

Original Article

Subgrade Improvement with the Addition of Molten Polyethylene Bags in Clay Soils

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Abstract - This research analyzes the improvement of clay soil subgrades by adding recycled molten polyethylene bags, offering a technical and ecological option for the construction of urban roads in Huancayo, Peru, where clay soils often weaken road structures. We will stabilize and improve their resistance using molten polyethylene bags as a stabilizer and measure their effect on soil resistance, in accordance with current standards. We analyzed three types of soil, verifying their physical and mechanical properties with methods such as Particle Size Distribution (PSD), Atterberg Limits, USCS and AASHTO classification, Modified Proctor Test(MPT) and California Bearing Capacity (CBR) test, and then incorporated molten polyethylene bags in proportions of 0.5%, 1.0% and 1.5% to observe the behavior of the soil at 95% and 100% of its maximum dry density. The results showed that the gradual addition of plastic increased the CBR index for soils with less than 60% fines and a plasticity between 14% and 17%, and that with a compaction of 95% and a dosage of 1.5%, the CBR reached approximately 6.71%, representing an improvement of around 15% compared to the untreated soil. However, in soils with more than 70% fines, where clay predominates, the improvement was minimal and did not meet the minimum standards. These results contribute to establishing technical guidelines for the use of this additive in urban road projects.

Keywords - ASTM Standards, CBR Index, Clay Soils, Subgrade, Polyethylene bags.

1. Introduction

A very important topic for geotechnical engineering is soil improvement, especially for clay soils, because these soils have high Plasticity and are therefore very unstable when they come into contact with water, subsequently shrinking upon drying [1]. To begin, we must mention that our focus is on road construction, because roads are in direct contact with the soil, and we need stable soil to guarantee the stability and durability of these roads. In our country, Peru, there are highways located above 3,000 meters above sea level. These are major roads that exhibit continuous failures and cracking [2]. Therefore, when analyzing the soil on which these roads are built, we observe that it contains a high percentage of clay [3], which, as mentioned before, contributes to the poor condition of the roads [4]. We want this problem to be far removed from our city, but unfortunately, it is also present in our city, Huancayo, where we can see many roads in poor condition [5]. It is precisely this state of the roads that prevents people from traveling to carry out their daily activities, including commerce. The Peruvian government has observed these problems and has therefore issued regulations to address this issue. These regulations contain minimum standards that must be met to

ensure the stability of the roads, which is something we are beginning to seek.

In other words, we want a suitable solution for soil improvement to enhance the strength of the roads in our city. Our research proposes using recycled polyethylene bags, previously melted, as an additive to improve the properties of the subgrade because in Peru approximately 6000 plastic bags are discarded per minute, which is a large source of pollution and we seek to help not only to improve the resistance of the soils but also to have a solution to the problem of pollution of our planet, seeking a positive environmental impact.

There is previous research on using plastic waste to improve subgrade strength. We can mention the work of researchers Eltayeb and Attom, who carried out their research at the American University of Sharjah [6]. In this study, the authors evaluated the incorporation of shredded plastic waste from water bottles as a stabilizing agent in weak soils, using dosages ranging from 0.5% to 3.0%, with increments of 0.5%. Their results showed that the addition of 1.5% plastic allowed for a doubling of resistance in highly plastic soils, compared to their behavior without additives.



Fadhil and Ahmed [7] in Iraq analyzed the use of plastic waste such as Polyethylene Terephthalate (PET) and Nylon, and did so in proportions of 1%, 1.5%, 2% and 2.5% in relation to the dry weight of the soil for the purpose of improving the geotechnical properties of clay soils, and this was demonstrated in compression and consolidation tests without confinement, which showed that PET increased the cohesion by up to 246.42% with an addition of 2.5%, while nylon reduced the compression index from 0.26 to 0.15 with an addition of 2%. In the end, these results demonstrate that plastic waste significantly improves the strength and mechanical behavior of the soil, constituting a sustainable alternative for its stabilization.

We should also mention the work carried out by researcher Amena at Jimma University [8], who analyzed the use of plastic waste as a reinforcement material to improve the strength and mitigate the swelling of expansive soils used in the subgrade of clay soils. He achieved this by incorporating plastic strips in proportions of 0.25%, 0.5%, 1%, 1.5%, and 2% into the clay soil, the soil improved, as the results showed a notable increase in compressive strength: this went from 80 kPa in the sample without additive to 192.8 kPa when incorporating 0.5% plastic with dimensions of 8×15 mm, demonstrating the favorable effect of plastic reinforcement on the mechanical behavior of the soil.

In this subject, we also have Peruvian researchers such as Dr. Mora [9], who belongs to the National University of Jaén. Mora aimed to identify the mechanical influence generated by the incorporation of polyethylene terephthalate in a subgrade classified as A-6, evaluated by CBR tests with dosages of 1.5%, 3%, and 6%. The results showed that, at 94% compaction, the natural sample reached a CBR of 3.83%, while by adding 3% polyethylene, the value increased to 4.65%, demonstrating an improvement in the soil's bearing capacity.

Despite these advances and our efforts to investigate further the use of molten polyethylene as a soil stabilizer, both in our country and abroad, we regret that research is scarce, especially that aimed at improving clay soils for different purposes, thus, few studies have evaluated whether this technique allows compliance with the minimum requirements established by road design standards, which represents a gap in research, particularly relevant in developing regions where soil conditions and the management of plastic waste pose significant challenges.

In this context, the present study aims to evaluate the effect of incorporating molten polyethylene bags on the mechanical properties of clay soils that will serve as road subgrades in the city of Huancayo, Peru. We must clarify that, unlike previous studies that mainly use plastic in the form of fibers or crushed particles, this research explores the use of molten polyethylene, which allows a different

interaction mechanism with the soil matrix, acting as a binding agent that improves cohesion between particles and the variation in CBR values for different doses of additive (0.5%, 1.0% and 1.5%) and compaction conditions (95% and 100% of the maximum dry density) to determine its effectiveness and compliance with Peruvian technical standards and this not only evaluates the mechanical improvement, but also provides information on the applicability of this technique under local soil conditions, contributing to the development of alternative and sustainable stabilization methods.

2. Materials and Method

To develop the improvement of the subgrade by incorporating previously melted recycled polyethylene bags, the process began with the search for a road that presented predominantly clay soils, and we found a road with these characteristics that is located in the Elinio urbanization, located in the city of Huancayo, Peru, which has an approximate length of 1.35 km, as can be seen in Figure 1, in which the extraction of three representative samples of the soil to be studied was carried out which were taken at a depth of 1.50 meters, in accordance with the relevant regulations.

2.1. Materials



Fig. 1 Roads of urbanization elino

2.1.1. Polyethylene Bags

Plastic bags are made from polyethylene, which comes from ethylene found in petroleum or natural gas [11]. This flexible and durable polymer is used in many everyday products. Its low cost makes it common in homes and industries. There are two main types: Low-Density Polyethylene (LDPE) and High-Density Polyethylene (HDPE) [12], which can be recognized by their symbols in Figure 2. To make the bags, recycled plastic waste is chosen, cleaned, and melted. The melted plastic is then mixed into the soil at 0.5%, 1.5%, and 1.5% levels for the study. The process of melting plastic bags was carried out using a homemade system consisting of two metal oil containers

connected by a galvanized pipe, in which we put approximately 1 kg of plastic in one container, while the other contained water to retain the vapors. The heating was applied directly to the fire, reaching estimated temperatures between 90 °C and 105 °C, which were indirectly controlled by adjusting the intensity of the fire to avoid degradation of the material. This lasted approximately 10 minutes until the polyethylene melted completely, then it was incorporated into the still-hot soil and mixed manually to achieve a homogeneous distribution. Doses of 0.5%, 1.0%, and 1.5% were used, with at least three replicates per condition.

2.1.2. Clay Soil

Clay soil is mainly composed of the minerals Kaolinite, Illite and Montmorillonite, characterized by extremely fine particles, generally less than 2 microns [13] which have the particularity of contracting when losing moisture and expanding when regaining it [14], therefore, due to these physical properties, clay soils usually have a low bearing capacity and limited compaction, a consequence of their high compressibility, their cohesion and their reduced permeability [15] and that is why the three samples were obtained manually in the field, using appropriate tools and ensuring their transport in airtight bags that guaranteed their preservation until their arrival at the laboratory.



Fig. 2 Symbol representing high and low-density polyethylene

2.1.3. Technical Standards

In order to ensure compliance with the standards and guarantee the validity of the results obtained, standardized procedures were used according to the American ASTM standard, which required that the standard sample be subjected to a granulometric analysis according to ASTM D422 [16] and the determination of its consistency limits following ASTM D4318 [17], for that reason, the three samples were additionally evaluated using the Modified Proctor test (MPT), following the guidelines of the ASTM D1557 standard [18], and the bearing capacity of the material was determined using the California Bearing Ratio (CBR) test in both the standard samples and those with the percentages of the proposed additive, according to the methodology established in the ASTM D1883 standard [19].

Finally, the results obtained were compared with the minimum parameters established in the Highway Manual,

Soils and Pavements Section, in order to verify the suitability of the treated material for its eventual use in subgrade layers.

2.2. Research Methodology

To achieve the research objective, it is essential to identify the properties of the samples through a series of laboratory tests that allow for the scientifically rigorous recognition of the soil structure and the understanding of its physical and mechanical properties, both in its natural state and in its modified condition, for that reason, the three soil samples were first identified and extracted, and then the corresponding analyses were carried out, such as particle size distribution, consistency limits, and soil classification, culminating in the Modified Proctor and CBR tests to obtain quantifiable results that allow for the evaluation and verification of the changes produced in the structure of the samples.

2.2.1. Particle Size Analysis Test (PSA)- Sieve Analysis

The granulometric analysis test aims to separate the material according to its different particle sizes, using sieves with openings ranging from more than 75 mm to 0.075 mm, which follows the ASTM D422 standard [16], using the necessary equipment for its correct execution, such as metal sieves, electronic balance, drying oven, trays and brushes that were used from the initial part where first the material had to be dried exposed to the open air, continuing with the quartering of the material, then taking a representative sample, which was dried in an oven at an approximate temperature of 105 °C for 24 hours, subsequently, the sample was carefully crumbled to avoid breaking the particles and recording the initial weight.

The sieving process was started by placing the sample on top of the series of sieves and shaking it for a period of fifteen minutes, then weighing the material retained on each sieve, and thus determining the percentage of material retained on each mesh, which was done with the following equation (1).

$$\% \text{Retained} = \frac{W_r}{W_t} \times 100 \quad (1)$$

W_r = mass retained on the sieve (kg)

W_t = initial total mass of the sample (kg)

Once the percentage of material retained on each sieve was determined, the cumulative retained percentage was calculated. From this value, the passing percentage was obtained, which is determined as the difference between 100 and the accumulated retained percentage. This calculation allows us to establish the proportion of material that passes through each sieve, essential information for constructing the particle size distribution curve of the soil.

2.2.2. Consistency Limit Test- Atterberg Limits Test

The objective of performing the consistency limit test was to determine the moisture values at which the soil modifies its behavior and, based on this, to classify the analyzed samples following the ASTM D4318 standard properly [17], which tells us that the liquid limit is the parameter that indicates the minimum moisture content at which a soil changes from a plastic state to a liquid state and for its determination, the material that passes through the No. 40 sieve was selected, using dry samples of 150 to 200 grams, as established by the standard.

On the other hand, the plastic limit corresponds to the minimum moisture content at which a cohesive soil can be molded and deformed without cracking or breaking, which was determined using the material previously prepared for the liquid limit test, using an approximate sample of 25 grams, to finally obtain the plastic index using the following equation (2)

$$PL = LL - PL \quad (2)$$

- IP = Plasticity index
- LL = Liquid limit
- LP = Plastic limit

The equipment and accessories used included containers for storing and mixing the material, a No. 40 sieve, a flexible blade spatula, the Casagrande cup, capsules for determining moisture content, an electronic balance, and a glass plate at least 300 mm on each side, square in shape, and 10 mm thick.

2.2.3. Modified Proctor Test

The objective of the Modified Proctor test is to determine the relationship between the moisture content of the soil and the maximum dry density that it can reach under controlled compaction conditions, for which it was applied to the three samples extracted in the field, preserved in their natural state and its execution was carried out in accordance with the guidelines established in the ASTM D1557 standard [18]. To carry out the procedure, a representative soil sample is initially prepared, which is partially dried and sieved to remove particles exceeding the size of sieve No. 4. Once the sample is conditioned, an initial amount of water is added and mixed until a homogeneous moisture distribution is obtained. Subsequently, the material is compacted inside the Proctor mold, placing it in five uniform layers and applying 25 blows per layer, until the total volume of the mold is filled.

Once the soil was compacted inside the mold, the mass of the sample was determined and recorded, then the material was extracted from the mold, and a representative portion was taken to determine its moisture content. This same process was repeated at a minimum of four points, each compacted with different moisture contents, in order to

construct the compaction curve with which we will determine the maximum dry density and the optimum moisture content, which are fundamental parameters provided by the test and which serve as a reference for compaction controls in the field. We will use equation (3), employed to calculate the wet density, and equation (4), which provides the dry density.

$$\rho_{wet} = \frac{W_{mold+soil} - W_{mold}}{V_{mold}} \quad (3)$$

ρ_{wet} = The resulting wet density

$W_{mold+soil}$ = Weight of the compaction mold filled with wet, compacted soil

W_{mold} = Weight of the empty compaction mold

V_{mold} = The known volume of the mold

$$\rho_{dry} = \frac{\rho_{wet}}{1+w/100} \quad (4)$$

ρ_{dry} = Dry Density

ρ_{wet} = Wet Density

w = Moisture Content

2.2.4. CBR Test

The objective of the California Bearing Ratio test is to determine the soil's resistance capacity to penetration stresses and in the present study, this test allowed comparing the behavior of the sample in its natural state with that of the samples modified by incorporating different dosages of melted polyethylene bags, in order to evaluate the changes in their mechanical properties according to the guidelines established in the ASTM D1883 standard [19].

Among the main equipment and tools used in the test are the CBR metal molds, with dimensions of 15.24 cm in diameter and 17.78 cm in height, as well as the spacer discs and the loading discs, in addition to a 2.5 kg compaction rammer and an electronic scale, electric ovens for drying the samples, trays, containers for handling the material and an immersion tank intended for the saturation stage. For the penetration phase, the CBR press was used, as well as minor tools such as spatulas, spoons, sieves, and devices for measuring moisture. The procedure began with the selection and preparation of the soil, which was previously homogenized and sieved, and then proceeded to the continuous compaction of the material in five successive layers, applying 12, 26, and 55 blows per layer, with a tamper that transmitted the impact from a height of 30.5 cm.

Subsequently, the surface of the sample was leveled, and the metal mold from the CBR test was removed to proceed with the immersion of the molds in water. For seven days, daily measurements were made with the Expansion (Swell) Test Apparatus in order to monitor the variations in the

height of the sample during the saturation process. Once this stage was completed, the samples were extracted from the water, surface dried, and placed in the CBR press, where the load was applied using the penetration piston. Finally, the results obtained were compared with the subgrade category established by the standard, presented in Table 1, in order to evaluate the differences between the samples without an additive and those containing the corresponding dosages of melted bags.

Table 1. Soil classification based on CBR value

SUBGRADE CATEGORY	CBR
S0: Inadequate Subgrade	CBR < 3%
S1: Insufficient subgrade	De CBR ≥ 3% A CBR < 6%
S2: Regular Subgrade	De CBR ≥ 6% A CBR < 10%
S3: Good Subgrade	De CBR ≥ 10% A CBR < 20%
S4: Very Good Subgrade	De CBR ≥ 20% A CBR < 30%
S5: Excellent Subgrade	CBR ≥ 30%

3. Results and Discussion

3.1. Results of Particle Size Distribution (PSD)

The results of the sieving particle size analysis test are presented in Tables 2, 4, and 6, corresponding to Samples 1, 2, and 3, respectively, which were used to classify the material according to ASTM D2487 [20] and AASHTO M145 standards.

Table 3 shows the granulometric distribution of Sample 1, in which it can be seen that the predominant materials correspond to the silt-clay and sand fractions, whose joint participation exceeds 90% of the total composition of the material and shows the predominance of fine and medium particles within the analyzed sample.

Figure 3 shows the particle size distribution curve for Sample 1, obtained from the data in Table 2 and according to [21]. The particle size distribution is classified as continuous and is concentrated in the fine particle range, which allows the identification of a material with low permeability, high sensitivity to moisture, and a bearing capacity that varies from low to medium.

Table 2. Sieve analysis table - sample 1

GRANULOMETRIC SIEVING TEST		
SIEVE SIZE (in)	SIEVE SIZE (cm)	% PASSING
3"	7.5	100.00%
2"	5	100.00%
1 1/2"	3.75	100.00%
1"	2.5	100.00%

3/4"	1.9	100.00%
1/2"	1.25	98.37%
3/8"	0.95	96.75%
1/4"	0.63	95.90%
N°4	0.475	95.13%
N°10	0.2	89.30%
N°20	0.085	79.65%
N°40	0.0425	72.47%
N°60	0.025	65.77%
N°100	0.015	56.31%
N°200	0.0075	50.08%

Table 3. Particle distribution - sample 1

GRANULOMETRIC CLASSIFICATION		
SILT AND CLAY	SAND	GRAVEL
50.08%	45.05%	4.87%

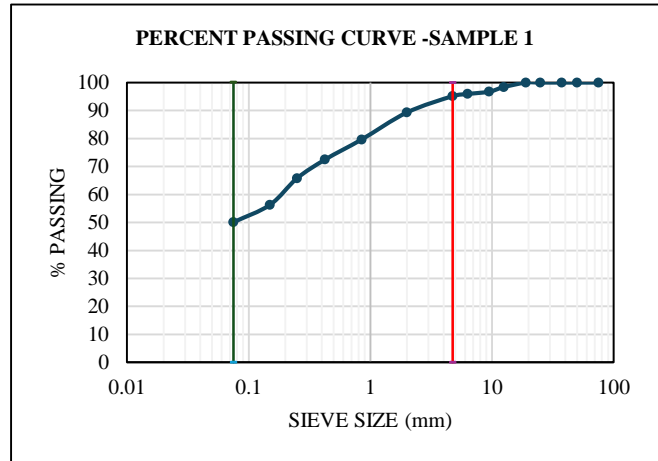


Fig. 3 Percent passing curve -sample 1

Table 4. Sieve analysis table - sample 2

GRANULOMETRIC SIEVING TEST		
SIEVE SIZE (in)	SIEVE SIZE (cm)	% PASSING
3"	7.5	100.00%
2"	5	100.00%
1 1/2"	3.75	100.00%
1"	2.5	100.00%
3/4"	1.9	97.77%
1/2"	1.25	96.74%
3/8"	0.95	94.21%
1/4"	0.63	93.24%
N°4	0.475	91.95%
N°10	0.2	87.25%
N°20	0.085	78.65%
N°40	0.0425	69.35%
N°60	0.025	59.45%
N°100	0.015	51.75%
N°200	0.0075	47.25%

Table 5 presents the particle size distribution of Sample

2. Compared to Sample 1, there is a 3.18% increase in gravel content. Furthermore, Sample 2 contains 91.95% fines, while Sample 1 contains 95.13%. These differences indicate that both samples have a very similar particle size distribution, with only minor variations in the proportion of their fractions.

Table 5. Particle distribution – sample 2

GRANULOMETRIC CLASSIFICATION		
SILT AND CLAY	SAND	GRAVEL
47.25%	44.70%	8.05%

Figure 4 presents the granulometric curve corresponding to Sample 2, which was extracted at an approximate distance of 450 m from Sample 1, and the comparative analysis of both curves shows a continuous and very similar granulometry, which indicates a comparable granulometric composition between the two samples, with little significant variation in the distribution of their fractions.

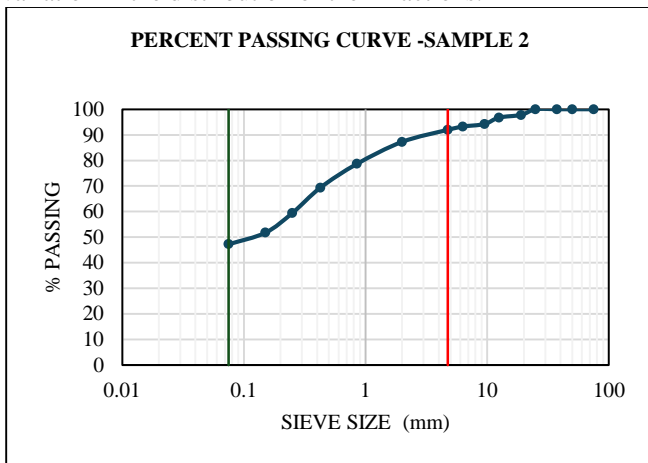


Fig. 4 Percent Passing curve -sample 2

Table 6. Sieve analysis table - sample 3

GRANULOMETRIC SIEVING TEST		
SIEVE SIZE (in)	SIEVE SIZE (cm)	% PASSING
3"	7.5	100.00%
2"	5	100.00%
1 1/2"	3.75	100.00%
1"	2.5	100.00%
3/4"	1.9	100.00%
1/2"	1.25	100.00%
3/8"	0.95	99.58%
1/4"	0.63	96.32%
N°4	0.475	94.47%
N°10	0.2	91.63%
N°20	0.085	90.38%
N°40	0.0425	86.56%
N°60	0.025	84.13%
N°100	0.015	81.07%
N°200	0.0075	75.93%

Table 7 presents the particle size distribution of Sample 3, in which a predominance of silts and clays is observed, and in comparison with the previous samples, this fraction exceeds by approximately one-seventh the proportion corresponding to said material, evidencing a greater presence of fine particles.

Table 7. Particle distribution – sample 3

GRANULOMETRIC CLASSIFICATION		
SILT AND CLAY	SAND	GRAVEL
75.93%	18.54%	5.53%

Figure 5 shows the particle size distribution curve of sample 3, which shows a particle size distribution ranging from 9.5mm to 0.075mm. This characteristic indicates that the soil is predominantly fine and potentially unstable, leading to a limited load distribution due to the scarce presence of coarse particles that provide structural support.

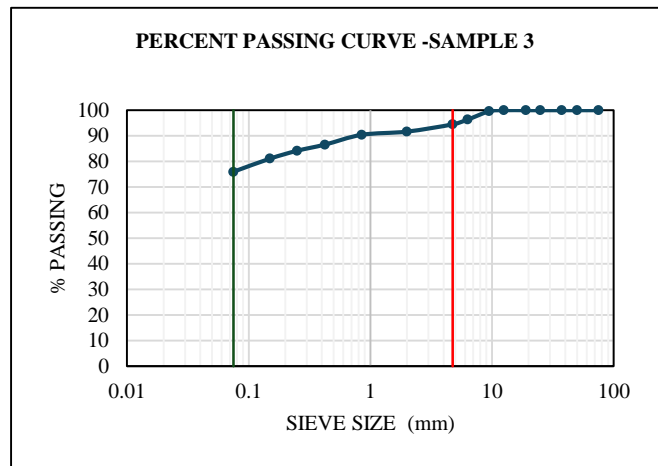


Fig. 5 Percent passing curve -sample 3

3.2. Soil Consistency Limits Results

Tables 8, 9, and 10 show, respectively, the laboratory results of the liquid limit, plastic limit, and plasticity index tests obtained for the three field samples that were carried out in accordance with the American Standard ASTM D4318 [17], of which the results indicate that the samples present medium Plasticity, characteristic of clay soils. This classification is based on the fact that the plasticity index of the three samples falls within the 7% to 20% range established for this type of material.

Table 8. Soil consistency limits – sample 1

THE ATTERBERG LIMITS	
LIQUID LIMIT (LL)	32.52%
PLASTIC LIMIT (PL)	15.72%
PLASTICITY INDEX (PI)	16.80%

Table 9. Soil consistency limits – sample 2

THE ATTERBERG LIMITS	
LIQUID LIMIT (LL)	30.70%
PLASTIC LIMIT (PL)	16.33%
PLASTICITY INDEX (PI)	14.38%

Table 10. Soil consistency limits – sample 3

THE ATTERBERG LIMITS	
LIQUID LIMIT (LL)	34.87%
PLASTIC LIMIT (PL)	20.42%
PLASTICITY INDEX (PI)	14.45%

3.3. Classification of Samples

For soil classification according to the Unified Soil Classification System [20], the results of the particle size analysis of the three samples obtained in the field were used, specifically considering the percentages of material passing through sieves No. 4 and No. 200, as well as the Atterberg limits, furthermore, for soil classification according to the AASHTO system, the percentages of material passing through sieves No. 10, No. 40, and No. 200 were taken into account, along with the corresponding Atterberg limits for each of the three analyzed samples.

Tables 11, 12, and 13 present, respectively, the results of the classification of the three soil samples, including their symbol and corresponding designation according to the USCS and AASHTO classification systems.

Table 11. Soil classification -sample 1

SOIL CLASSIFICATION – SAMPLE 1	
USCS	Low Plasticity Clay (CL)
ASSHTO	A-6
	Plastic Clay Soils

Table 12. Soil classification -sample 2

SOIL CLASSIFICATION – SAMPLE 2	
USCS	Clayey Sand (SC)
ASSHTO	A-6
	Plastic Clay Soils

Table 13. Soil classification -sample 3

SOIL CLASSIFICATION – SAMPLE 3	
USCS	Low Plasticity Clay (CL)
ASSHTO	A-6
	Plastic Clay Soils

3.4. Modified Proctor Test Results

Figures 6, 7, and 8 present the results of the Modified Proctor compaction test corresponding to the three soil samples, carried out according to ASTM D1557 [18]. The

results indicate that the second sample achieves the highest maximum dry density with a lower moisture content, demonstrating a more favorable compaction behavior. In contrast, samples 1 and 3 require higher moisture contents to achieve their maximum density, which is attributed to the higher proportion of fines present in their composition.

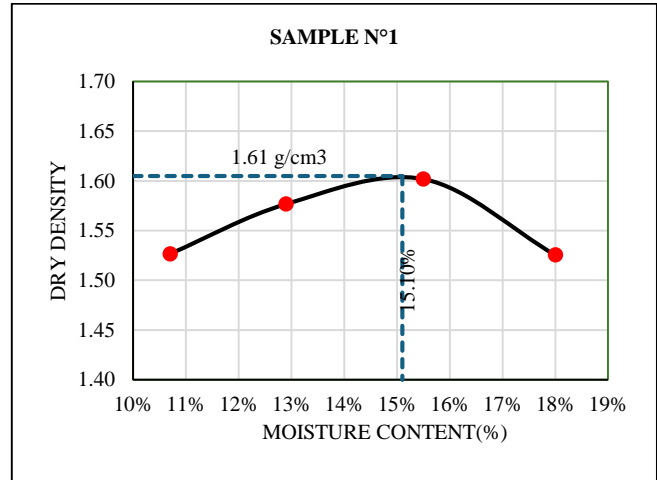


Fig. 6 Compaction curve– sample 1

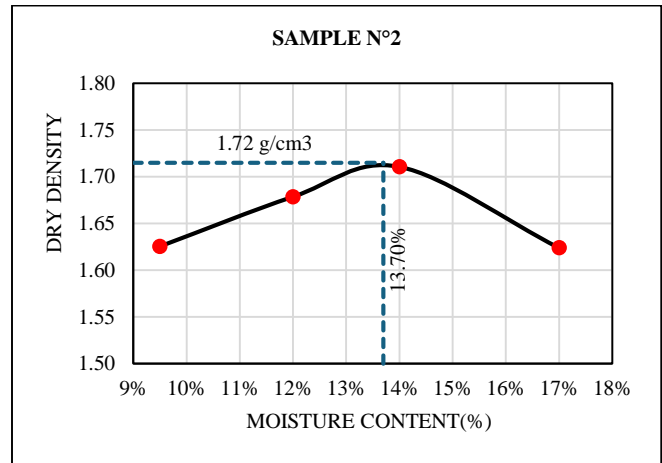


Fig. 7 Compaction curve– sample 2

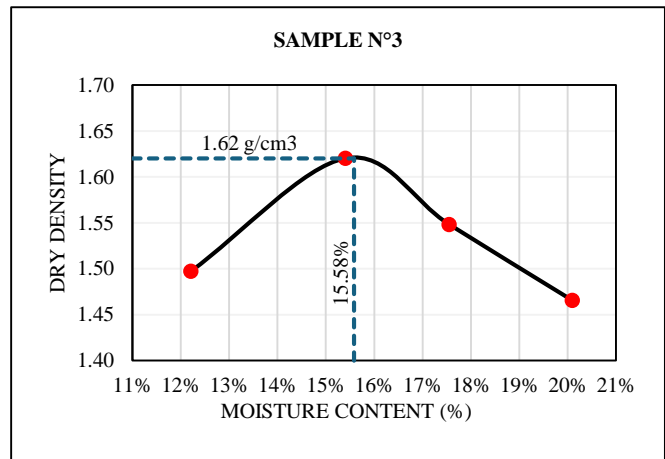


Fig. 8 Compaction curve– sample 3

3.5. California Bearing Ratio (CBR) Results

Under ASTM D1883 [19] standards, CBR tests were performed on both the natural samples and those with the addition of melted bags, according to the previously proposed dosages. The results were determined for compaction levels of 95% and 100%, considering penetrations of 0.1” and 0.2” in both cases, obtained from the corresponding CBR curve.

Tables 14, 15, and 16 present the calculated CBR test results for Sample 1, Sample 2, and Sample 3, respectively, in their unmodified state. Analyzing the CBR values at 95% compaction, Samples 1 and 3 are classified, according to standard, as Insufficient Subgrade (S1) because they have values below 6%; in contrast, Sample 2, registering a CBR value above 6% (0.69%), falls into the regular subgrade category. However, these results generally indicate a low bearing capacity, primarily attributable to the high fines content present in the analyzed samples.

Table 14. CBR test with 95% and 100% compaction, without additive – sample 1

TEST		
CBR	0.1"	0.2"
100%	6.65%	7.02%
95%	5.85%	6.16%

Table 15. CBR test with 95% and 100% compaction, without additive – sample 2

TEST		
CBR	0.1"	0.2"
100%	7.62%	8.03%
95%	6.69%	7.04%

Table 16. CBR test with 95% and 100% compaction, without additive – sample 3

TEST		
CBR	0.1"	0.2"
100%	5.51%	5.79%
95%	4.85%	5.11%

Tables 17, 18, and 19 present the CBR test results for the samples with the addition of 0.5% melted plastic bags, which show a slight improvement in the material's load-bearing capacity. In particular, the results for Samples 1 and 2 reach values considered acceptable according to the criteria established by the Peruvian standard.

Table 17. CBR test with 95% and 100% compaction, plus a 0.5% additive – sample 1

TEST		
CBR	0.1"	0.2"
100%	6.98%	7.18%
95%	6.03%	6.34%

Table 18. CBR test with 95% and 100% compaction, plus a 0.5% additive – sample 2

TEST		
CBR	0.1"	0.2"
100%	7.85%	8.24%
95%	6.89%	7.27%

Table 19. CBR test with 95% and 100% compaction, plus a 0.5% additive – sample 3

TEST		
CBR	0.1"	0.2"
100%	5.67%	5.98%
95%	4.99%	5.26%

The results of the CBR test with the addition of 1.0% additive are shown in Tables 20, 21 and 22, respectively, for the three samples studied, which are compared with the dosage of 0.5% and a more significant improvement in the values obtained is observed, especially at 95% of the maximum dry density which is the most representative condition of typical field compaction practices. In particular, samples 1 and 2 maintain acceptable values as subgrade, demonstrating the favorable effect of increasing the additive dosage.

Table 20. CBR test with 95% and 100% compaction, plus a 1 % additive – sample 1

TEST		
CBR	0.1"	0.2"
100%	7.30%	7.38%
95%	6.41%	6.51%

Table 21. CBR test with 95% and 100% compaction, plus a 1 % additive – sample 2

TEST		
CBR	0.1"	0.2"
100%	8.08%	8.48%
95%	7.09%	7.46%

Table 22. CBR test with 95% and 100% compaction, plus a 1 % additive – sample 3

TEST		
CBR	0.1"	0.2"
100%	5.84%	6.15%
95%	5.14%	5.41%

Tables 23, 24, and 25 present the results for Samples 1, 2, and 3, respectively, with the addition of 1.5% additive, and compared to the 0.5% and 1.0% dosages, more favorable results are evident in terms of load-bearing capacity. Furthermore, although Sample 3 continues to register values below the acceptable limit, a progressive improvement is observed associated with the increase in the additive dosage.

Table 23. CBR test with 95% and 100% compaction, plus a 1.5 % additive – sample 1

TEST		
CBR	0.1"	0.2"
100%	7.62%	7.72%
95%	6.71%	6.77%

Table 24. CBR test with 95% and 100% compaction, plus a 1.5 % additive – sample 2

TEST		
CBR	0.1"	0.2"
100%	8.38%	8.81%
95%	7.41%	7.77%

Table 25. CBR test with 95% and 100% compaction, plus a 1.5 % additive – sample 3

TEST		
CBR	0.1"	0.2"
100%	6.06%	6.38%
95%	5.34%	5.61%

Table 26 shows the increase in CBR value obtained in Sample 1 as a result of incorporating the melted plastic additive at the evaluated dosages and shows clearly an increasing trend in CBR as the additive dosage increases, demonstrating a progressive improvement compared to the untreated soil.

In particular, the 1.50% dosage produces the greatest increase, reaching 14.70% compared to the control sample. It is worth noting that, with all the proposed dosages, the original soil shows sufficient improvement to achieve CBR values considered acceptable for use as a subgrade according to standard.

Table 26. % increase in CBR 95% - sample 1

% ADDITIVE	CBR	%INCR.
0.00%	5.85%	
0.50%	6.03%	3.08%
1.00%	6.41%	9.57%
1.50%	6.71%	14.70%

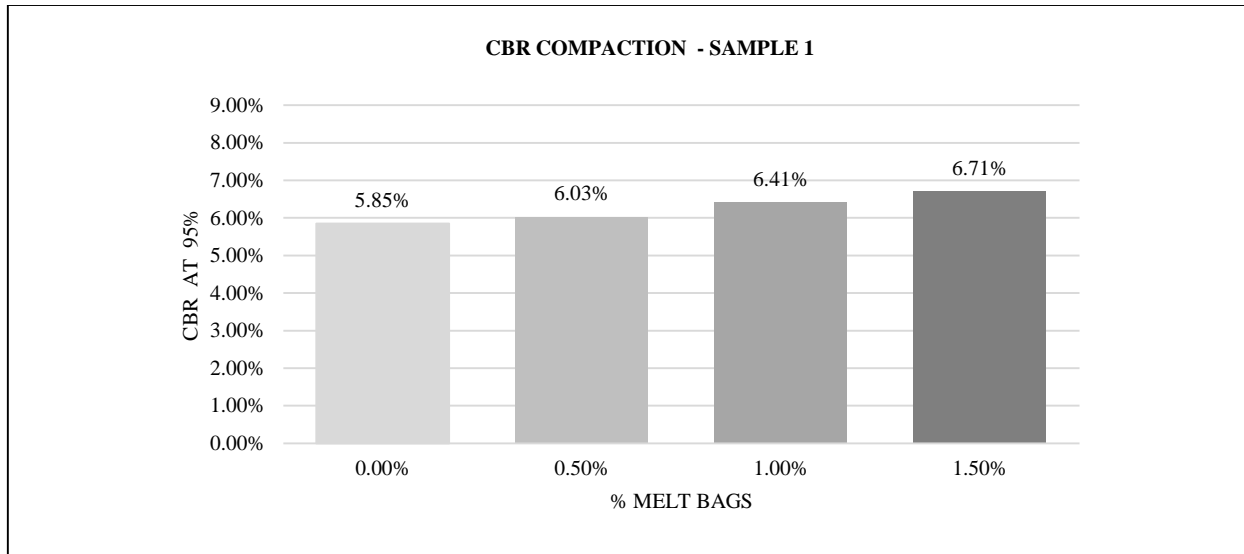


Fig. 9 CBR compaction – sample 1

Figure 9 presents a summary of the CBR value increase corresponding to the dosages of 0.0%, 0.5%, 1.0%, and 1.5% applied to Sample 1, evaluated at a compaction level of 95%. Moreover, shows a progressive improvement in CBR with the incorporation of the additive; although the increase is not high, the tested dosages allow the material to overcome the insufficient subgrade condition, reflecting an effective improvement in its bearing capacity under representative compaction conditions.

Table 27 presents the increase in the CBR value obtained in Sample 2 as a result of the incorporation of the molten plastic additive at the evaluated doses and the results

show that the 1.50% dose produces the greatest increase in the CBR, reaching an increase of 10.77% compared to the control sample, which demonstrates the positive effect of the additive on improving the soil's bearing capacity.

Table 27. % increase in CBR 95% - sample 2

% ADDITIVE	CBR	%INCR.
0.00%	6.69%	
0.50%	6.89%	2.99%
1.00%	7.09%	5.98%
1.50%	7.41%	10.76%

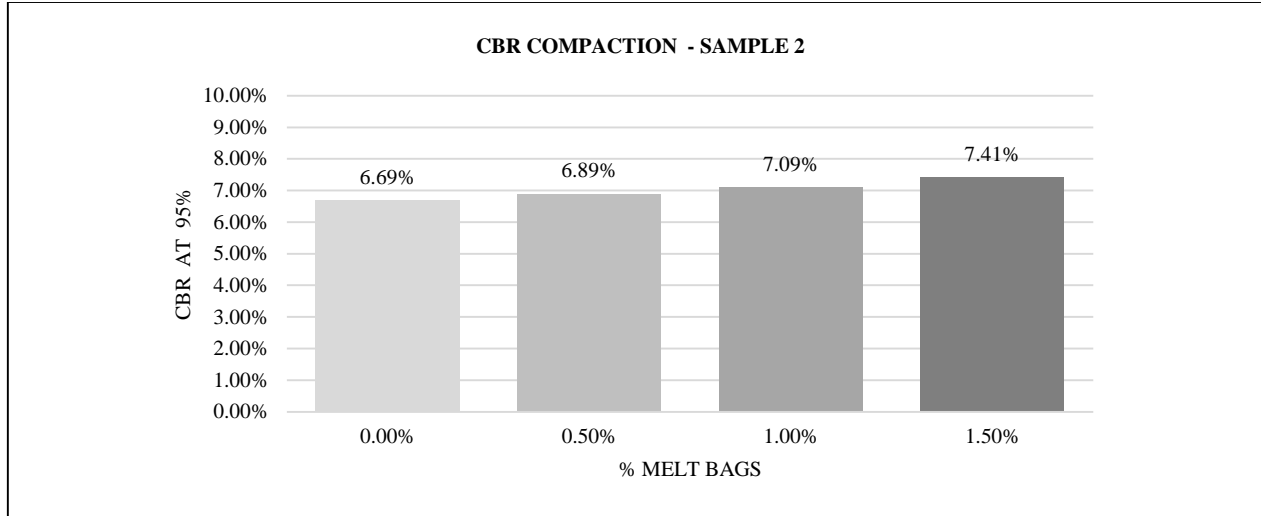


Fig. 10 CBR compaction – sample 2

Figure 10 presents a summary of the increase in CBR value corresponding to the dosages of 0.0%, 0.5%, 1.0%, and 1.5% applied to Sample 2, evaluated at a compaction level of 95%. Moreover, shows that the standard sample exceeds 6% CBR, a value considered the minimum acceptable, and that, consistently, the incorporation of the proposed additive generates an additional improvement in the behavior of the material, showing an increase in its load-bearing capacity under representative compaction conditions.

Table 28 presents the increase in the CBR value obtained in Sample 3 as a result of the incorporation of the melted plastic additive in the evaluated dosages. The results indicate that the 1.50% dosage generates the greatest increase in CBR, reaching an increase of 10.10% compared to the standard sample; However, despite the improvement observed, the values obtained do not reach the minimum requirement established.

Table 28. % Increase in CBR 95% - sample 3

% ADDITIVE	CBR	%INCR.
0.00%	4.85%	
0.50%	4.99%	2.89%
1.00%	5.14%	5.98%
1.50%	5.34%	10.10%

Figure 11 presents a summary of the increase in CBR value corresponding to the dosages of 0.0%, 0.5%, 1.0%, and 1.5% applied to Sample 3, evaluated at a compaction level of 95%. The results show that the incorporation of the three dosages of melted plastic bags only generates a limited improvement in soil performance, without any of the proposed dosages allowing the minimum required value of 6% CBR to be reached. This behavior is attributed to the high fines content present in Sample 3, a condition that restricts the effectiveness of the additive in improving the load-bearing capacity of the material.

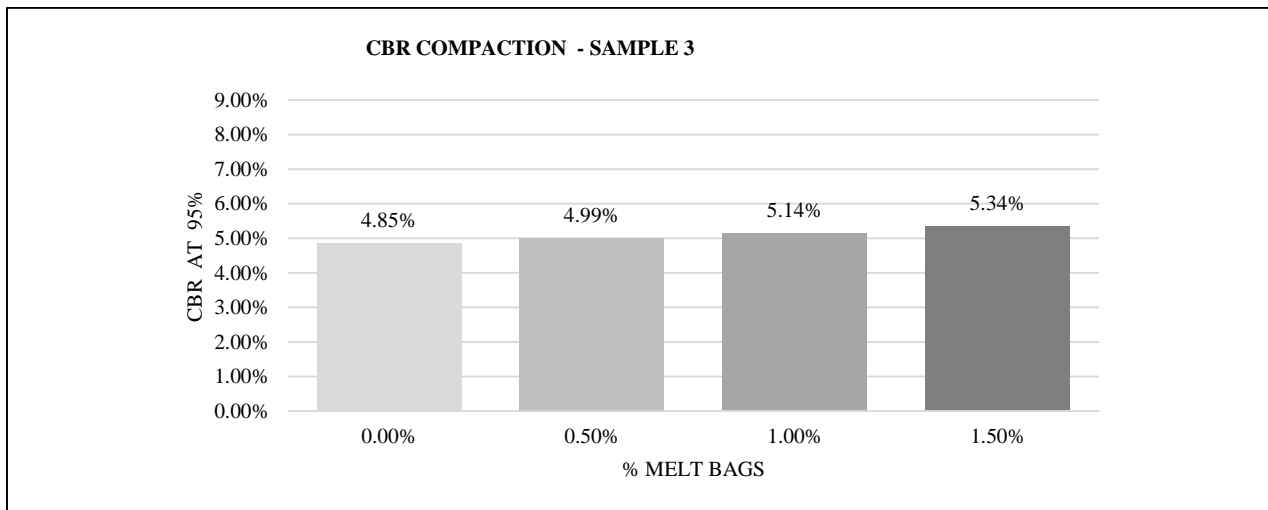


Fig. 11 CBR compaction – sample 3

3.6. Field Application and Upscaling

The results obtained in this research correspond to controlled laboratory conditions that, to be applied at the field scale, require considering several additional technical aspects, such as the need to implement controlled heating processes to reach adequate temperatures and ensure a homogeneous mixture with the soil. In addition, for large-scale applications, specialized equipment such as mobile heating systems and mechanical mixers will be required to ensure uniform distribution of the material throughout the soil mass. Operational factors such as material transport, plastic waste management, and on-site processing must also be taken into account.

While this study does not include field validations, it is important to note that soil stabilization techniques using alternative materials have been successfully applied in road projects, suggesting that the use of molten polyethylene could be a viable alternative provided the necessary technical adaptations are made; and we recommend that future research include pilot-scale tests to validate the results obtained in the laboratory under real operating conditions.

3.7. Application of ANOVA

The influence of the additive percentage on the CBR of materials M1, M2, and M3 was examined using a one-way ANOVA with a 95% confidence level, which showed a very low F value (0.2813) and a high p value (0.8376), indicating that there are no significant differences between the additive levels evaluated: 0%, 0.5%, 1%, and 1.5%. These findings are valuable because they statistically demonstrate that, within the analyzed range, the additive does not have a significant impact on the CBR, but they lay the groundwork for future studies, where performing additional repetitions or using higher percentages of additive could help determine if it is possible to achieve a significant improvement in the CBR.

4. Conclusion

Improving the subgrade made up of clay soils by adding melted plastic bags is a technically viable alternative, provided that the natural material meets certain physical and mechanical characteristics. In the present investigation it was determined that soils with a plasticity index between approximately 14% and 17%, as well as with fines contents less than 60%, present a more favorable response to the incorporation of the additive, as it was shown that the presence of a significant granular fraction, with percentages

of sand and gravel greater than 40%, contributes positively to the increase of the soil's bearing capacity.

The progressive incorporation of melted plastic bags at doses of 0.5%, 1.0% and 1.5% of the dry weight of the samples showed a gradual increase in the CBR index of the evaluated soils, determined at 95% of the maximum dry density and a penetration of 1 inch and with the dose of 0.5%, a minimum increase of 2.89% was recorded in the three samples analyzed; whereas with the addition of 1.0%, the increase reached minimum values of 5.98%, reflecting a more significant mechanical improvement of the material and a favorable response to the performance criteria established for subgrades.

In this context, the 1.5% dose proved to be the most efficient among the evaluated values, achieving CBR results of up to 6.71% at 95% of maximum dry density and a penetration of 0.1 inches, representing a 14.70% increase compared to the soil without the additive. Furthermore, samples 1 and 2 exceeded the minimum value of 6% established by current regulations to be classified as acceptable subgrade, thus demonstrating the effectiveness of using melted plastic bags as an additive to improve clay soils. We also noted that sample 3, characterized by a high fines content exceeding 75%, showed a progressive improvement in the CBR test results with the proposed doses, but did not reach the minimum required value at 95% compaction and a penetration of 0.1 inches. This highlights that soils with high clay and silt content have a limited response to effective improvement using this type of additive.

Finally, the research highlights the importance of defining clear technical parameters, such as fines content, plasticity index, and optimal additive dosage, in order to guarantee an efficient and technically sustainable application of melted plastic bags in road infrastructure projects, also contributing to an alternative for the valorization of plastic waste.

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