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Stabilization of Lateritic Soil Using PET Bottle Shreds and Periwinkle Shell Ash for Subgrade Layer of Road Pavement

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Abstract

This study investigates the stabilization of lateritic soil with polyethylene terephthalate bottle shreds and periwinkle shell ash for use in the subgrade of road pavements. The main aim is to enhance the engineering properties of lateritic soil to make them suitable for use as a road construction material. The lateritic soil used for this research work was obtained from Iju, Ota, Ogun state, while other materials were PET bottle shreds and periwinkle shell ash. The experimental Laboratory tests in this project are moisture content, specific gravity determination, particle size distribution, Atterberg limits, permeability, unconfined compressive strength, compaction test, and California bearing ratio test. Results show that adding 6% PET bottle shreds optimizes the soil's unconfined compressive strength (UCS) and improves it considerably in compressive strength. Further stabilization with varying percentages of periwinkle shell ash, 2%, 4%, 6%, 8%, and 10%, shows that the mix of 6% PET bottle shreds and 6% periwinkle shell ash produces a CBR value of 19.5%, while the natural soil had a CBR value of 5.5%. Other improvement parameters from this combination also prompted the best suitability for subgrade applications through its permeability and compaction characteristics. This study therefore concludes that the use of PET bottle shreds and periwinkle shell ash as stabilizers can eventually improve the mechanical properties of lateritic soil to a great extent, hence providing a sustainable solution in road pavement construction.

1 INTRODUCTION

Soil is the basic material that supports every civil engineering structure, and the strength of a structure depends greatly on the ground beneath it. A good understanding of soil properties and the factors affecting them is therefore necessary before any construction work is carried out (Gowtham et al., 2020; Iravanian & Haider, 2020). Weak soils with low bearing capacity often lead to excessive settlement and long-term damage to structures built on them (Aydenlou, 2020), and replacing the entire soil mass with a better material is usually not practical or affordable (Ali Said Al Alawi et al., 2023; Iravanian & Haider, 2020). For this reason, soil stabilization, which involves improving the properties of the existing soil rather than replacing it, is often the preferred solution. Road pavements require a stable subgrade for the layers above it to perform well under long term traffic loading (Totten, 2018). The subgrade, sub-base and base layers are one of the common areas of concern in highway construction, as they require durable materials, which are often lacking (Okonkwo et al., 2022). Lateritic soils are widely available and used in road construction in Nigeria (Gidigasu, 1974), but its high clay content raises concerns about strength and stability, especially under load or in the presence of moisture (Silva et al., 2021). Stabilization is therefore usually required before lateritic soil can be used for pavement construction (Segun & Olufikayo, 2016). The soil can be made more suitable for bearing by adding different additives (Renjith et al., 2021). At the same time, waste materials from various industries continue to create environmental and disposal problems (Ali Said Al Alawi et al., 2023). The growing demand for bottled drinks has increased the volume of non-biodegradable PET plastic waste generated yearly (Novakovic et al., 2023), with plastics reported to make up about 12.3% of total waste generated (Dogu et al., 2021), and about 35 billion plastic bottles discarded yearly in the United States alone (Tulchinsky et al., 2023). Using this waste as a soil additive is both an economical and an environmentally responsible option

(Ogundairo et al., 2021; Abdulrahman B et al., 2022; Akinwumi et al., 2022). In a similar way, periwinkle shells, which are widely consumed in many parts of Nigeria and West Africa, are often disposed of indiscriminately after consumption, creating a burden for geo-environmental engineers (Attah & Yohanna, 2020). The shells can be burnt to obtain periwinkle shell ash (PSA) which has pozzolanic properties that can be put to use in soil stabilization to resolve the problem of waste disposal and enhance weak soils (Ekpo et al., 2021; Etim et al., 2022). The use of either shreds from PET bottles or periwinkle shell ash alone as soil stabilizers has been included in a several studies; however, the combined effect of both in a single soil mix has not been extensively investigated. This study focuses on the suitability of PET bottle shreds used in the subgrade layer of road pavements; therefore, lateritic soil has been stabilized with shreds of PET bottles and periwinkle shell ash. The specific objectives are to characterize the properties of the untreated soil, find the optimum PET bottle shred content, evaluate the combined effect of PET bottle shreds and periwinkle shell ash at varying percentages, and compare properties of the treated soil to the properties of the untreated soil and relevant standards.

2 MATERIALS AND METHODS

2.1 Location of sample

In this study, lateritic soil was collected from Iju, Ota region of Ogun State, Nigeria. The AASHTO and USCS classification systems classify the soil as A-7-6 and CL, respectively. To get a consistent sample for analysis, it was air dried, powdered, and run through a 4.75 mm sieve.

2.2 Preparation of PET bottle shreds

Used PET bottles were collected, washed, and fed into a plastic shredder to produce shreds of about 2 mm to 4 mm in length. To find the content that improves strength the most, the shredded PET was applied to the soil at different percentages of 2, 4, 6, 8, and 10% by dry weight of soil.

2.3 Incorporation of periwinkle shell ash (PSA)

Local seafood processing facilities in Ota provided the periwinkle shells. After being cleaned to get rid of any biological material, the shells were allowed to air dry before being torched in an open environment. The resulting ash was thermally treated at 600°C for 3 hours to enhance its pozzolanic properties and then ground to pass through a 75 μm sieve. Based on the results obtained from the PET bottle shred optimization stage, a PET bottle shred content of 6% was kept constant while periwinkle shell ash was added using various percentages of 2, 4, 6, 8 and 10% by weight.

2.4 Experimental methodology

Natural moisture content, specific gravity, particle size distribution (sieve and hydrometer analysis), Atterberg limits, standard proctor compaction, unconfined compressive strength (UCS), California bearing ratio (CBR), and permeability were among the numerous laboratory tests conducted on the stabilised mixes and natural soil. The moisture content of the soil was determined according to the oven

moisture method described by Segun & Olufikayo (2016) where a known mass of soil was oven dried for 24 hours at 105–110°C. Specific gravity was determined using a pycnometer with distilled water (Kiran Kumar & Praveen Kumar, 2020). Compaction tests were used to evaluate each mix's maximum dry density (MDD) and optimal moisture content (OMC). UCS and CBR tests were carried out on samples compacted in cylindrical moulds and loaded axially to failure, with readings taken from the load and deformation dials (Ahmed & Rahman, 2007). Permeability was determined using a falling head permeameter(Okonkwo et al., 2022). PET bottle shred content was first varied alone at 2, 4, 6, 8 and 10% to identify the optimum content, after which this optimum content (6%) was fixed while periwinkle shell ash was varied at 2, 4, 6, 8 and 10% to obtain the combined optimum mix. The results from the treated soil were then compared with the untreated soil to evaluate the improvement in engineering properties.

3 RESULTS AND DISCUSSIONS

3.1 Basic properties of lateritic soil

The natural lateritic soil was classified as A-7-6 and CL according to the AASHTO and USCS classification systems. Table 1 summarizes its basic geotechnical properties. More than 35% of the soil passed the No. 200 sieve, with 47.5% fines, a liquid limit of 40% and a plasticity index above 10%, all of which support the A-7-6 classification. The natural moisture content of 13.5% falls within the range typically reported for lateritic soils, while the coefficient of permeability of 2.3×10^{-5} cm/s falls within the range for silty sand and silt. The specific gravity of 2.53 places the soil within the range reported for halloysitic lateritic soils (Nnochiri, 2017).

Table 1
Basic properties of natural (untreated) lateritic soil.

Property	Value
Natural moisture content (%)	13.5
Specific gravity	2.53
Liquid limit (%)	40
Plastic limit (%)	20
Plasticity index (%)	20
Passing No. 200 sieve (%)	47.5
AASHTO classification	A-7-6
USCS classification	CL
Maximum dry density (kg/m3)	1772
Optimum moisture content (%)	15.1
CBR (%)	5.5
UCS (kN/m2)	120.5
Coefficient of permeability (cm/s)	2.3 x 10 − 5

3.2 Optimization of PET bottle shred content

PET bottle shreds were first added to the natural soil alone at 2, 4, 6, 8 and 10% by weight to identify the content that gives the best improvement in unconfined compressive strength. The highest UCS value obtained was 222.0 kN/m2 at 6% PET bottle shreds, compared with 120.5 kN/m2 for the untreated soil, and this content was found to give the best performance among all the percentages tested. This agrees with the general observation that fibre-reinforced soils have an optimum fibre content beyond which strength begins to decline as the fibres start to interfere with particle packing rather than improve bonding (Bozyigit et al., 2021; Naser et al., 2021). The 6% PET bottle shred content was therefore fixed for the rest of the study, while periwinkle shell ash was varied.

3.3 Compaction and density tests

Table 2 shows the results of the compaction tests carried out on the soil at 6% PET bottle shred content with periwinkle shell ash varied from 0 to 10% (the 0% row represents the untreated natural soil, included as the baseline for comparison). The maximum dry density (MDD) decreased steadily from 1772 kg/m3 for the untreated soil to 1700 kg/m3 at 6% PET and 10% PSA, while the optimum moisture content (OMC) increased correspondingly from 15.1% to 16.2% (Table 2, Figs. 1 and 2). This decrease in MDD with increasing PSA content agrees with similar findings reported for periwinkle shell ash treated lateritic

soils (Nnochiri, 2017), and may be attributed to the relatively low specific gravity of the ash particles compared with the soil particles they are replacing.

Table 2
Compaction test results (6% PET bottle shreds, varying PSA).

PSA (%)	MDD (kg/m3)	OMC (%)
0*	1772	15.1
2	1760	15.5
4	1740	15.7
6	1720	15.9
8	1705	16.0
10	1700	16.2

3.4 Atterberg limits

Table 3 shows the Atterberg limit results for the soil at 6% PET bottle shred content with varying periwinkle shell ash. Both the liquid limit and plastic limit increased with increasing PSA content, from 40% and 20% respectively for the untreated soil to 46% and 32% at 10% PSA. However, the plasticity index decreased from 20% at 0% PSA to about 14% at 8–10% PSA, which represents an improvement in the workability of the soil (Basha et al., 2005). According to the Federal Ministry of Works and Housing specification, a liquid limit below 50% and a plasticity index below 30% are generally considered acceptable for soils used as road subgrade or fill material, both of which are satisfied by all the mixes tested in this study.

Table 3
Atterberg limits (6% PET bottle shreds, varying PSA).

PSA (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
0*	40	20	20
2	42	24	18
4	43.5	26	17.5
6	44	29	15
8	45	31	14
10	46	32	14

3.5 Unconfined compressive strength

The UCS results for the soil at 6% PET bottle shred content with varying periwinkle shell ash are presented in Table 4. The highest UCS value of 273.3 kN/m2 was obtained at 6% periwinkle shell ash, compared with 222.0 kN/m2 for the soil stabilized with 6% PET bottle shreds alone, and 120.5 kN/m2 for the untreated soil. Beyond 6% PSA, the UCS reduced to 249.1 kN/m2 and 222.6 kN/m2 at 8% and 10% PSA respectively (Table 4, Fig. 3). This shows that there is an optimum ash content beyond which the excess fine material begins to disrupt the bonding between soil particles rather than improve it (Attah & Yohanna, 2020; Nnochiri, 2017).

Table 4
Unconfined compressive strength (UCS) test results (6% PET bottle shreds, varying PSA).

PSA (%)	UCS (kN/m2)
0*	222.0
2	204.9
4	239.1
6	273.3
8	249.1
10	222.6

3.6 California bearing ratio

Table 5 shows the unsoaked CBR results. The untreated soil recorded a CBR of 5.5%, which is below the minimum value generally recommended for subgrade material (Okonkwo et al., 2022). The CBR value improved considerably with the addition of the stabilizers, reaching a peak of 19.5% at 6% PET bottle shreds and 6% periwinkle shell ash, before reducing to 14.7% and 9.8% at 8% and 10% PSA respectively (Table 5, Fig. 4). This peak CBR value represents more than a three-fold improvement over the untreated soil and shows that the 6% PET and 6% PSA combination is the most effective mix identified in this study for subgrade applications.

Table 5
Unsoaked California bearing ratio (CBR) results (6% PET bottle shreds, varying PSA).

PSA (%)	CBR (%)
0*	5.5
2	8.4
4	9.1
6	19.5
8	14.7
10	9.8

3.7 Permeability

Table 6 shows the coefficient of permeability of the soil at 6% PET bottle shred content with varying periwinkle shell ash. The coefficient of permeability reduced from 2.3 x 10^{-5} cm/s for the untreated soil to a minimum of 6.6 x 10^{-6} cm/s at 6% periwinkle shell ash, before increasing slightly to 7.7 x 10^{-6} cm/s and 9.1 x 10^{-6} cm/s at 8% and 10% PSA respectively. This reduction in permeability with the addition of the stabilizers suggests that the fine ash and shredded plastic particles fill up the pore spaces within the soil matrix, reducing its ability to transmit water (Ali Said Al Alawi et al., 2023).

Table 6
Coefficient of permeability (6% PET bottle shreds, varying PSA).

PSA (%)	Coefficient of permeability, K (cm/s)
0*	2.3 x 10 − 5
2	1.4 x 10 − 5
4	8.6 x 10 − 6
6	6.6 x 10 − 6
8	7.7 x 10 − 6
10	9.1 x 10 − 6

**The 0% row in* Tables 2, 3, 4, 5 and 6 *represents the untreated natural soil, included as the baseline for comparison.*

3.8 Discussion

It is concluded from overall results that the use of PET bottle shreds and periwinkle shell ash along with lateritic soil enhances the engineering properties of the lateritic soil more than either one alone. The 6% PET and 6% PSA mix exhibited the desired strength and bearing capacity with the CBR value increasing from 5.5% to 19.5% and the UCS value increasing from 120.5 kN/m2 to 273.3 kN/m2.. This improvement can be attributed to the fibre-like reinforcement provided by the shredded PET, which increases the tensile resistance of the soil matrix, combined with the pozzolanic reaction of the periwinkle shell ash, which agrees with (Attah et al.'s, 2019) report of cementitious compounds such as calcium silicate hydrate and calcium aluminate hydrate forming at the inter-particle contact of soil grains. Comparable calcium–alumino–silicate hydrate phases have been identified by SEM-EDX in binders produced from agro-industrial waste ashes (Oyebisi et al., 2020), supporting the attribution of the observed strength gain to pozzolanic reaction products.

The reduction in maximum dry density with increasing periwinkle shell ash content is consistent with the relatively low specific gravity of the ash compared with the soil it replaces, while the corresponding rise in optimum moisture content suggests that the ash particles require more water for adequate compaction (Nnochiri, 2017). The reduction in permeability at moderate PSA content is beneficial in limiting water infiltration into the subgrade, although the slight increase observed beyond 6% PSA should be considered where a consistently low permeability is required.

Beyond 6% periwinkle shell ash, both the UCS and CBR values began to decline. This is likely due to an excess of fine ash particles disrupting the cohesion between the soil, PET shreds and ash, rather than continuing to improve the bonding between them. This shows that there is an optimum stabilizer content beyond which further addition does not continue to improve the soil, and this should be considered in mix design for field applications.

The peak CBR value of 19.5% obtained in this study did not meet the CBR requirement generally specified for base course material, but it represents a substantial improvement over the untreated soil and is considered adequate for use in the subgrade layer of lightly trafficked roads (Attah et al., 2019). Further work involving durability testing with repeated wetting and drying and microstructural examination would help verify the durability of this stabilized soil in the field.

4 CONCLUSION

The lateritic soil adopted for the study was found to belong to A-7-6 classification in AASHTO classification system and CL in USCS system having natural moisture content of 13.5% and CBR value of 5.5% which indicates that the soil is of intermediate plasticity and low natural bearing capacity. PET bottle shreds were found to give the best improvement in strength at 6% content, and this was fixed while periwinkle shell ash was varied. The combination of 6% PET bottle shreds and 6% periwinkle shell ash provided the best overall enhancement in the engineering properties of the soil, raising the CBR value to 19.5% and the UCS value to 273.3 kN/m2. The maximum dry density decreased and optimum moisture content increased with increased periwinkle shell ash content and the permeability of the soil

generally decreased as the stabilizers were added. The results indicate that the properties of the lateritic soil can be significantly improved by incorporating waste materials such as PET bottle shreds and periwinkle shell ash to be used as sub grade soil in road pavement construction, and that it can lead to more sustainable waste management.

Declarations

FUNDING

This research was funded personally by the researchers.

AUTHOR CONTRIBUTIONS

Odokuma and Akande prepared the manuscript, Adamu and George proofread, and all the others participated in the laboratory analyses.

ETHICS, CONSENT TO PARTICIPATE, AND CONSENT TO PUBLISH DECLARATIONS

Not applicable.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Figures

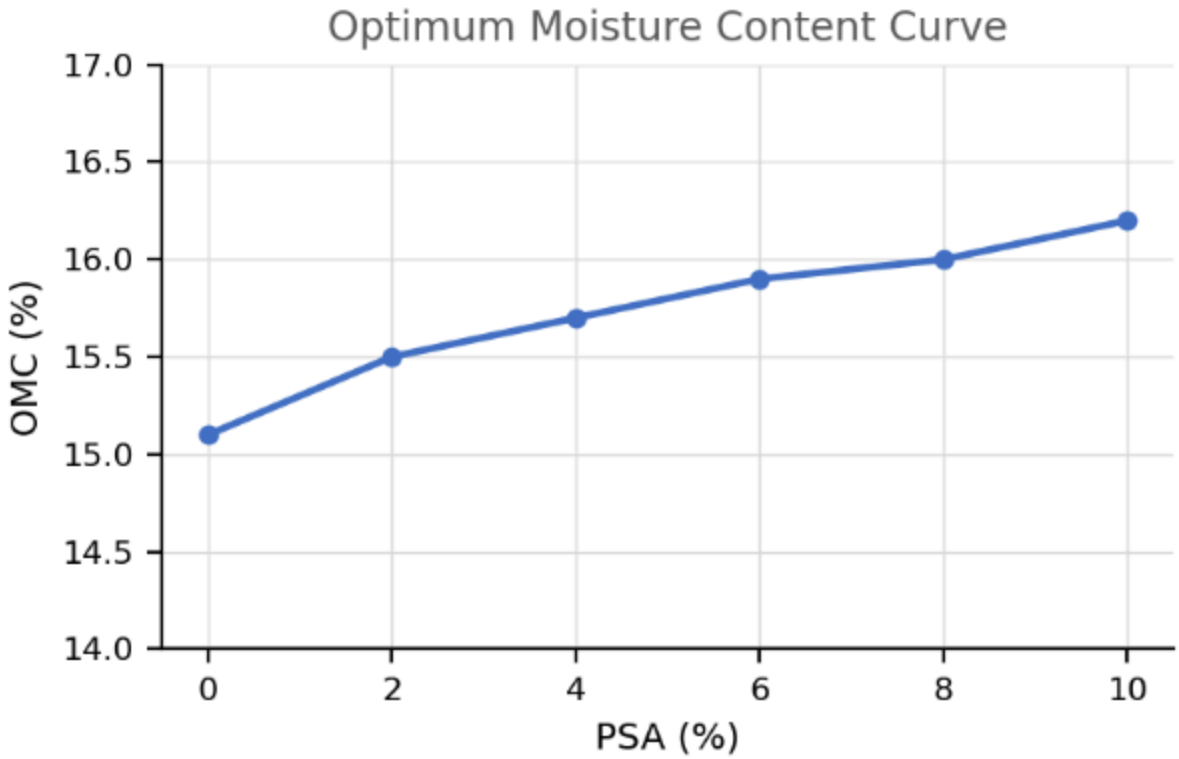


Figure 1

Optimum moisture content of the different mixes.

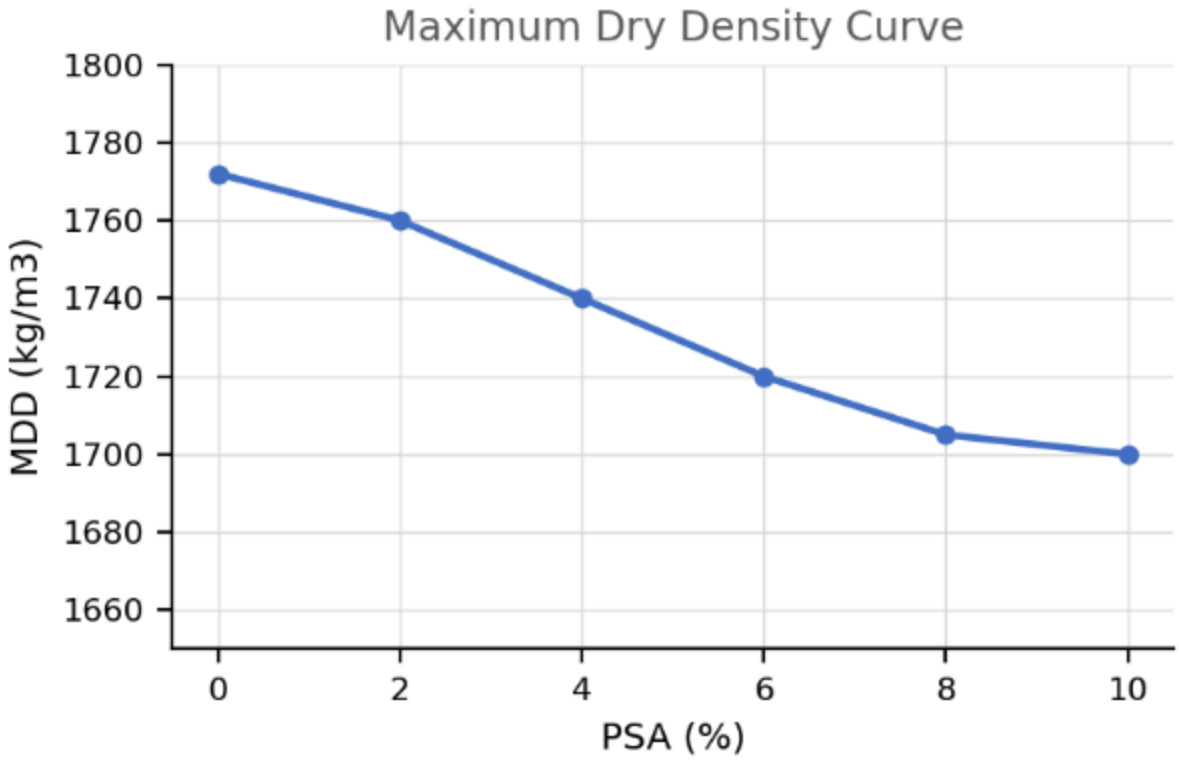


Figure 2

Maximum dry density of the different mixes.

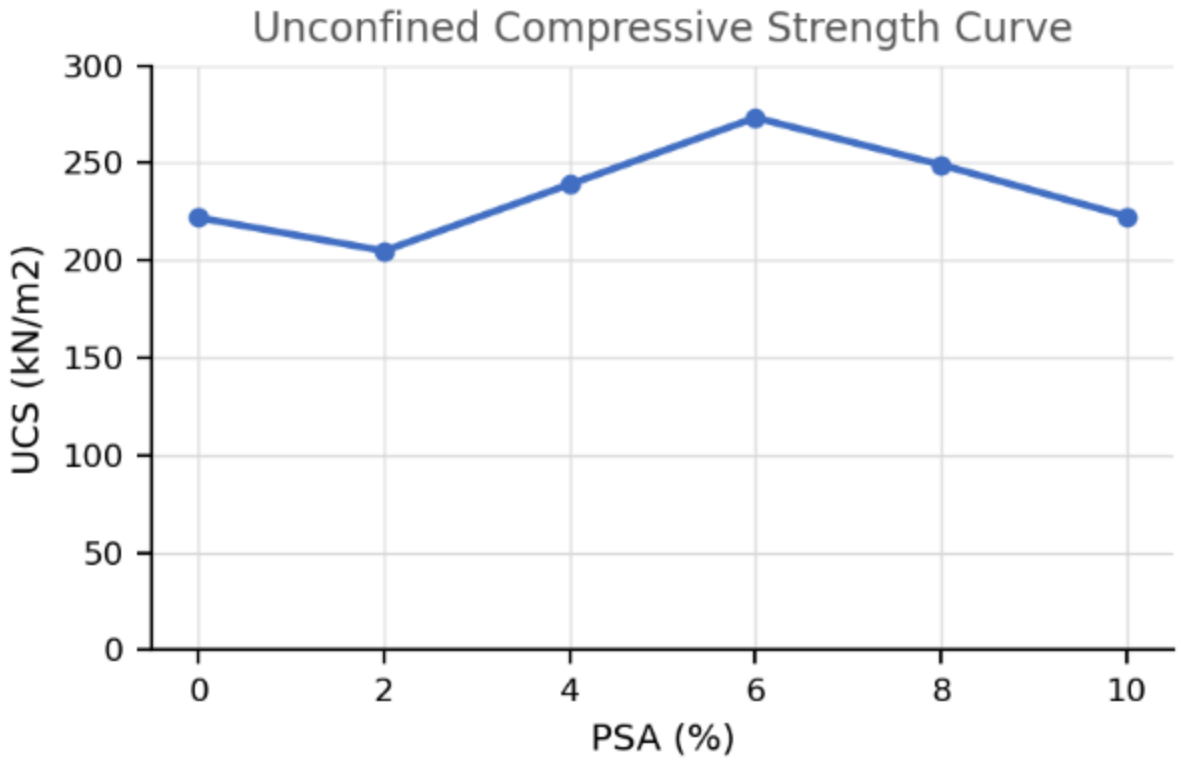


Figure 3

Unconfined compressive strength curve showing maximum strength attained.

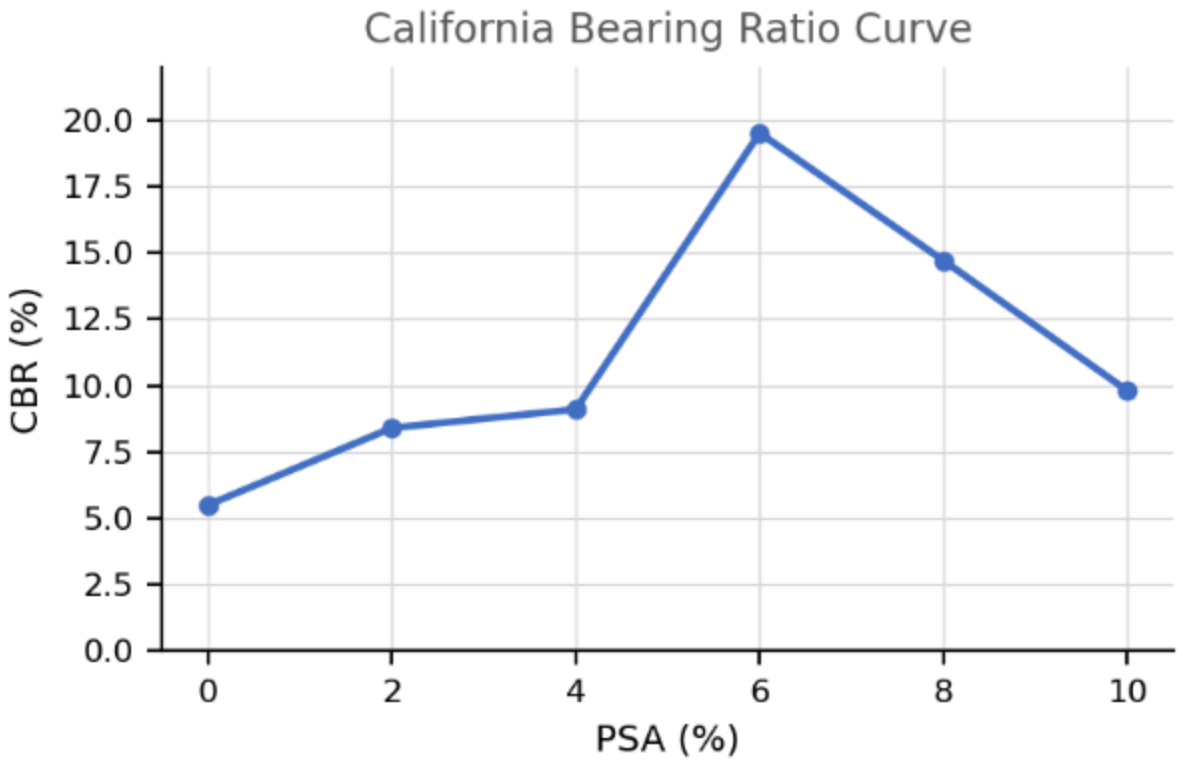


Figure 4

California bearing ratio curve showing maximum value attained.