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Sustainable Subgrade Soils: Impact of Pine Ash and Donax Obesulus Dust

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Abstract*– Road infrastructure plays a crucial role in economic growth and promoting decent employment by connecting different regions and cities through roads and highways. The use of recycled materials offers an alternative to optimize and reduce resources while improving the physical and mechanical properties of the soil, which in turn reduces costs. The purpose of this study was to evaluate the effect of pine ash (CP) and Donax obesulus dust (PDO) on the natural soil sample with dosages of 10% and 16%. It is a basic type study, with a quantitative approach and according to its explanatory level, with a quasi-experimental design with post-test. The most optimal dosage was 16% CP and 16% PDO, a variation with respect to the natural soil (NS) of MDS of 1,680 gr/cm³ to 1,799 gr/cm³, OCH of 5.87% to 2.00% and CBR of 8.4% was achieved. to 24.17%. According to statistical tests, the parallel dosages of both materials contribute to good compaction, bearing capacity and resistance in low quality soils intended for subgrade.

***Keywords*-- pine ash; Donax obesulus dust; resistance; compaction; subgrade.**

INTRODUCTION

In several Latin American countries, roads exhibit deficiencies such as cracks, fractures, sinkholes, seepage, and potholes. For instance, in Brazil, more than 50% of the roads show problems, and only 13% are paved [1]. In Mexico, the constant flow and presence of heavy cargo vehicles affect pavements due to soils with soft and clayey characteristics, as well as a low California Bearing Ratio (CBR) [2]. In Cuba, local soils are used for subgrade construction in road infrastructure projects. Chemical stabilization modifies soil properties, reducing plasticity and improving cohesion and bearing capacity [3]. Soils composed of inorganic clays with low to medium plasticity (CL) and silty clays (CM) exhibit properties that are not ideal. However, these can be significantly improved by adding materials such as rice husk, optimizing the mechanical properties of the CBR [4], [5], [6]. Additionally, this practice not only provides economic benefits but also environmental ones. As the number of blows applied with tampers increases, the dry density of the soil increases and its moisture content decreases [7], [8], [9], [10]. The design strength in CBR of pavement layers largely depends on the strength of the subgrade soil [11]. During the soil stabilization process, various reactions occur, such as hydration, cation exchange, flocculation, and pozzolanic reactions. Additionally, it is indicated that the soil can be stabilized by adding certain additives, such as lime, cement, fly ash, among others [12].

Sawdust can improve the geotechnical properties of soil, such as limited compressive strength and CBR, through a mixture of 3% sawdust and 97% soil. Additionally, mixing it with 0% and 7% sawdust reduces the soil's plasticity index (PI) from 64% to 36%, respectively [13], [14], [15]. As the percentage of sawdust in the soil increases, the permeability coefficient decreases from 0.18 to 0.08 [16], [17], [18]. The real benefits of soil improvement with sawdust can be evaluated through soaked and unsoaked CBR tests on stabilized samples, which could be conducted in future research [19], [20], [21], [22]. In road construction, sawdust can be considered an economical and suitable stabilizing agent to improve the geotechnical properties of soft clay soils [23], [24], [25]. Sawdust Ash (SDA) has great potential for use in the construction industry, meaning it can be used as an additional raw material or additive, increasing the reactivity of binders and reducing the porosity of materials [26], [27].

Focusing on seashells, in Sechura, northern Peru, more than 80% of the national production is managed. Additionally, up to 25,000 metric tons of empty hard shells are discarded annually as waste in municipal landfills [28]. The size of the crushed shells had a significant impact on the physical and mechanical properties of the concrete [29], [30], [31], [32]. The reduction in these properties was less when 20-25% of the fine aggregate and 20% of the coarse aggregate were replaced. Additionally, the shells are durable and can be used as a material to improve soil characteristics [33], [34], [35]; the bonding of powdered shell particles increases the ability to withstand compressive forces and decreases decomposition in the presence of water [36]. Clayey and silty soils are very sensitive to moisture content due to their high shrinkage rate. To stabilize them, shell ash patterns can be added in percentages of 5%, 10%, 15%, and 20%, which will decrease the plasticity index and make the soil more compact [37], [38], [39].

Pine leaf ash (PLA) and *Donax obesulus* dust (DOD) are alkaline substances that, when added to clayey soils, reduce their plasticity index [40], [41], [42], [43]. Additionally, it has been shown that adding 2% pine leaf ash and *Donax obesulus* dust in proportions of 5% and 10%, respectively, can increase soil strength and CBR [44], [45], [46]. Mollusk shells originate from the accumulation of protective substances containing calcium carbonate ($CaCO_3$) and are very durable. After the mollusk's death, these shells usually settle on the seabed and, over time, fossilize and turn into rocks [47], [48], [49].

In recent years, Peru has experienced various natural phenomena that have caused damage to roads and hindered vehicular traffic, among other adverse effects [50]. The variety of terrain forms, different climates, and traffic in our country contribute to the more intense deterioration of our roads, as pavements are subjected to extreme conditions [51], [52]. In this regard, it is proposed to evaluate the effect of pine ash and *Donax obesulus* dust on the subgrade soils of a busy main avenue.

MATERIALS AND METHODS

A. *Materials*

Natural Soil Sample (NS):

Soil samples were extracted through seven open-pit test pits, each with a depth of 1.50 meters and covering an area of 1.20x1.20 m². For each sampling point, soil samples were collected in two 50 kg capacity bags, which were transported to the laboratory in thermal containers specifically designed to preserve their intrinsic characteristics. In the laboratory, tests were conducted for Moisture Content (ASTM D-2216), Atterberg Limits (ASTM D-4318), Particle Size Analysis (ASTM D-42), Modified Proctor (ASTM D-1883), which measures soil compaction and maximum density, and finally the California Bearing Ratio (CBR) (ASTM D-1883), to assess soil resistance to penetration under load.

The results obtained revealed that the most critical soil was found in test pit No. 06. Table I shows the basic properties of this critical soil.

TABLE I
BASIC PROPERTIES OF THE SOIL FROM TEST PIT NO. 06.

Properties	Value
Sand (%)	91.2
Fines (%)	5
Gravel (%)	3.8
D10 (mm)	0.096
D30 (mm)	0.205
D60 (mm)	0.496
Plastic limit (%)	NP
Liquid limit (%)	NP
Plasticity index	NP
Moisture content	1.77
Cu	5.16
Sc	0.89
SUCS Classification	SP
AASHTO Classification	A-3 (0)
MDD (gr/cm³)	1.68
OMC (%)	5.87
CBR al 95% de MDD 0.1" (%)	8.4

Cu = Coefficient of Uniformity; Sc = Slope Coefficient; MDD = Maximum Dry Density; OMC = Optimum Moisture Content; CBR = California Bearing Ratio.

Fig. 1 shows the particle size distribution of the critical soil sample from test pit No. 06.

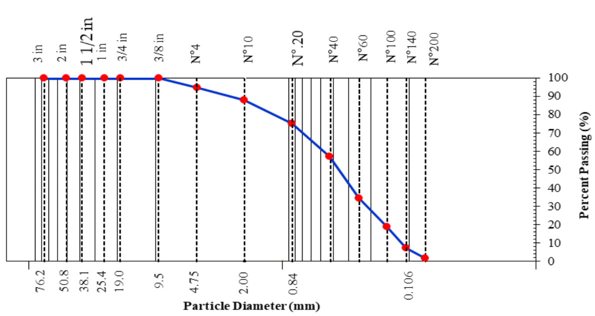

Fig. 1 Particle Size Distribution Curve of the Soil from Test Pit No. 06

Pine Ash (PA):

The pine tree sawdust was obtained from a local sawmill in a district of Trujillo, Peru. This material is a byproduct of pine wood processing. The average particle size of the sawdust was 0.130 mm. To ensure material uniformity, a homemade sieve was used to remove larger debris. Afterwards, it was dried at room temperature under sunlight for 4 hours to remove moisture before controlled incineration. The incineration was carried out at 400°C for 3 hours in a muffle furnace. Fig. 2 shows this material (pine sawdust) in its natural and incinerated states.

Fig. 2 Photographs of (a) pine sawdust collection; (b) weighing of pine sawdust for incineration; (c) pine ash (PA).

Table II details the chemical composition obtained through X-ray Fluorescence (XRF) analysis, a non-destructive analytical technique that identifies the elements present in a sample and quantifies their concentration.

TABLE II
CHEMICAL COMPOSITION OF PINE ASH.

Parameter	Composition (%)
Calcium Oxide (CaO)	10.90
Aluminum (AI_2O_3)	8.60
Potassium Oxide (K_2O)	8.94
Sodium Oxide (Na_2O)	3.05
Ferric Oxide (Fe_2O_3)	8.03
Silicon Dioxide (SiO_2)	58.21

Donax Obesulus Dust (DOD):

The *Donax obesulus* shells were collected from a fishing terminal in the district of Víctor Larco Herrera, Trujillo, Peru. They were then meticulously washed and disinfected, followed by air drying under direct sunlight. To optimize grinding, the shells underwent additional drying in an oven at 120°C for 2 hours. The grinding was done manually in a mortar until an average size of 1 mm was achieved. Then, they were introduced into a ball mill, processing 1.6 kg per cycle for 1.5 hours, totaling 4.80 kg. Finally, a fine powder with a particle size of 0.15 micrometers (μm) was obtained through ring mill pulverization. Figure 3 shows this material (*Donax obesulus*) in its natural and powdered states.

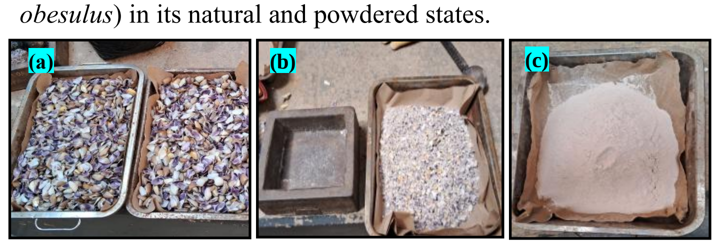

Fig. 3 Photographs of **(a)** *Donax obesulus*; **(b)** Crushed *Donax obesulus*; **(c)** *Donax obesulus* Dust (DOD).

Table III details the chemical composition obtained through X-ray Fluorescence (XRF) analysis.

TABLE III
CHEMICAL COMPOSITION OF *DONAX OBESULUS* DUST (DOD).

Element	Result (%)	Method used
Calcium Oxide (CaO)	99.77	X-Ray Fluorescence Spectrometry
Sulfur Oxide (SO_3)	0.20	
Zirconium Oxide (ZrO_2)	0.03	

B. Methods

Dosages:

The determination of dosages for addition to the natural soil was based on meticulous analyses of previous research. Regarding pine ash, average proportions of 80% natural soil (NS) combined with 10% PA and 10% DOD were adopted [53], [54], [55], [56], [57], as well as a mixture of 68% NS, 16% PA, and 16% DOD.

Experimental Design:

A post-test quasi-experimental design was employed, incorporating two experimental groups and a control group for rigorous comparison. The first experimental group was given a mixture of 10% PA and 10% DOD, while the second group received a higher proportion, consisting of 16% PA and 16% DOD. The control group was maintained with soil in its natural state, i.e., 100% soil without additives, to establish a baseline for the research (Table IV).

TABLE IV
EXPERIMENTAL DESIGN SCHEME.

Groups	Experimental treatment	Measurement of effect
G_1: 100% NS	------------	O_1
G_2: 80% NS + 10% PA + 10% DOD	X_1=10%	O_2
G_3: 68% NS + 16% PA + 16% DOD	X_2=16%	O_3

Testing Methods: Trials

The standards considered for the tests, analysis, and validation of the results are detailed in Table V.

TABLE V
STANDARDS FOR LABORATORY TESTING.

Description	Properties	Tests	Standards
Natural Soil Sample	Physical	Moisture content	ASTM D 2216
		Liquid limit	ASTM D 4318
		Plastic limit	ASTM D 4318
	Mechanical	Granulometry	ASTM D 422
		Modified Proctor	ASTM D1883
		CBR	ASTM D1883
Adding PA and DOD	Mechanical	Modified Proctor	ASTM D 1883
		CBR	ASTM D 1883

Quantity of material:

The amount used for each group and test is detailed below in Table VI.

TABLE VI
AMOUNT OF MATERIAL BY GROUP AND TEST.

Groups	Partial (kg)			Total, for 3 iterations (kg)		
	NS	PA	DOD	NS	PA	DOD
G_1: 100% NS	6	---	---	18	---	---
G_2: 80% NS + 10% PA + 10% DOD	4.8	0.6	0.6	14.4	1.8	1.8
G_3: 68% NS + 16% PA + 16% DOD	4.08	0.96	0.96	12.24	2.88	2.88

Descriptive and Statistical Analysis:

For data analysis, the statistical software SPSS, version 26, was used. Initially, a descriptive comparative analysis was performed. Subsequently, to verify the results, the Shapiro-Wilk test was applied, which confirmed that some data met the normality test while others did not. Then, the ANOVA and Tukey tests were conducted to examine the variation of means among the groups that met normality; otherwise, the Kruskal-Wallis test and the Dunn or Dunn-Bonferroni Post Hoc method were used.

RESULTS

A. Physical and Mechanical Properties of 100% Natural Soil

Stratigraphic profile:

During the excavation of the test pits, strata consisting mainly of poorly graded sand with a low content of gravel and fines were identified. However, an exception was observed in test pit number 1, where a fill layer was found at a depth of 0.10 m. The specific details of the strata are presented in Table VII.

TABLE VII
STRATIGRAPHIC PROFILE OF THE 7 TEST PITS.

Test Pit No.	Depth (m)	Detail	Description
C - 1	0 a 0.10		Backfill
	0.10 a 1.50		Poorly Graded Sand with Low Gravel and Fines Content.
C – 2 a C - 7	0 a 1.50		

Moisture content:

The specific details of the strata are presented in Table VIII and Fig. 4.

TABLE VIII
NATURAL MOISTURE CONTENT OF THE 7 TEST PITS.

Test Pit No.	Moisture content W%
C - 1	1.74
C - 2	3.78
C - 3	3.89
C - 4	2.74
C - 5	2.5
C - 6	3.39
C - 7	1.77

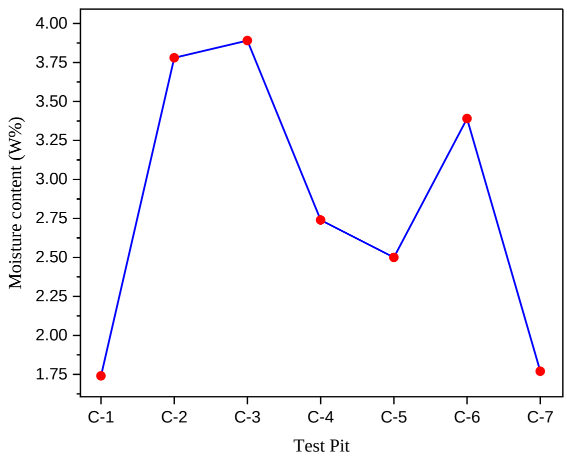

Fig. 4 Moisture content of the 7 Test Pits Under Study.

Grain Size Analysis:

Regarding the AASHTO soil classification, it was determined that the soil present in all the test pits corresponds to type A-3(0). In contrast, according to the Unified Soil Classification System (USCS), it was identified that, with the exception of test pit No. 3 classified as SP-SM, the predominant soil type in the other test pits was SP. The maximum amounts of gravel, sand, and fines were recorded in test pits No. 06 with 5.24%, No. 04 with 95.39%, and No. 03 with 5.91%, respectively. The specific details of the strata are presented in Table IX.

TABLE IX
GRAIN SIZE ANALYSIS RESULTS OF THE 7 TEST PITS.

Test Pit No.	AASHTO	SUCS	Gravel	Sand	Fine
C - 1	A-3 (0)	SP	3.98	91.56	4.46
C - 2	A-3 (0)	SP	3.92	93.11	2.97
C - 3	A-3 (0)	SP-SM	4.43	89.67	5.91
C - 4	A-3 (0)	SP	2.30	95.39	2.30
C - 5	A-3 (0)	SP	3.35	94.00	2.65
C - 6	A-3 (0)	SP	5.24	93.31	1.45
C - 7	A-3 (0)	SP	3.79	91.24	4.98

Modified Proctor:

When performing the Modified Proctor test, the Maximum Dry Density (MDD) was determined, with the lowest value corresponding to test pit No. 07 at 1.628 g/cm³, while the highest was recorded in test pit No. 01 at 1.736 g/cm³. Regarding the Optimum Moisture Content (OMC), the maximum value was observed in test pit No. 07 at 8.56%, and the minimum in test pit No. 01 at 3.63%. These results indicate variability in compaction and the soil's water properties across different sampling locations. The previously described data and observations are detailed in Table X.

TABLE X
MODIFIED PROCTOR TEST RESULTS OF THE 7 TEST PITS.

Test Pit	OMC (%)	MDD (gr/cm³)
C - 1	3.63	1.736
C - 2	6.22	1.694
C - 3	6.52	1.677
C - 4	4.81	1.686
C - 5	4.91	1.701
C - 6	5.87	1.68
C - 7	8.56	1.628

The MDD represents the highest density that the soil can achieve under controlled compaction conditions, while the OMC indicates the amount of water necessary to reach that maximum density. These results reflect the variability in soil compaction characteristics at different locations, which is fundamental for the planning and execution of civil works. Figure 5 illustrates the soil compaction data collected in the preceding table with greater precision and detail, providing a clear visualization of the variations and trends observed in the different samples analyzed.

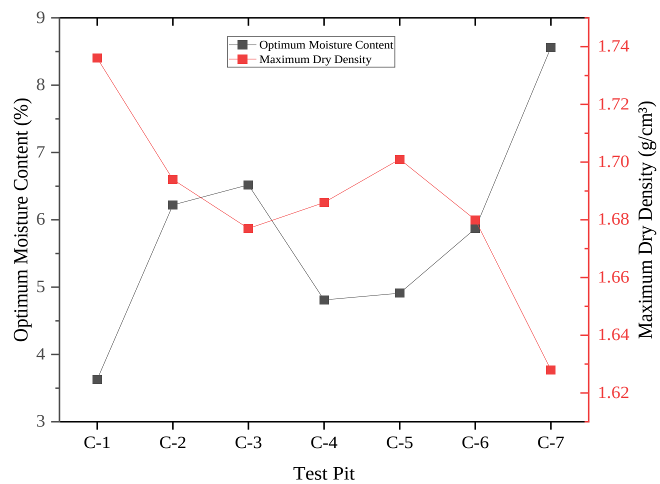

Fig. 5 MDD and OMC of the 7 Test Pits Under Study.

California Bearing Ratio (CBR)

CBR values vary significantly among the samples. The C-1 test pit shows the highest value of 13.9%, indicating a soil with excellent bearing capacity. On the other hand, test pit C-6 presents the lowest value with a CBR of 8.4%, classifying it as soil for use in subgrades of regular quality. Based on these results, the soil from test pit No. 06 has been selected for additional testing, dosing it with proportions of 10% and 16% of PA and DOD, respectively. The mentioned data and observations are presented in Table XI and Fig. VI.

TABLE XI
CBR RESULTS OF THE 7 TEST PITS.

Test Pit	C - 1	C - 2	C - 3	C - 4	C - 5	C - 6	C - 7
CBR (%)	13.9	12.3	10.6	10.1	9.6	8.4	9.5

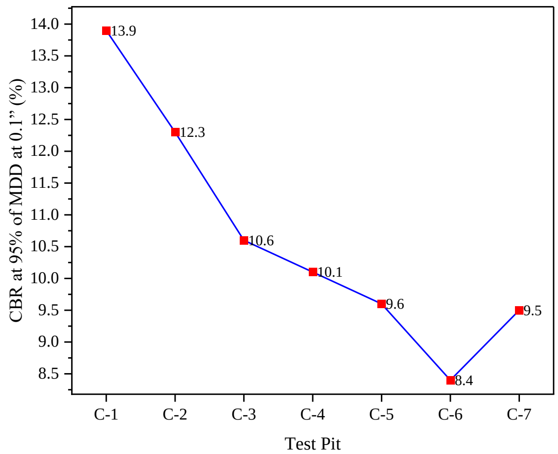

Fig. 6 CBR of the 7 Test Pits Under Study.

B. *Mechanical properties of dosed soil*

Modified Proctor:

The average results of the Modified Proctor test on the natural soil and the soil modified with 10% PA and 10% DOD are presented in Table XII and Fig. 7.

TABLE XII
MODIFIED PROCTOR SOIL TEST AVERAGES ACCORDING TO GROUPS.

Groups	MDD (g/cm³)	OMC (%)
G1: 100% NS	1.68	5.87
G2: 10%PA + 10%DOD	1.760	2.85
G3: 16%PA + 16%DOD	1.799	2.00

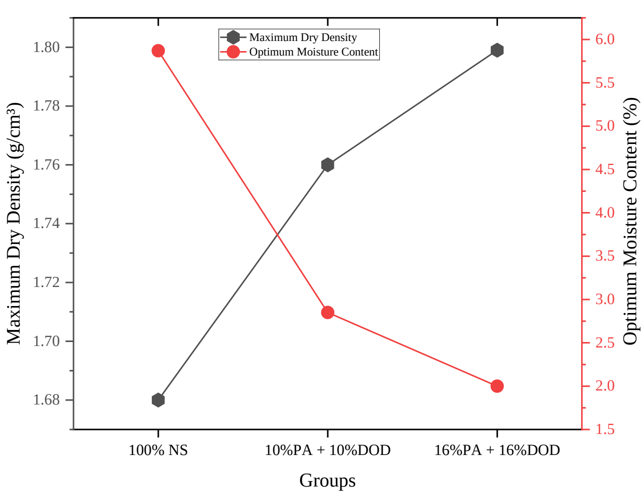

Fig. 7 Development of MDD and OMC of natural and modified soil.

California Bearing Ratio (CBR):

The CBR test for the natural soil and with the addition of 10% CP and 10% PDO provided the following results, which are detailed in Table XIII.

TABLE XIII
CBR AVERAGES FOR NATURAL AND MODIFIED SOIL.

Groups	CBR (%)
G1: 100% NS	8.4
G2: 10%PA + 10%DOD	17.07
G3: 16%PA + 16%DOD	24.17

Note: CBR at 95% of MDD at 0.1".

C. *Statistical analysis*

Normality Test:

In Table XIV, it is observed that the MDD and CBR data satisfy the normality test (> 0.05), which allowed the use of the ANOVA test for equality of variances and the post hoc Tukey test. However, the OMC did not meet the normality test, and therefore, the Kruskal-Wallis test and the Dunn or Dunn-Bonferroni post hoc method were used.

TABLE XIV
SHAPIRO-WILK NORMALITY TEST.

Testing	Shapiro-Wilk		
	Statistical	gl	p-value
MDD	0.834	9	0.050
OMC	0.777	9	0.011
CBR	0.887	9	0.185

Homogeneity Test of Variances, ANOVA and Tukey for MDD and CBR:

Table XV shows that the MDD groups have equal variances (> 0.05) and the CBR groups have different variances (< 0.05).

TABLE XV
LEVENE'S TEST.

Testing		Levene	p-value
MDD	is based on the mean	3.45	0.100
CBR	is based on the mean	6677.00	0.030

Table XVI shows the average and standard deviation in the three dosages for MDD and CBR.

TABLE XVI
PRESENTATION OF MEANS AND STANDARD DEVIATIONS FOR MDD AND CBR.

Testing	Dosages	Repetitions	Mean	Standard deviation
MDD (g/cm³)	100% NS	3	1.68	0.000
	80% NS + 10% PA + 10% DOD	3	1.76	0.007
	68% NS + 16% PA + 16% DOD	3	1.80	0.007
CBR (%)	100% NS	3	8.40	0.000
	80% NS + 10% PA + 10% DOD	3	17.07	0.551
	68% NS + 16% PA + 16% DOD	3	24.17	2.011

Table XVII shows a statistically significant difference between the three MDD dosage groups (p=0.000<0.05). A similar situation is observed for the CBR (p<0.05) when adding the 10% and 16% dosages of PA and DOD to the natural soil (NS). Table XVIII indicates that there are very significant differences (p<0.01) in terms of MDD and CBR between the natural soil and the modified samples, favoring the samples containing PA and DOD.

TABLA XVII
ANOVA TEST.

Testing	F	p-Value
MDD	327.280	0.000
CBR	129.102	0.000

TABLE XVIII
TUKEY POST HOC TEST FOR MULTIPLE COMPARISONS.

Testing	Dosages (I)	Comparison between groups (J)	Difference of Means (I-J)	p-Value
MDD	100% NS	10% PA + 10% DOD	-.080333*	0.000
		16% PA + 16% DOD	-.119000*	0.000
	10% PA + 10% DOD	16% PA + 16% DOD	-.038667*	0.000
CBR	100% NS	10% PA + 10% DOD	-8.666667*	0.000
		16% PA + 16% DOD	-15.766667*	0.000
	10% PA + 10% DOD	16% PA + 16% DOD	-7.100000*	0.001

Kruskal-Wallis and Dunn-Bonferroni Test for OMC:

In Table XIX, it is shown that the two-tailed asymptotic significance (p=0.024<0.05) confirms that there are significant differences in at least two dosage groups for the CBR. In Table XX, it is confirmed that the sample with 16% PA + 16% DOD has a very significant difference (p=0.006<0.01) compared to the natural soil sample.

TABLE XIX
KRUSKAL-WALLIS TEST FOR INDEPENDENT SAMPLES

Description	Value
N total	9
Test statistic	7,448
Degree of freedom	2
Asymptotic sig. (bilateral test)	0.024

TABLE XX
DUNN-BONFERRONI - PAIRWISE COMPARISONS OF DOSAGES.

Comparisons		Test statistic	Deviation Test statistic	P value
16% PA + 16% DOD	10% PA + 10% DOD	3	1.365	0.172
16% PA + 16% DOD	100% NS	6	2.729	0.006
10% PA + 10% DOD	100% NS	3	1.365	0.172

DISCUSSION

Analyses such as stratigraphy, granulometry, Atterberg limits, Modified Proctor, and CBR were conducted. It was determined that the soil was primarily sandy with low silt and gravel content, classified as SP-SM according to SUCS and A-3(0) by AASHTO. The highest natural moisture content was found in test pit No. 06 with 3.39%. The soil did not exhibit liquid or plastic limits, and the Modified Proctor and CBR tests indicated a maximum dry density of 1.680 g/cm³, an optimal moisture content of 5.87%, and a CBR of 8.4%, suggesting an acceptable but somewhat poor-quality soil. Comparative studies of soil properties reveal significant variations. For instance, a clayey soil with high Atterberg limits and low dry density was identified [58], as well as similar results with clayey and sandy soil and a low CBR [59]. High Atterberg limits and a CBR of 5% were also reported [60]; and an SM-SP type soil with higher dry density and low optimal moisture content was observed [61]. These findings suggest that, although the studied soils show improved properties compared to previous ones, there is still room to optimize these characteristics, especially in terms of dry density and moisture content.

This study aimed to optimize the MDD (Maximum Dry Density) and OMC (Optimal Moisture Content) of a sandy soil with low silt and gravel content from a heavily trafficked road, by adding pine tree ash and powder from the shells of a bivalve mollusk called *Donax obesulus*. The optimal dosage was found to be G3 (16% PA and 16% DOD), with which a variation in MDD and OMC was observed, from 1.680 g/cm³ to 1.80 g/cm³ and from 5.87% to 2.00%, respectively, compared to the natural soil, representing an increase in MDD by 7.14% and a decrease in OMC by 3.87%. These results are very promising and represent significant modifications, as a higher dry density increases the soil's bearing capacity [55], an essential condition in the construction of urban roads and highways. Additionally, an adequate moisture content facilitates soil compaction, cohesion, and stability [57]. Previous studies indicate that with the incorporation of this material into the natural soil, the MDD increases by 3.4% and the OMC decreases by 1.05% [41], following the same trend found in the present research. Conversely, with a high dosage of 55% shell powder, increases in MDD of 2.2% and in OMC of 0.8% are obtained [30]. Regarding pine ash, it has been shown that the incorporation of 16% of this product provides the best values, increasing the MDD by 22.14% and decreasing the OMC by 13.8% [17]. These findings demonstrate that the higher the proportion of pine ash, the greater the increase in MDD and the greater the reduction in OMC. *Donax obesulus* powder also contributes positively and reduces moisture when added in proportions similar to pine ash; therefore, combining both materials in equal proportions complements each other and achieves better results in the Modified Proctor test.

The CBR test showed that the dosage of group G3 (16% PA and 16% DOD) significantly increased the soil's bearing capacity from 8.4% to 24.17%. This result is based on the fact that pine ash can reduce soil plasticity, improving workability and compaction, which is beneficial for sandy soils that tend to be non-plastic. Additionally, Donax obesulus powder has the potential to provide calcium carbonate, which acts as a natural cementing agent that helps bind sandy soil particles, enhancing their strength and stability. The combination of these two natural materials provides an effective solution for improving the properties of sandy soils with low silt and gravel content. This is evidenced in [30], where the CBR of a natural soil increased from 13.6% to 58.3% with 55% shell powder, classifying it as excellent for subgrade. Similarly, a CBR improvement from 5% to 18% was achieved with 5% pine ash, making the soil suitable for subgrade [34]. Improvements in soil strength were also observed with optimal dosages of shell powder and ash, respectively [17], [41]. In conclusion, higher dosages improve the soil's bearing capacity as a subgrade.

Finally, it is worth noting that with the most critical sample having a CBR of 8.4%, dosages were implemented that increased the Maximum Dry Density and reduced the Optimal Moisture Content, resulting in a notable increase in the CBR: 17.07% for the 10% dosage and 24.17% for the 16% dosage. The statistical tests used validated the results and confirmed significant variations in MDD and CBR between the natural and modified soil.

CONCLUSIONS

Pine ash and Donax obesulus powder positively influenced the quality of the soil for use as subgrade. This was most notably achieved with a 16% dosage of both materials, as there was a reduction in moisture and an increase in density, allowing for better compaction. Regarding bearing capacity, the soil improved from being suitable for regular subgrade to very good.

The physical and mechanical characteristics of the soil under study indicated that it is a sandy soil with low silt and gravel content, classified as A-3(0) according to AASHTO and SP-SM according to SUCS.

The moisture content was 3.39%. According to the mechanical characteristics obtained through the Proctor test, a Maximum Dry Density of 1.68 g/cm³ and an Optimal Moisture Content of 5.87% were achieved. In the soil bearing capacity test at 95% of MDD with 0.1" penetration, a CBR of 8.4% was obtained.

Through the Modified Proctor test, it was observed that the 16% dosage yields better results in Maximum Dry Density (MDD) and Optimal Moisture Content (OMC), evidenced by a difference in MDD of 0.039 g/cm³ and in OMC of 0.85% compared to the 10% dosage. This suggests that the 16% dosage is more effective in improving the soil's mechanical properties, which is crucial for civil engineering projects where soil stability and strength are fundamental. This finding opens the door to future research that could further explore the practical applications and long-term benefits of these dosages in soil stabilization.

The soil's bearing capacity and strength, as measured by the CBR test, reached a value of 17.07%, categorized as good subgrade (S2: 10% < 17.01% < 20%) and 24.17%, categorized as very good subgrade (S3: 20% < 24.17% < 30%), using the G2 and G3 dosages, respectively. These results demonstrate that the G3 dosage significantly improves the soil's bearing capacity, classifying it within a higher category for subgrade use. This increase in CBR reflects considerable potential for application in construction and paving projects, where high-quality subgrade is essential for structural durability and stability.

Finally, comparing the natural soil samples (G1) with the modified soil samples (G2 and G3) demonstrates that the G2 and G3 dosages significantly improve the soil's mechanical properties, with the G3 dosage showing the most notable changes. These findings are promising for civil engineering and construction, as they indicate that stabilizing the soil with PA and DOD can be an effective alternative to enhance the soil's load-bearing capacity and strength.

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