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Subgrade Stabilization Using Recycled Vehicle Oil and Stone Powder

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Abstract The purpose of the research is to determine the behavior caused by the addition of recycled vehicle oil (RVO) and stone powder (SP) in subgrade stabilization, using an applied methodology, a quasi-experimental design, and a quantitative approach. The natural state soil has an A-6 classification (low plasticity clayey soils), with a plasticity index of 16%, a maximum dry density of 1977 kg/m³, and an optimal moisture content of 10.30%. Additionally, the unconfined compressive strength is 265863.64 kg/m², and its California Bearing Ratio (CBR) is 12.20%, indicating it is a good subgrade in relation to this last property. Subsequently, the addition of RVO and SP to the natural sample showed favorable results in all evaluated properties except for the unconfined compressive strength. In this regard, the dosage of 6% RVO and 15% SP presented the best values, reducing the plasticity index to 8%, increasing the maximum dry density (MDD) to 2047 kg/m³, lowering the optimal moisture content (OMC) to 4.90%, the unconfined compressive strength obtained a value of 100251.00 kg/m², and the CBR at 95% increased to 25.50%, classifying it as a very good subgrade. Finally, it is concluded that the subgrade soil with the addition of RVO and SP improves its physical-mechanical properties.

Keywords Stabilization, Subgrade, Oil, Stone

1. Introduction

Internationally, the authorities responsible for transportation routes and communications in each nation allocate large amounts of money for the maintenance and/or replacement of previously constructed pavements [1]. Colombia, considered one of the major developing countries in the South American region, faces the need to increase the construction of transportation routes. This results in the necessity of obtaining suitable materials for their construction, which presents a greater challenge. Consequently, alternative construction methods have emerged, including the addition of stabilizing agents (lime, oils, cement, etc.) to stabilize soils [2].

In the case of Peru, although there are unaltered soils that meet the required properties for pavement projects, they are found in a lower percentage compared to soils that do not react adequately according to current regulations. This may be due to unfavorable climatic, meteorological conditions, and/or heavy traffic. For this reason, poor quality soils are replaced with optimal ones, considering that obtaining new suitable materials can be more challenging than expected [3]. Unfortunately, if roads continue to be built while ignoring the deficient properties of the subgrade soil in the projected area and without taking corrective actions, new road projects will inevitably experience failures shortly after construction, leading to increased maintenance or replacement costs.

For these reasons, it is recommended to stabilize the subgrade by applying physical, chemical, or mechanical methods aimed at improving the soil's properties to serve effectively as a foundation for pavement construction. Mechanical stabilization primarily involves compacting the soil through static or dynamic means to modify its density, compressibility, permeability, and porosity. It may also include mixing soils with different gradations to meet specific requirements. In contrast, physical stabilization adjusts the soil by altering grain size distribution, applying drying or freezing techniques, using heat treatments, or employing electrical methods [4]. Among these, thermal stabilization improves soil properties such as density and strength by applying high temperatures, while reducing plasticity; however, challenges remain regarding energy efficiency and scalability [5]. Electrical stabilization, meanwhile, uses electro-osmosis: a direct current is passed through the soil, causing pore water to migrate toward the cathode. This increases soil strength by reducing water content, although the method is costly and mainly used for drainage purposes [6]. Additionally, geosynthetic stabilization involves placing geotextiles or geogrids combined with a granular layer over weak, saturated soils. This technique strengthens the soil, prevents fine material intrusion, enhances load-bearing capacity, and reduces deformationespecially important for roads and pavements [7].

Chemical stabilization, on the other hand, involves incorporating materials or chemicals into the soil to modify its properties through physicochemical reactions or by forming a cohesive matrix [8]. The choice of stabilizer depends on the soil type. Portland cement is suitable for granular soils, while lime is used for highly plastic soils to lower plasticity and increase strength. In soils with low fines content, lime is often combined with fly ash. Bituminous materials help waterproof and reinforce granular soils, whereas fibers can enhance strength, albeit sometimes at the expense of workability. Polymer emulsions, based on polyvinyl acetate copolymers, also offer excellent adhesion, stiffness, and water resistance, similarly to bituminous treatments. Additionally, non-traditional additives like acids, lignin derivatives, enzymes, resins, and silicates are available; their effectiveness, however, varies significantly. Generally, granular soils require binders like cement, polymers, or asphalt emulsions for cohesion, while finer soils may benefit more from alternative stabilizers [9].

Moreover, salts, polymers, silicates, and lignin derivatives are also used depending on the project's requirements. For example, calcium chloride enhances moisture retention and stabilizes silty and clayey soils, although its performance depends on pore retention. Sodium chloride behaves similarly by forming a dense mat that reduces evaporation and shrinkage. Sodium silicate improves strength and impermeability but is less suitable for long-term applications. Polymers such as calcium acrylate strengthen soil cohesion by polymerizing within the soil matrix. Chrome-lignin, a by-product of paper manufacturing, temporarily binds particles due to its solubility. Other additives like waterproofers (alkyl chlorosilanes, siliconates), flocculants (calcium chloride), dispersants (sodium hexametaphosphate), and phosphoric acid combined with wetting agents are used for specific soil improvements, particularly to enhance water resistance, compaction, or chemical stability [10].

In addition, coarse-grained soils with low fine content can be stabilized using combinations of lime and fly ash or lime-cement-fly ash, as the ash reacts with lime to form a cementitious matrix of high strength. For clay soils, lime is often combined with Portland cement or asphalt to improve workability and mixing, addressing the limitations of each individual stabilizer. Although these methods may incur higher costs, they are particularly viable in areas where suitable aggregates are scarce or expensive [11].

According to the concepts and options proposed by different authors, the reuse of waste motor oil is considered an alternative to common soil stabilizers, as its incorporation has been studied multiple times, showing improvements when used in dosages of 3.5%, 4%, 7.5%, 12% and 16%, according to the investigations made by [12], [13], [14], [15], [16], respectively. This material is defined as the byproduct of using oils for the lubrication and cooling of automobiles, containing a complex combination of aliphatic and aromatic hydrocarbons [17]. Used lubricating oils are generally composed of two main components. The first, making up about 65% of the total, consists of a mineral or synthetic base oil with additives. The remaining 35% includes contaminants such as water; residual additives like phenols; compounds of zinc (Zn), chlorine (Cl), and phosphorus (P); acids formed by sulfur (S) oxidation; metallic particles from engine wear; as well as sulfur compounds, chlorinated substances, and organometallic compounds with lead (Pb) and polycyclic aromatic hydrocarbons (PAHs) [18]. Additionally, used oil may contain hazardous substances like heavy metals (e.g., chromium, cadmium, arsenic, lead), benzene, chlorinated solvents, and polychlorinated biphenyls (PCBs), many of which are toxic and carcinogenic [19]. However, research and laboratory analyses have shown that used oils generally do not contain significant levels of PCBs [16]. These findings underscore that, with proper treatment and quality control, used oils can be rendered suitable for secondary applications without posing major environmental or health risks.

As reported by Fong et al. [19], the metal content in used oil collected from various sources at a lubrication center was measured using the Karl Fischer method, and the results are summarized in Table 1. The presence of elements such as zinc, chlorine, calcium, sodium, and iron is consistent with the chemical profile of many industrial by-products already in use. In fact, recycled vehicle oil shares key chemical characteristics, particularly hydrocarbons and resins, with conventional materials used in asphalt mixtures, which are widely accepted in pavement engineering [20]. This chemical compatibility supports the feasibility of employing recycled oil in road stabilization, provided it is handled with adequate treatment and technical oversight.

Table 1. Characterization of used oils according to [19]

Element	Content (ppm)
Zinc (Zn)	825.56
Chlorine (Cl)	330.00
Calcium (Ca)	285.34
Sodium (Na)	216.81
Iron (Fe)	121.19
Phosphorus (P)	18.37
Aluminum (Al)	16.95
Copper (Cu)	14.29
Silicon (Si)	2.27
Sulfur (S)	1.29

In this study, the recycled vehicle oil used was subjected to a preliminary filtration and basic treatment process aimed at removing solid residues and minimizing the presence of harmful compounds [21]. While the material is not entirely free of contaminants, it represents a significantly lower environmental hazard compared to untreated waste oil and can be considered safe for controlled engineering applications [22].

On the other hand, stone dust is also considered an alternative stabilizing agent, supported by research validating its effectiveness when added in proportions of 20%, 16%, or 10%, according to the studies of [23], [24], [25], respectively. This material consists of the accumulation of fine fragments generated during the stone crushing process for specific purposes. Its primary composition includes reactive silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and various similar components. These additional components may vary, containing a range of minerals and elements present in the original crushed stone, which contribute to the overall composition and properties of the stone powder [26]. In conclusion, given the issues related to deteriorated roads and highways, the use of a mixture of recycled motor oil and stone powder is proposed as a stabilizing agent for subgrades with poor characteristics and properties.

The stabilization of subgrade soil through the addition of stone dust and recycled motor oil provides multiple benefits. First, using recycled motor oil as an additive helps mitigate environmental pollution by repurposing a material that is often discarded improperly, in large quantities, directly onto the ground, where it can reach groundwater sources and cause their degradation [27]. Additionally, incorporating stone dust, a byproduct of the quarrying process often treated as waste, promotes its sustainable reuse, further enhancing the environmental and economic benefits of this stabilization method.

On the other hand, improper use of vehicle oil, without adequate control or environmental safeguards, can cause serious and irreversible damage to ecosystems, as previously noted. For this reason, the present study did not involve the uncontrolled disposal of oil onto natural soil. Instead, recycled vehicle oil was incorporated in controlled dosages (6% and 8%) and thoroughly blended with stone dust and subgrade soil, ensuring its encapsulation within a compacted matrix [28]. According to the authors' empirical observations, stabilizing fine cohesive soils with low percentages of used motor oil results in a homogeneous and impermeable mixture that retains the oil within the soil structure, thereby minimizing the risk of groundwater and soil contamination, though further research is recommended to validate these findings [16]. Moreover, the treated subgrade is confined between the underlying natural ground and the overlying asphalt layer [29], further reducing exposure and the potential for oil migration.

2. Materials and Methods

The main objective of this article is to determine the influence of recycled motor oil and stone dust during the stabilization of subgrades. This was carried out through a quasi-experimental, applied research study with an explanatory level and a quantitative approach.

The selected population and sample was the Huamilancha road, located in Peru. This road has an approximate length of 1.80 km, from which three test pits (C-1, C-2, C-3) were excavated at a depth of 1.50 m, each separated by a distance of 500 m. The grain size distribution and consistency limits of the three test pits were then analyzed according to ASTM D4318 [30] to obtain the AASHTO classification of each one, aiming to identify the soil with the most unfavorable characteristics.

Based on the results obtained, test pit C-3 exhibited the worst characteristics, being classified as a low-plasticity sandy clay, A-6(A). Therefore, the soil sample from this test pit was used for subsequent laboratory tests. (Table 2)

Table 2. Selection of the most unfavorable test pit

Test pit code	% Passing Mesh N °200	Plastic Index	AASHTO Class.	Description
C-1	31.87	-	A-2-4 (0)	Silty sand
C-2	46.41	2	A-4 (0)	Silty sand
C-3	53.26	6	A-6(A)	Low plasticity sandy clay

The subgrade soil sample obtained from test pit C-3 was studied both in its natural state and after the addition of the mixture of recycled motor oil and stone dust in various dosages. (Table 3)

Table 3. Dosages of RVO and SP

Test pit code	Recycled vehicle oil	Stone powder	Dosages	Sample code
C-3	0% RVO	0% SP	M-01 + 0 % SP + 0 % RVO	M-01
	6% RVO	10% SP	M-01 + 6% SP + 10% RVO	M-02
		15% SP	M-01 + 6% SP + 15% RVO	M-03
	8% RVO	10% SP	M-01 + 8% SP + 10% RVO	M-04
		15% SP	M-01 + 8% SP + 15% RVO	M-05

The recycled vehicle oil was obtained from a local auto service center, which, after performing oil changes for its customers, stores the residual waste in a 200 L drum. Once the necessary amount of recycled motor oil (RVO) was extracted, it was analyzed to determine its viscosity level using a rotational coaxial cylindrical viscometer, also known as a Brookfield viscometer. The results described the substance as having low viscosity at room temperature (180 cP).

On the other hand, the stone was sourced from a quarry located at an altitude of approximately 2,800 meters above sea level. After collection, a portion was used to conduct the Los Angeles abrasion and impact resistance test, following the ASTM C131-03 standard [31]. The test results classified the stone as a fine coarse aggregate with an abrasion wear of 44.65%, meaning it is considered efficient, low-abrasive, and of high quality, as its wear remained below 50% after testing. Subsequently, the stone was crushed and sieved through a No. 40 mesh to obtain the stone dust required for the research. This stone dust was chemically analyzed using X-ray fluorescence testing to determine the chemical elements and oxides present in the sample (Table 4). According to the test results, it can be inferred that the silicon oxide, through its pozzolanic behavior, will help improve the subgrade soil's properties in terms of compaction, penetration resistance, etc. Likewise, the iron oxide will contribute to subgrade stabilization due to its frequent reaction against the clayey properties of soils.

Table 4. Chemical elements and oxides present in stone dust

Element	Results (%)	Oxides	Results (%)
Iron (Fe)	33.988	Silicon Oxide (SiO_2)	37.173
Silicon (Si)	28.253	Iron Oxide (Fe_2O_3)	23.787
Aluminum (Al)	17.588	Aluminum Oxide (Al_2O_3)	21.207
Barium (Ba)	5.461	Sulfur Oxide (SO_3)	6.347
Sulfur (S)	4.410	Barium Oxide (BaO)	3.309
Manganese (Mn)	3.653	Manganese Oxide (MnO)	2.355
Calcium (Ca)	2.903	Calcium Oxide (CaO)	2.237
Potassium (K)	1.923	Potassium Oxide (K_2O)	1.296
Titanium (Ti)	0.834	Titanium Oxide (TiO_2)	0.755
Phosphorus (P)	0.507	Phosphorus Oxide (P_2O_5)	0.673
Strontium (Sr)	0.275	Strontium Oxide (SrO)	0.143
Copper (Cu)	0.104	Zirconium Oxide (ZrO_2)	0.060
Zirconium (Zr)	0.102	Copper Oxide (CuO)	0.057

The analyzed subgrade properties included plasticity index, maximum dry density, optimal moisture content, penetration resistance, and unconfined compressive strength, in accordance with ASTM D4318, ASTM D1557, ASTM D1883, and ASTM D2166 standards (Figure 1).

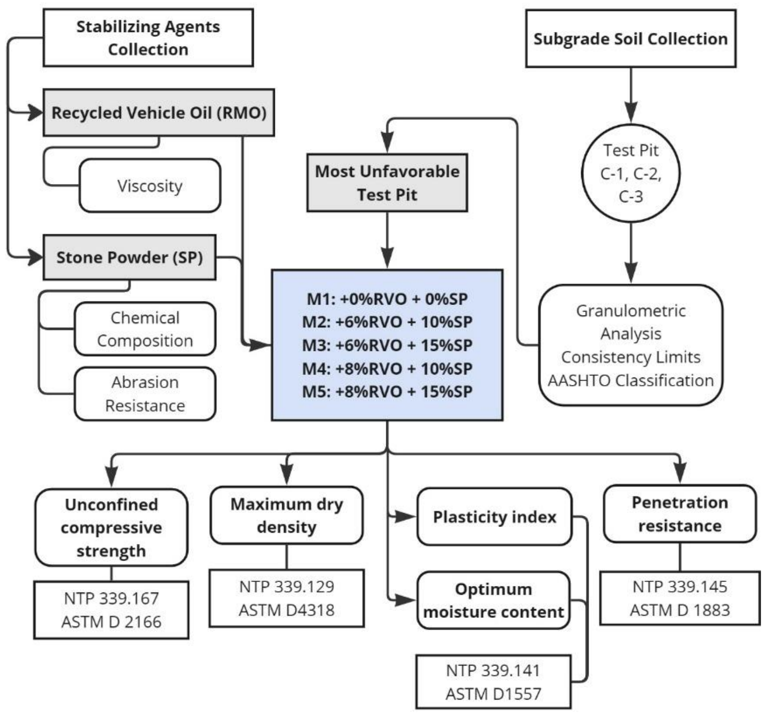

Figure 1. Investigation process

3. Results

3.1. Plastic Index

The results presented in Figure 2 indicate that the addition of recycled vehicle oil and stone dust reduces the consistency limits compared to the natural subgrade soil (a medium plasticity clayey soil). The greatest variation occurs when adding 6% RVO and 15% SP, resulting in a 50% decrease.

It can be confirmed that the incorporation of 6% RVO and 15% SP results in the greatest reduction in the plasticity index, as lower moisture contents were obtained during the liquid limit test with this dosage (Figure 3). This is primarily due to the oil, which was added before water during sample preparation for the test. As a result, the oil formed a coating around the soil particles, reducing the water's ability to act as an adhesive between the clay particles that contribute to plasticity [16]. Additionally, stone dust plays a crucial role, as its high iron oxide content helps diminish the presence of clays in the soil by reducing the critical coagulation concentration, controlling particle dispersion, and mitigating expansion [32].

3.2. Maximum Dry Density

The maximum dry density (MDD) results, obtained from the modified Proctor test following the guidelines of ASTM D1557 [33], show an almost negligible increase in values with the addition of stabilizing agents. However, it is worth noting that the highest increase in MDD compared to the control sample (MDD of 1977 kg/m^3) occurs with the dosage of 6% RVO + 15% SP, resulting in a 3.54% increase (MDD of 2047 kg/m^3) (Figure 4).

The increase in MDD values with the addition of recycled motor oil and stone dust is due to the presence of cations, particularly iron and aluminum, in the stone dust. These cations reduce the thickness of the diffuse double layer, causing soil particles to come closer together. As a result, highly dense particle clusters are formed with a reduced number of voids [25].

Figure 5 presents the compaction curves from the modified Proctor tests conducted with all the dosages considered in the study. These graphs clearly confirm that the addition of 6% RVO and 15% SP results in the highest maximum dry density, as its peak reaches the greatest height compared to the others.

3.3. Optimum Moisture Content

Regarding the optimum moisture content (OMC) obtained through the modified Proctor test, a consistent reduction is observed as the amount of recycled motor oil and stone dust increases. This is evidenced by a 59.22% decrease compared to the control sample when 8% RVO and 15% SP are added.

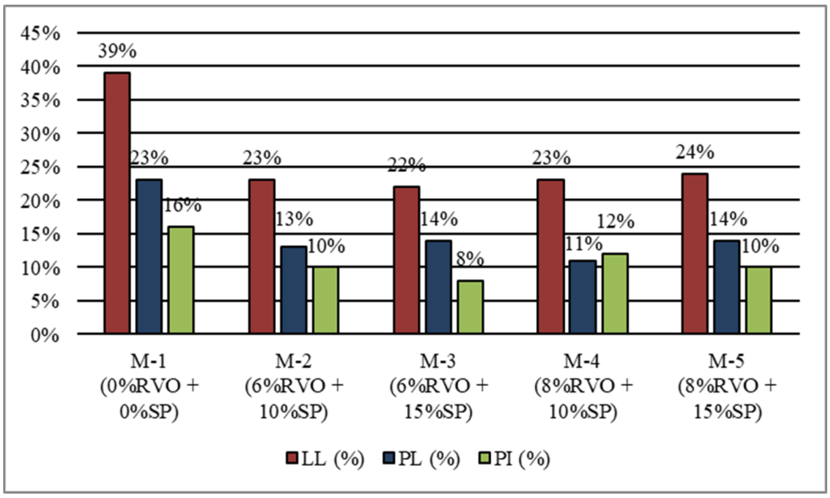

Figure 2. Comparative bar chart of the liquid limit, plastic limit, and plasticity index of the natural subgrade soil with the addition of RVO and SP

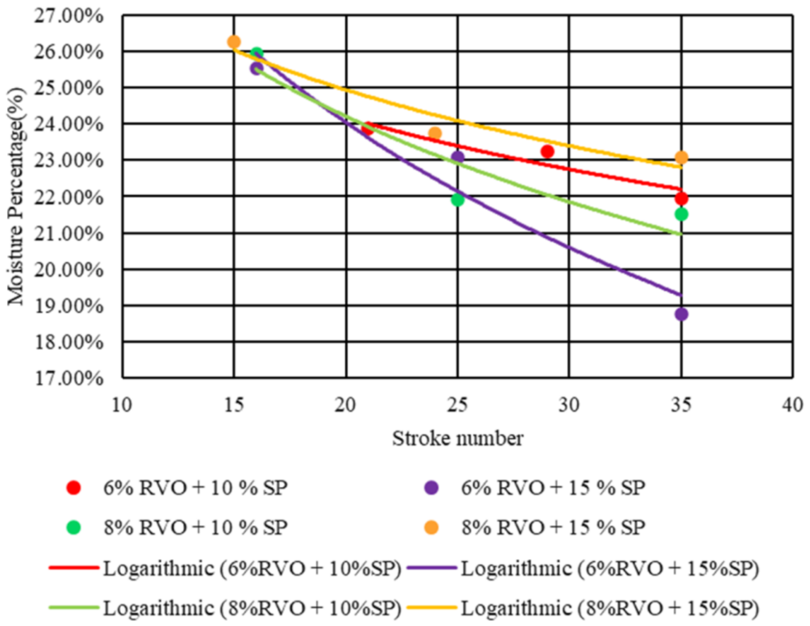

Figure 3. Liquid limit test with different dosages

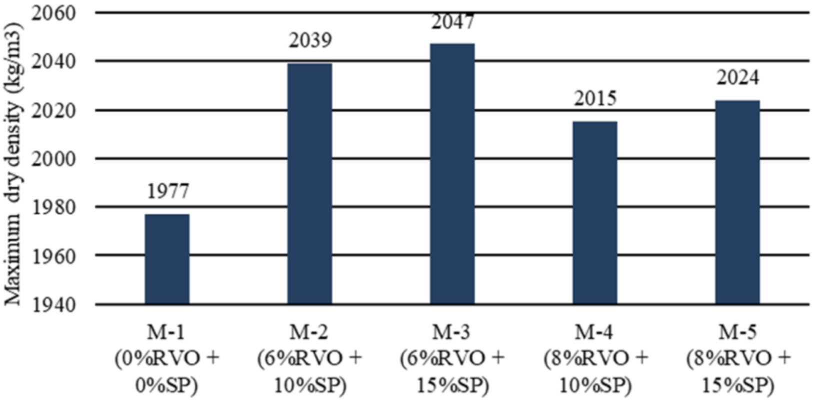

Figure 4. Plasticity index obtained for materials from different authors

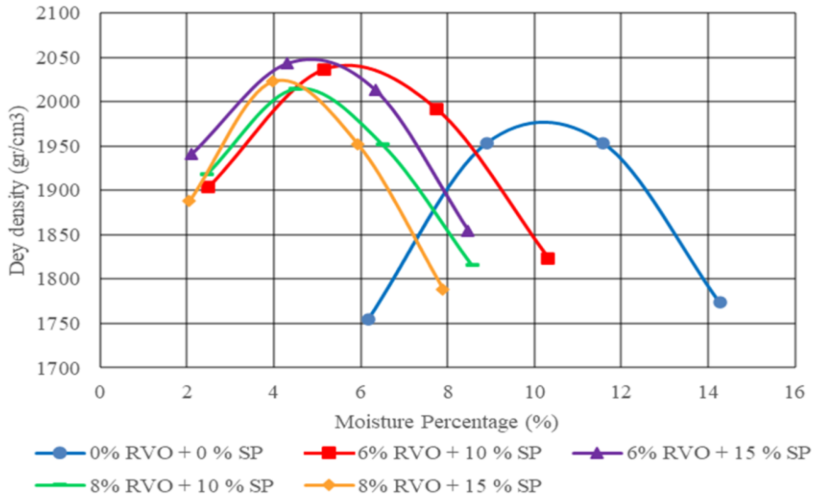

Figure 5. Compaction curves from the modified Proctor test with different dosages

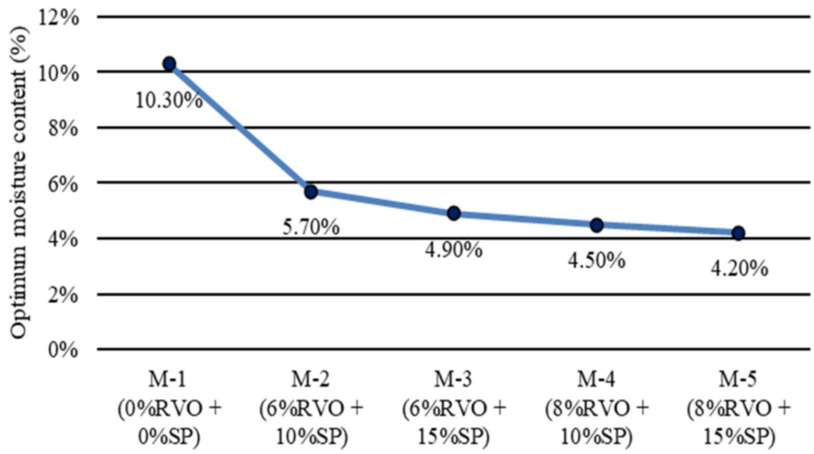

Figure 6. Frequency polygon of the OMC (%) of subgrade soil with the addition of RVO and SP

The results for optimum moisture content show a consistent decrease as the amount of stone dust and recycled motor oil increases. The proposed explanation is that the alteration of the diffuse layer caused by the stone dust, along with the aggregation of soil particles, reduced their ability to retain water. Additionally, the oil played a crucial role, as its low viscosity allows it to replace water, thereby reducing the amount needed during compaction. Furthermore, referring back to Figure 6, we can confirm that as RVO and SP are added to the control sample, its moisture content decreases. This is evident as the compaction curves shift negatively along the X axis with increasing dosage percentages.

3.4. Penetration Resistance

The CBR (0.1”) results, obtained following ASTM D1883 [34], at both 100% and 95% of the maximum dry density, demonstrate that the addition of recycled motor oil and stone dust significantly and positively increases the percentages (Table 5).

When evaluating the results of the CBR (0.1”) test at 95% of the maximum dry density with the addition of RVO and SP, it was observed that the subgrade soil improved from a “good” classification in its natural state (12.20%) to a “very good” classification in all treated cases. This classification is based on the criteria established by MTC [35], which categorizes subgrade quality according to CBR values, ranging from “inadequate” to “excellent”.

The improvement can be largely attributed to the cementitious properties of the stone dust, due to its high silica content and pozzolanic behavior [36].

The variation percentages shown in Figure 7 indicate a significant increase in CBR values with the addition of RVO and SP. Additionally, the results suggest that adding 6% RVO yields better outcomes compared to 8%. However, the data are inconclusive when determining whether 10% or 15% stone dust is more effective. On the other hand, there is no doubt that the most substantial improvement occurs with the dosage of 6% RVO + 15% SP, resulting in a 109.02% increase compared to the natural subgrade soil.

3.5. Unconfined Compressive Strength

This test was conducted following ASTM D2166 [37]. The results of the unconfined compressive strength of the natural subgrade soil after the addition of RVO and SP, indicate that incorporating these stabilizing agents significantly reduces both unit deformation and stress. According to the soil consistency classification based on unconfined compressive strength, presented in MTC [38], the natural soil presents a very firm consistency compared to its condition after the stabilization. Finally, although the soil's consistency decreases, with the addition of 6% RVO and 15% SP, the variation is minimal compared to the control sample, remaining within an acceptable range (Table 6).

Similarly, the stress-strain curves obtained during the laboratory test (Figure 8), indicate that while the control sample exhibits the highest stress peak, the second highest peak is achieved with the addition of 6% RVO and 15% SP.

Table 5. Subgrade category in relation to penetration resistance

Sample	CBR (0.1") at 100%	CBR (0.1") at 95%	Category [35]
M-1 (0%RVO + 0% SP)	18.40%	12.20%	Good subgrade
M-2 (6%RVO + 10% SP)	31.00%	23.50%	Very good subgrade
M-3 (6%RVO + 15% SP)	33.80%	25.50%	Very good subgrade
M-4 (8%RVO + 10% SP)	28.00%	22.70%	Very good subgrade
M-5 (8%RVO + 15% SP)	24.10%	18.80%	Good subgrade

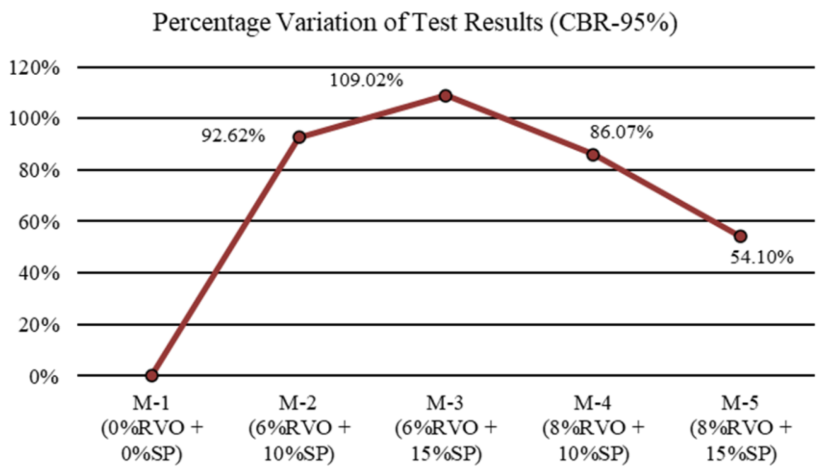

Figure 7. Frequency polygon with CBR test results

Table 6. Soil consistency in relation to unconfined compressive strength

Sample	Unit Deform. (ε)	Stress (kPa)	Consistency according to MTC [38]
M-1 (0%RVO + 0% SP)	0.009	265.86	Very Firm
M-2 (6%RVO + 10% SP)	0.021	60.81	Medium
M-3 (6%RVO + 15% SP)	0.013	100.25	Firm
M-4 (8%RVO + 10% SP)	0.016	41037.21	Soft
M-5 (8%RVO + 15% SP)	0.016	78953.18	Medium

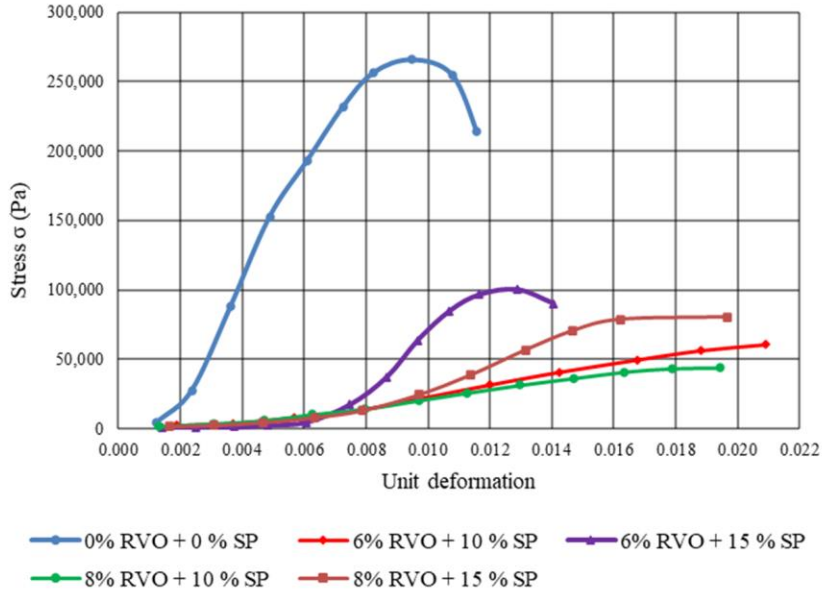

Figure 8. Stress-strain graph obtained from the unconfined compression test

4. Discussion

Various studies have been made on the effect of additives such as recycled vehicle oil (RVO) and stone powder (SP) on soil stabilization. Regarding RVO, previous research has established that optimal addition rates range between 4% and 20%, according to Iqbal et al. [13] and Gadouri & Meziani [39], while other studies like Huarsaya [14], Jalanoca [12], Camacho & Huamán [15] and Del Castillo & Orobio [16] suggest values of 7.5%, 3.5%, 12% and 16%, respectively. On the other hand, the addition of stone powder has proven most effective in concentrations ranging from 10% to 20%, according to the studies by Salih [24], Basack et al. [25], Ruíz [40] and Pino [23]. This analysis aims to compare the results obtained in this study with previous research.

When comparing the PI results obtained with those reported by other authors, we observe a similar trend. Four out of five authors who analyzed the PI with the addition of RVO (at dosages of 4%, 12%, and 16%) reported a reduction in values compared to their control sample. Similarly, two out of three authors who studied the PI with the addition of SP (at dosages of 10% and 20%) also observed a decrease in values compared to their control sample (Figure 9).

Similarly, all authors who analyzed MDD with the addition of RVO (at dosages of 3.5%, 4%, 7.5%, 12%, and 16%), reported an increase in values compared to their control sample. Likewise, all authors who studied MDD with the addition of SP (at dosages of 10%, 16%, and 20%) observed an increase in values compared to their control sample (Figure 10).

On the other hand, when comparing the results of this study with those of multiple researchers (see Figure 11), we find a consensus that the addition of RVO (at dosages of 3.5%, 4%, 7.5%, 12%, and 16%) and SP (at dosages of 10%, 16%, and 20%), each individually, leads to a reduction in OMC compared to the natural state sample.

The discussion comparing the results of this study with those of other authors regarding penetration resistance with the addition of RVO and SP (see Figure 12) revealed that 4 out of 5 authors who analyzed this property with RVO (at dosages of 3.5%, 4%, 7.5%, and 12%) reported an increase in values compared to their control sample. Similarly, all three authors who studied the addition of SP (at 10% and 20%) agreed on the increase in CBR values.

Finally, upon reviewing studies on this specific characteristic, we observed that the addition of RVO produces counterproductive results. For example, Del Castillo & Orobio [16] reported a decrease in unconfined compressive strength from 1,216 Pa to 1,138 Pa when incorporating 16% used motor oil. Similarly, Gadouri & Meziani [39] concluded that the higher the amount of RVO added, the more significant the decrease in unconfined compressive strength values.

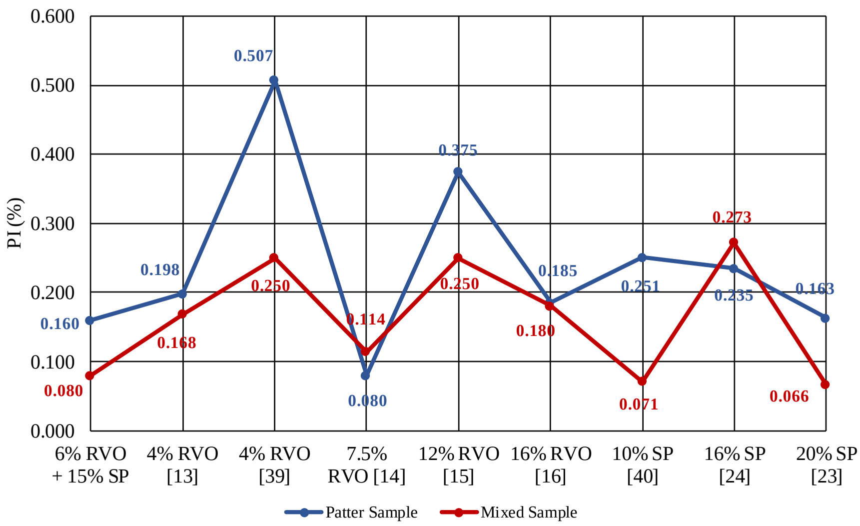

Figure 9. Plasticity index obtained for materials from different authors

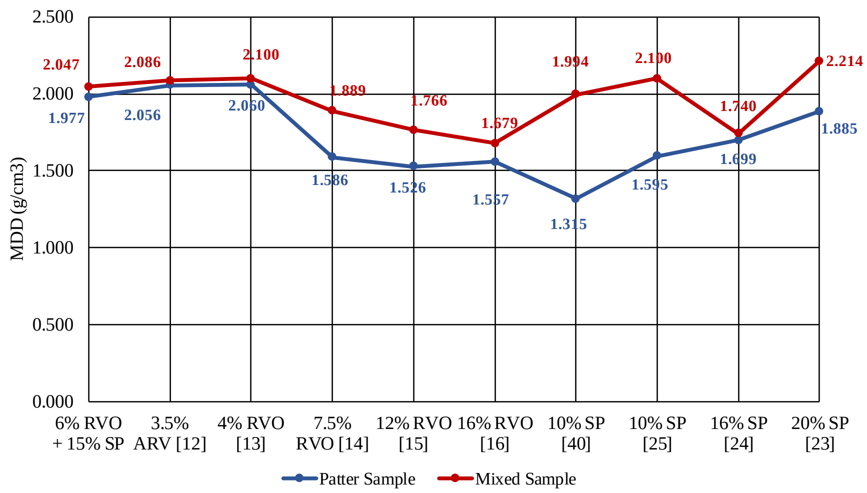

Figure 10. Maximum dry density obtained for materials from different authors

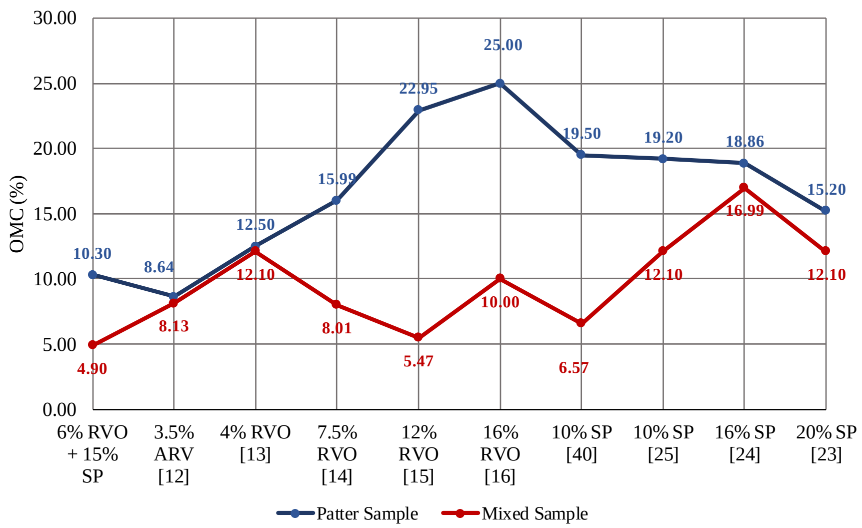

Figure 11. Optimum moisture content obtained for materials from different authors

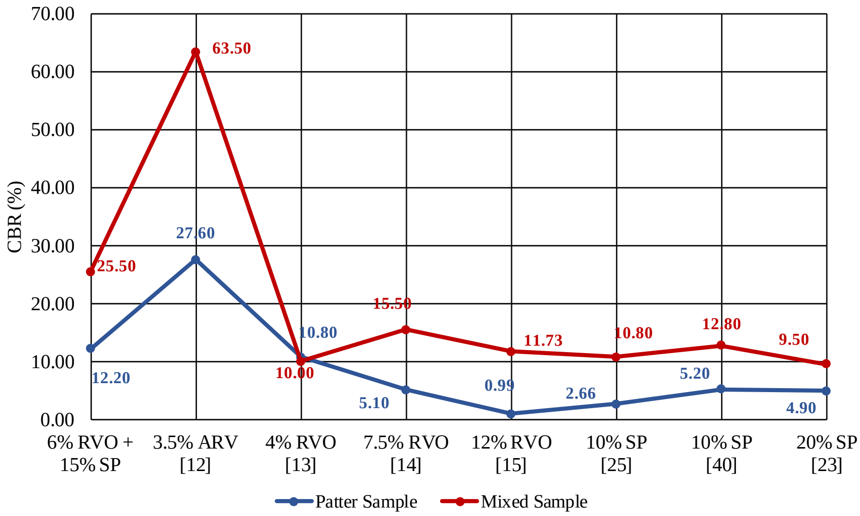

Figure 12. Penetration resistance obtained for materials from different authors

5. Conclusions

Regarding the plasticity index, the natural soil presents a PI of 16%. After the addition of stabilizing agents, a reduction was observed in all cases, with the lowest plasticity recorded at 8% for the 6% RVO + 15% SP dosage. Ultimately, it is determined that the use of recycled motor oil and stone dust influences the behavior of the subgrade and improves the soil's plasticity characteristics in its natural state.

Regarding the maximum dry density, the unaltered subgrade has a value of 1,977 kg/m^3. Following the addition of the stabilizing agents, an increase in maximum dry density values was observed. The most significant increase, at 3.14%, was recorded with the 6% RVO + 15% SP dosage, reaching 2,039 kg/m^3. It is concluded that the use of recycled motor oil and stone dust results in a slight increase in maximum dry density.

Concerning the optimum moisture content, the study clearly demonstrates that as the percentage of recycled motor oil and stone dust increases, the moisture content significantly decreases in most cases. This trend is evident, as sample M1, without any additives, has a value of 10.30%, whereas samples M2, M3, M4, and M5 present values of 5.70% (-44.66%), 4.90% (-52.43%), 4.50% (-56.31%), and 4.20% (-59.22%), respectively.

The results obtained from the penetration resistance analysis indicate that, although the natural subgrade exhibits good quality with a CBR (0.1”) at 95% of MDD of 12.20, the addition of all four stabilizer dosages significantly improves its resistance, upgrading its classification from "good" to "very good." The most notable improvement is observed with the 6% RVO + 15% SP dosage, reaching a value of 25.50%. This confirms that the use of recycled motor oil and stone dust enhances the penetration resistance of the subgrade.

Finally, the unconfined compressive strength of the subgrade soil after the addition of RVO and SP shows a decline in results, which is more evident when compared to its original state. Without additives, the soil exhibits an unconfined compressive strength of 265,863.64 kg/m^2, indicating a very firm consistency. In contrast, the incorporation of 6% RVO + 10% SP and 8% RVO + 15% SP results in medium consistency, with strengths of 60,808.25 kg/m^2 and 78,953.18 kg/m^2, respectively. The use of 8% RVO + 10% SP results in a soft consistency, with a value of 41,037.21 kg/m^2. On the other hand, the addition of 6% RVO + 15% SP achieves a strength of 100,251.00 kg/m^2, maintaining a firm consistency. These findings demonstrate that the use of recycled motor oil and stone dust negatively impacts unconfined compressive strength, with the 6% RVO + 15% SP dosage being the least detrimental.

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