a fused bead while Na_2O was analysed on a pressed pellet using a wavelength-dispersive XRF spectrometer (Rigaku-Primus IV). Loss on ignition (LOI) was determined by heating the sample to 950°C.Consistency limits and particle size distribution including hydrometer test of the soil was determined in accordance with the procedures outlined in the British Standard (1990). Free swell index (FSI) which is an indication of the degree of expansion of a soil, was determined on the soil following the procedure outlined in IS 2720-40 Part XL), (1977). I0 g of oven dried soil fractions finer than 0.425 mm were placed in two 100 ml graduated glass cylinders. One of the cylinders was filled with kerosene while the other was filled with distilled water. The final volume of soil samples in each cylinder was read after 24 hours and the FSI was calculated using equation 1.

$$(FWI) = \frac{\text{soil volume in distilled water} - \text{soil volume in kerosene}}{(\text{soil volume in Keosene})} \times 100 \quad ..(1)$$

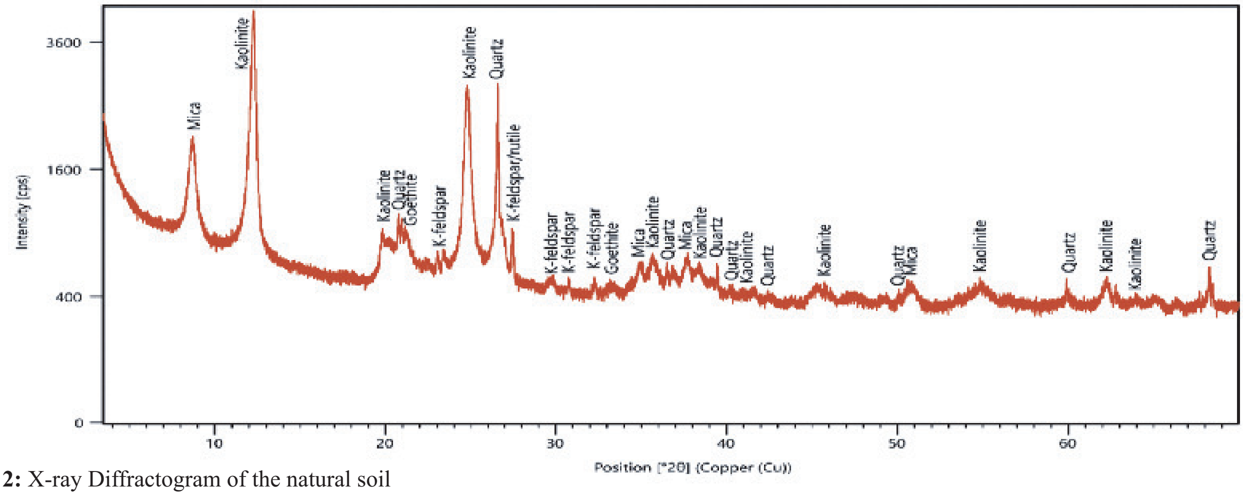

Fig. 2: X-ray Diffractogram of the natural soil

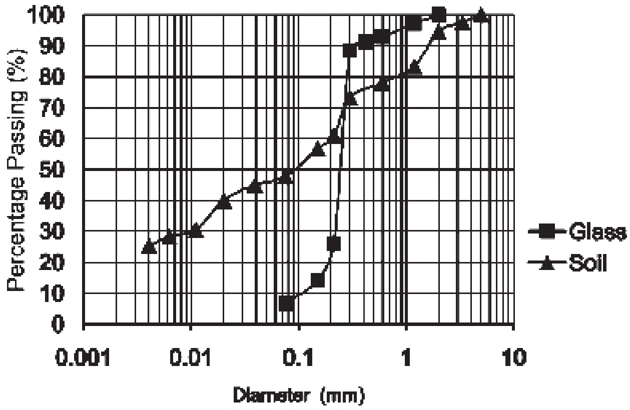

Fig. 3: Grading curves of the natural soil and the PWG

Moisture-dry density relationship was determined on soil factions finer than 0.425 mm in accordance with the specification of British Standard 1377 – 4. Both Standard Proctor and Modified Proctor compaction level were used. Samples compacted at OMC and MDD were used for soaked and unsoaked CBR test following the British Standard 1377 – 4 (1990).

Thereafter, pulverized waste glass (stabilizer) was mixed with the soil in varying proportions (0.5%, 1%, 1.5% and 2%) by dry weight of the soil. Properties such as consistency limits, free – swell, moisture- dry density relationship and CBR were carried out on stabilized samples. CBR test was repeated on the samples after soaking them for 7 days, 14 days and 21 days to investigate the long-term effect of the stabilizer on the soils. Analysis of Variance (ANOVA) was used to investigate the significance of observed differences in the geotechnical properties of the natural and stabilized samples at different stabilization concentrations. One-way ANOVA test was used because only stabilizer concentration was considered the only source of variation. The initial assumption (null hypothesis) was rejected when the calculated F-statistic (F_{CAL}) in absolute terms was greater than the critical F-value (F_{CRIT}) and the probability value (P-value) value was less than 0.05 ($F_{CAL} > F_{CRIT}$: $P \leq 0.05$).

Results and Discussion

Consistency Limits

Addition of PWG caused a decrease in liquid limit, plastic limit and plasticity index of the stabilized soil as shown in Table 3. The consistency limits consistently decreased with increasing percentage stabilizer. This indicates a linear relationship between percentage PWG and consistency limit due to progressive reduction in the soil's affinity for water with increasing glass content. Averagely, at addition of 2% additive, the percentage reduction in liquid limit, plastic limit and plasticity index are 65%, 64% and 67% respectively. This is consistent with the findings of (Blayi *et al.*, 2020; Ibrahim *et al.*, 2019; Jalal *et al.*, 2022). The percentage decrease in plasticity index of 67% obtained here is close and comparable to the 80% decrease obtained by (Jalal *et al.*, 2022) despite the higher percentage (6% - 22%) of glass powder used in their research. A decrease in the plasticity of a soil is an indication of reduced compressibility and sensitivity to moisture changes (Carter and Bentley, 1991), which is a desirable property in highway foundation soils. These changes can be attributed to both chemical and textural changes. Addition of the silica rich powder glass (Ezra *et al.*, 2024) to the originally low-silica soil has increased its silica content thereby, reducing its affinity for water. The texture of the originally silt and clay rich-soil has also been imparted by the addition of sand-size dominated PWG (Figure3), also contributing to a reduction in the soil's water absorption capacity. The federal ministry of works and housing (2013)recommends that improved subgrade materials and sub-base should have plasticity index not higher than 6%. The average plasticity index of soils stabilized with 2% PWG by dry weight of the soil is 5.9%. This implies that the studied soil, which was naturally unsuitable as subgrade material, has been improved sufficiently enough to meet up with the standard specification for improved highway subgrade by addition of 2% PWG by dry weight of the studied soils.

Table 3: Variation of the consistency limits of the soil with percentage stabilizer

	Liquid limit (%)			Plastic limit (%)			Plasticity index (%)		
PWG (%)	1	2	3	1	2	3	1	2	**3**
0	41.5	41.3	39	22.7	23.6	21.1	18.8	17.7	**17.9**
0.5	32.1	33.9	31.4	18.5	19.4	17.3	13.6	14.5	**14.1**
1	23.7	22.8	24.3	12.8	12.7	13	10.9	10.1	**11.3**
1.5	19.8	17.5	16	10.3	9.9	8.4	9.5	7.6	**7.6**
2	15.3	14.2	12.8	8.8	8	7.8	6.5	6.2	**5**

Linear shrinkage and free swell

Cyclic shrinking and swelling of highway foundation soils due to seasonal moisture variation can cause pavement instabilities such as longitudinal cracks, differential heaving, rutting, potholes and alligator cracking(Cerato and Lutenegger, 2006; Puppala and Cerato, 2009; Simic, 2013). Free swell index is a measure of the potential of as soil for expansion when moisture is increased, while linear shrinkage is a measure of how much a soil shrinks when it loses moisture. Any additive that can reduce expansion and/or shrinkage in foundation soil is an asset for management of expansive soils.Table4 presents the variation in the linear shrinkage and free swell characteristics of the studied soil with PWG addition. Both free swell and linear shrinkage reduced consistently with increase in amount of stabilizer. Up to 90.2% and 60.5% reduction in free swell and linear shrinkage respectively, was recorded with addition of 2% PWG of the weight of the soil. This result is consonance with previous research (Blayi *et al.*, 2020; Ibrahim *et al.*, 2019; Niyomukiza *et al.*, 2023). Decrease in the shrink-swell characteristic of the soil can be attributed to reduction in plasticity of the soil, corroborated by observed decrease in plasticity index of the soil. Plasticity has been linked with shrink - swell characteristics of soils(Carter and Bentley, 1991).

Table 3: Variation of the consistency limits of the soil with percentage stabilizer

PWG (% weight)	Linear shrinkage (%)			Free swell (%)		
	1	2	3	1	2	3
0	7.1	7.6	7.4	20.8	23.1	21.5
0.5	5.2	4.7	4.9	15.2	17.1	15.6
1	4.1	4.6	4.3	10.3	10.8	12.5
1.5	3.9	3.8	3.6	8.4	6.1	7.2
2	3.5	3	3.2	2.9	2.9	2.1
Decrease (%)	50.7	60.5	56.8	86.1	87.4	90.2

Moisture - dry density relationship

Laboratory compaction test to determine the moisture dry density relationship of highway subgrade and subbase soils is important because it helps to know the optimum amount of water necessary for on-site compaction. Compaction at the right moisture content and suitable energy of compaction helps to achieve highly dense foundation soil with reduced compressibility and enhanced strength. To investigate the suitable energy of compaction necessary to achieve best results with PWG addition, the soil was compacted using Standard Proctor and relatively higher Modified Proctor energy levels. For soil samples at compacted both energy levels, the compaction curves moved upwards in the direction of reduced moisture requirement (Figure 5). In both instances, OMC reduced and MDD increased with increasing PWG content in the soil (Table 5). Using the Modified Proctor method produced stabilized soils with slightly higher MDD and lower OMC than those compacted using the Standard Proctor method. This result agrees with the findings of previous works where higher concentration of glass was utilized for soil stabilization. Increased MDD can be attributed to improved grading of the stabilized soil with addition of PWG which is largely sand – sized. In addition to this, partial replacement of soil grains PWG grains creates a filling effect since its density is higher than that of the soil grains. Reduced OMC is a direct effect of partial replacement of hydrophilic clay and silt size soil grains with hydrophobic sand-sized PWG grains which creates lubrication and makes higher density achievable at lower water content.

Table 5: Variation of OMC and MDD with PWG content in the soil

PWG (%)	Standard Proctor						Modified Proctor					
	OMC (%)			MDD (g/cm^3)			OMC (%)			MDD (g/cm^3)		
	1	2	3	1	2	3	1	2	3	1	2	3
0	11.9	11.4	12.5	1.75	1.77	1.7	11	10.3	11.2	1.78	1.81	1.74
0.5	9.9	9.4	9.1	1.8	1.81	1.85	9.0	8.5	8.4	1.84	1.86	1.9
1	8.0	7.8	7.0	1.93	1.95	1.97	7.3	7.3	6.5	1.98	2.02	2.0
1.5	6.1	5.5	6.0	2.1	2.06	2.01	5.8	5.2	5.0	2.15	2.13	2.09
2	5.6	5.3	5.2	2.19	2.2	2.21	5.1	5.0	4.9	2.23	2.25	2.27

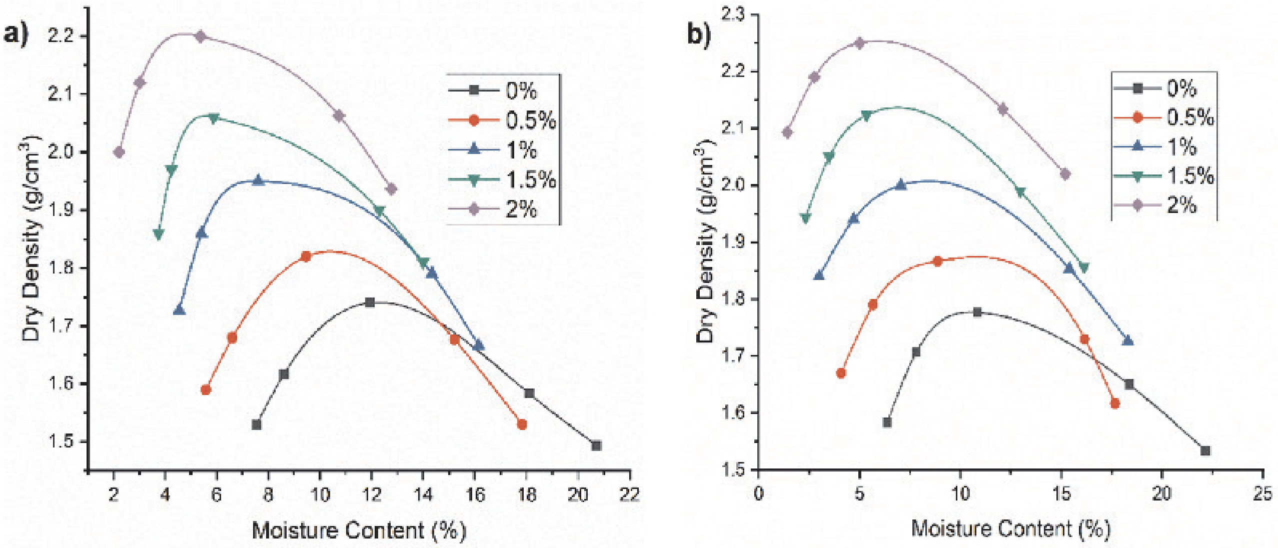

Fig. 4: Compaction curves of the stabilized soil samples a.) Standard Proctor; b.) Modified Proctor.

California Bearing Ratio

CBR provides an indirect method of assessing the shear strength and stiffness modulus of subgrade and subbase soils by comparing their strength with that of standard crushed rocks (Taskiran, 2010). It is it is a crucial design parameter normally used in the determination of the thickness of highway pavements. Unsoaked and soaked CBR increased steadily with increase in stabilizer amount (Figure 5). Soaked CBR was carried out on stabilized and natural un-stabilized samples after 7, 14 and 21 days to investigate the effect of aging and long-term sustained increase in moisture due to adverse environmental conditions such as flooding on stabilized soils. The natural soil seemingly good CBR rating for use as subgrade lost almost all its strength after been soaked for 21 days. However, all PWG stabilized soils (0.5 % -2%) much greater than the 3% four days soaked CBR recommended by the Nigerian Federal Ministry of works and housing. Unsoaked CBR increased by 173% with 2% PWG addition (Table 6). The percentage increment in soaked CBR of stabilized samples increased with length of soaking time. For instance, the percentage increment in soaked CBR taken at 21 days is more than three -fold the value recorded after 7days of soaking (Table 6). Also, strength loss (decrease ion CBR) due to soaking reduced with increase in percentage stabilizer (Table 6). This implies that the presence of PWG in the stabilized samples made them more resistance to strength loss due to soaking making them more resilient and durable. This strengthening, even in the presence of water, can be attributed to the pozzolanic and geopolymerization reactions between amorphous silica (SiO_2), sodium oxide (Na_2O) and calcium oxide (CaO) in PWG with the silica and alumina (Al_2O_3) in the kaolinite rich soil(Al-rawas and Hago, 2006; Olaniyan *et al.*, 2011). The presence of sodium oxide and calcium oxide in the PWG and soil creates an alkaline environment necessary for cementitious compounds to be produced leading to improved soil's strength and durability(Khale and Chaudhary, 2007). Increased strengthening with length of soaking time can be attributed to increasing alkalinity with length of soaking time(Alshaaer, 2013; Silva and Sirivivatnanon, 2007).

Table 6: Soaked and unsoaked CBR of the soils before after stabilization

PWG (%)	Unsoaked CBR (%)	Soaked CBR_ 7days (%)	Soaked CBR_ 14 days (%)	Soaked CBR_ 21 days (%)	Decrease in CBR (%)
0	30	12	8	2	93
0.5	52	26	16	11	79
1	65	38	25	13	80
1.5	74	45	32	20	73
2	82	51	43	25	70
Increase in CBR (%)	173	325	438	1150	

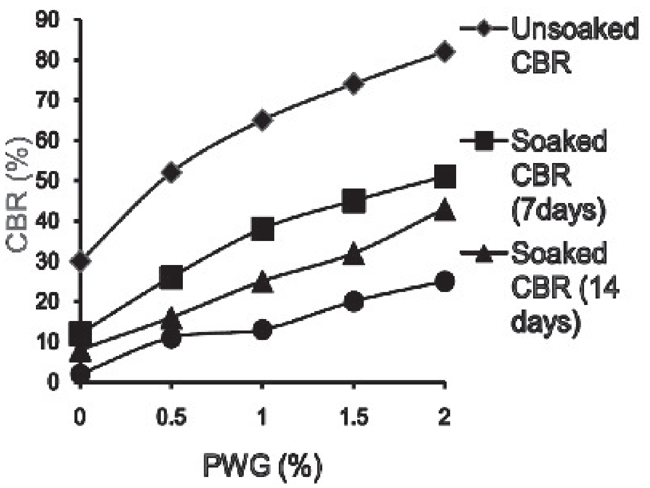

Fig. 5: Variation of CBR with stabilizer amount

Statistical Analysis

The result of the one-way ANOVA presented in the Table 8 shows that all the observed differences between the properties of the natural unstabilized and the stabilized samples are statistically significant. The null hypothesis was rejected, and the alternative hypothesis is validated. This implies that administration of PWG at low concentrations (0.5 -2%) used in this study successfully generated significant improvement in the geotechnical properties of the studied soil.

Conclusion

Improvement of AASHTO grade A6 soil with up to 2% sand-sized PWG by weight of the soil was attempted

Table 7: One-way ANOVA results for the proprieties of the stabilized soil samples

Property	Source of variation	F_{CAL}	P-value	F_{CRIT}	Remarks
Liquid Limit	WGP (% weight)	25.854	0.000948	5.3177	Significant
Plastic Limit	WGP (% weight)	23.842	0.00122	5.3177	Significant
Plasticity Index	WGP (% weight)	22.709	0.00141	5.3177	Significant
Shrinkage Limit	WGP (% weight)	21.668	0.00163	5.3177	Significant
Free Swell	WGP (% weight)	10.299	0.0124	5.3177	Significant
MDD (Standard Proctor)	WGP (% weight)	6.8987	0.0303	5.3177	Significant
MDD (Modified Proctor)	WGP (% weight)	7.6110	0.0247	5.3177	Significant
OMC (Standard Proctor)	WGP (% weight)	31.272	0.00051	5.3177	Significant
OMC (Modified Proctor)	WGP (% weight)	31.218	0.00052	5.3177	Significant
CBR (Unsoaked)	WGP (% weight)	42.548	0.00018	5.3177	Significant
CBR (Soaked 7 days)	WGP (% weight)	22.867	0.00139	5.3177	Significant
CBR (Soaked 14 days)	WGP (% weight)	15.200	0.00455	5.3177	Significant
CBR (Soaked 21 days)	WGP (% weight)	11.123	0.0103	5.3177	Significant

with a view to investigating its effectiveness as highway foundation soil stabilizer. Plasticity of the soil reduced indicating the ability of PWG to reduce soil compressibility even at low concentrations. Addition of 2% PWG of the weight of the soil caused reduction in free swell and linear up to 90.2% and 60.5% shrinkage respectively indicating a significant reduction the well shrink characteristics of the soil. Compaction characteristics of the soil was improved, indicating better workability in the soil. Soaked and unsoaked CBR significantly increased in all stabilized samples. Strength enhancement increased with length of soaking time indicating the ability of the stabilizer to prevent loss in highway foundation materials due to adverse environmental conditions such as flooding. One way ANOVA test showed that all the observed differences between the properties of the stabilized and un-stabilized soil samples are statistically significant. The changes are attributed to improvement in the grading characteristics of the soil and partial replacement of hydrophilic fine – grained clay and mica in the soil with hydrophobic sand-sized glass particles. It is also believed that geoplymerization and pozzolanic reactions in the soil - PWG mixture produced cementitious compounds which imparted strength and durability to the stabilized soil. Successful improvement of poor highway foundation soil with 2% waste glass makes recycling of glass for geotechnical applications more sustainable, scalable and practicable since only 200kg of glass powder will be required for improvement of 10 tons of soil.

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