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Original Article

Analysis of Subgrades with Low Bearing Capacity of 3% Stabilised with Neo Soil and Polyacrylamide for the Characterisation of the Mechanical Properties of Rigid Pavements in Urban Areas

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Abstract *- Access to adequate road infrastructure remains a challenge in many regions of Peru, especially in the province of Huancayo, where highly plastic silty and clayey soils predominate. The soils retain moisture, have a weak structure, and are easily deformable, which makes building and maintaining durable pavements in an urban setting especially challenging. In light of this issue, this study aimed to understand and characterise the empirical relations of mechanically stabilised sub-bases with 3% bearing capacity, using a combination of Neo Soil and polyacrylamide, to determine the possible use of such sub-bases in urban rigid pavements. Accordingly, preliminary characterisation tests such as granulometry, Atterberg limits, and moisture content were deployed, and then sub-bases of different mixtures of the two additives were tested. The modified Proctor and CBR tests were then employed to measure the strengths gained in the sub-bases. The extensive statistical tests employed to fully understand the data obtained were Shapiro-Wilk, ANOVA, Tukey, fragility curve, and CBR. The results showed significant improvements in bearing capacity, particularly for highly plastic clay, which, with the combination of 0.6% polyacrylamide and 6% Neo Soil, increased the CBR by 250.00% at 100% compaction. This finding was statistically confirmed by Shapiro-Wilk, ANOVA, and Tukey tests and reinforced by fragility curves, which showed its better performance compared to the other soils evaluated. Consequently, these findings demonstrate that the combined use of these additives significantly improves the mechanical behaviour of problematic soils in urban contexts. However, due to the natural variability of soils, it is recommended that additional studies be conducted in different locations and that their long-term performance be evaluated in order to consolidate their implementation as a replicable solution in road infrastructure.*

Keywords *- Neo Soil, Polyacrylamide, Silt, Elastic silt, Low plasticity clay, Low plasticity clayey silt, High plasticity clay, CBR.*

1. Introduction

Peru currently has a road network of approximately 26,017.07 kilometres, of which 12,444.93 km (48%) are paved, 11,150.91 km (43%) are gravel roads (subgrade), and the remaining 2,421.23 km (9%) are in the planning stage [1]. These figures reveal marked inequality in access to adequate road infrastructure, especially in provincial capitals in the interior of the country, where large areas remain unpaved [2]. A representative example is the Junín region, which has a considerable deficit of approximately 10,529 kilometres of unpaved roads, particularly affecting expanding urban areas such as the city of Huancayo [3]. In this scenario, the lack of paving increases local transport costs due to greater vehicle wear and tear and increased fuel consumption, as more energy is required to travel on deteriorated roads, in addition to reduced travel speeds, which reduces productivity and makes the service more expensive [4]. This problem is not only due to economic or management constraints, but also to the geotechnical characteristics of urban soils, which hinder construction and reduce the service life of pavements [5]. For example, in various sectors of this province, silty soils with low cohesion, high water retention, and limited bearing capacity predominate, conditions that negatively affect the durability of pavements, whether rigid or flexible [6]. Similarly, in the district of Sicaya, where population growth has led to the opening of new urban roads, it has been determined that more than 40% of the soil has highly plastic clay characteristics, making it susceptible to deformation in the presence of moisture. This condition increases the risk of cracks and differential settlement in pavements. In addition, many of the surrounding roads are only gravel, making them difficult to travel on during rainfall due to soil saturation, which compromises the stability of these unpaved roads [7]. Therefore, before carrying out urban paving works, it is essential to treat the ground using soil improvement techniques, as these roads are subject to heavy loads and require a base with optimal physical and mechanical properties to ensure their long-term stability and durability. Soil stabilisation with materials is economically justified. Various stabilisation materials act in a synergistic way. Soil polyacrylamide excels in durability. It is a synthetic polymer with a dual effect as it decreases permeability while increasing compressive strength [8]. Lime increases longevity as it decreases plasticity and compressibility of soils, hence, reinforcing strength [9]. Cement augments stable compressive strength and bearing capacity of soils, along with efficient compaction, which is economically justified as it decreases pavement layer thicknesses [10]. A geopolymer, fly ash, increases strength as it improves cohesion among particles [11]. GGBS improves the mechanical properties of soils as it increases shear strength and consolidation, while stiffness improves [12]. All these inputs are of great value in soil stabilisation. Therefore, the soil stabilisation alternatives need other inputs like Neo Soil. It is a volcanic ash pozzolanic polymer material. It forms a dense, more cohesive, and resistant polymer matrix upon reaction with water [13]. Neo Soil is therefore of enormous value as a soil stabilisation material. Therefore, the present study aims to analyse the stabilisation of silty and clayey subgrades using Neo Soil and polyacrylamide, in order to evaluate their technical and economic viability for application in urban pavements.

2. Literature Review

In China, with the aim of observing the reaction of polyacrylamide in lime-stabilised soil, they investigated different proportions of the additive, including mixtures with 0% and 0.24% polyacrylamide without lime, as well as mixtures with 0%, 0.12%, 0.24%, 0.36%, 0.48%, and 0.6% polyacrylamide, all with 8% lime. They analysed the compressive strength, porosity index, and consolidation of the soil and found that a proportion of 0.24% polyacrylamide reduced the compression of lime-stabilised soil, increasing the porosity index by 15.4%, which favoured surface water drainage and accelerated the consolidation rate by 413.2%, reflecting a significant reduction in the time required for soil consolidation and stabilisation [14].

In India, they investigated the stabilisation of clay soils and clays using polyacrylamide, specifically the commercial derivative Polycom-A, because it is a polymer with a wide range of applications for improving soil properties. They applied this additive to highly compressible clay and clayey sand samples, conducting tests that measured the relationship between dry density and moisture content, as well as Unconfined Compressive Strength (UCS) tests, where they obtained results showing that the highly compressible clay improved its compressive strength by 160%, while clayey sand showed a 150% increase, in addition to a 40% increase in cohesion and internal friction angle, indicating a significant improvement in the stability and mechanical behaviour of soils treated with polyacrylamide [15, 16].

In Iraq, the civil engineering department conducted studies motivated by previous evidence that polyacrylamide (PAM) is an effective polymer for improving the properties of soils used in road construction. For this purpose, they used various doses of PAM, ie, 0.001%, 0.002%, 0.004%, and 0.008% of PAM, on clay soils and assessed their impact on dry density, Unconfined Compressive Strength (UCS), elastic modulus, and mineralogical analysis by means of X-ray diffraction. The findings revealed that 0.002% PAM produced a 0.75% increase in dry density, a 20% increase in compressive strength, and an 11.6% increase in elastic modulus. Moreover, the mineralogical analysis showed that, post-treatment, there was no change in the constituents of the minerals forming the soils, thus confirming that PAM enhances the soil's mechanical properties without modifying the mineralogical content of the material [17].

In Indonesia, as part of the research undertaken for the Master's programme in Applied Infrastructure Engineering, the use of Polyacrylamide (PAM) in silty soils and the enhancement of the soil's geotechnical properties were studied. For this purpose, different doses of PAM were applied, and shear strength tests were carried out at different curing days, 1, 3, 7, and 14, as well as consolidation and triaxial tests were conducted. The applied PAM doses were 0.2%, 0.4%, 0.6%, 0.8% and 1%. The results were positive in that the addition of PAM was able to increase the shear strength, and the degree of increase was affected by the curing time. The behaviour of the soil concerning consolidation was improved, too. In terms of bearing capacity, it was concluded that a minimum dose of 0.4% PAM was adequate, as it met the necessary requirements for use as a structural fill material [18].

In Australia, the Civil Engineering Department evaluated the use of polyacrylamide in a catari-type soil, selected because it is typical of the sub-bases used in pavement structures in the Middle East and North Africa. To do this, they conducted simple compression strength, stiffness modulus, and toughness tests to analyse the performance of the treated soil. The results showed that the application of a 50% w/w aqueous solution of a polyacrylamide derivative, specifically an amphoteric terpolymer, at a dosage of 2% relative to the dry weight of the soil, provided the best values in all three tests. This combination significantly improved the mechanical properties of the soil, establishing itself as an effective alternative for subgrade stabilisation in arid áreas [19].

In Australia, the Faculty of Science, Engineering and Technology investigated the use of Polyacrylamide (PAM) as an additive for soil stabilisation, applying it to silty gravel, clayey sand and clayey gravel, where they conducted tests on dry density, Unconfined Compressive Strength (UCS), elastic modulus, tensile strength (energy absorption capacity) and tensile strength tests, obtaining as a result that the maximum dry density increased between 1.4% and 1.7%, especially in soils with a higher fines content, while the unconfined compressive strength improved between 13.4% and 30.5%, being more significant in soils with a lower proportion of fines; in addition, the elastic modulus increased between 16.6% and 31.9%, particularly in soils with a higher fine content, and toughness also increased, enhancing the soil's capacity to absorb energy and withstand higher loads, with a maximum increase of 62.3% in clayey sand. Finally, tensile strength showed improvements between 3.4% and 9.9%, with a lesser effect observed in soils with few fines, such as silty gravel, and a greater improvement in finer soils, such as clayey sand and clayey gravel [20].

The Faculty of Civil and Construction Engineering in Australia trialed polyacrylamide (PAM) as a sustainable alternative for soft clay cementitious stabilising agents and additives as sub-base and subgrade pavements binders stabilising agents and additives. In order to evaluate the mechanical behaviour of soils treated with PAM and measure the changes in the soil's mechanical properties (dry density, elastic modulus, resilient modulus, and response to repeated loading), a number of tests were conducted. The findings concluded that dry density improved by 1% to 1.3% and the elastic modulus improved by 19.3% to 26.3% especially in soils with higher fines content. The resilient modulus improved in granular and cohesive soils (31% and 46% respectively) but improved far less and more slowly (8% only) in clay soils. In terms of the constitutive models used, the three-parameter deviator stress model resulted in a more accurate fitting of the actual resilient moduli, with the k_3 parameter values between 2.03 and 5.51, and PAM-treated soils having higher values. By bridging together findings of Pam as a sustainable alternative to the structural improvements of materials used in pavements for future road infrastructures with a decreased carbon footprint, it is an all-encompassing advantage [21].

In China, researchers from the Faculty of Civil Engineering and Architecture investigated expansive soils treated with Cationic Polyacrylamide (CPAM) in proportions of 0%, 0.2%, 0.4%, 0.6%, 0.8% and 1%, as this type of soil often causes numerous problems in the construction of roads, railways, and underground buildings. They observed that as the CPAM content increased, the liquid limit and plasticity index decreased, while the plastic limit increased. In addition, the soil improved with 0.6% showed less tendency to disintegrate and greater stability against water. An increase in shear strength was also recorded, while the compressive strength peaked at 410.1 kPa at 0.8% CPAM, a notable improvement in its mechanical properties [22].

The Civil Engineering Department in Dhaka studied the stabilisation of coastal embankments damaged by floods and cyclones using polyacrylamide, cement, and fly ash. Geo-engineering the soil samples taken from Chattogram in the laboratory, they treated the samples with varied proportions of the stabilisers and conducted a series of geotechnical experiments to assess the changes in the samples' physical and mechanical properties. They found that the mixture of the stabilisers gained the soil strength and stability whose effects surpassed the use of polyacrylamide individually, improving the coastal embankment sustainability. In addition, it was determined that workability and strength are key to selecting the optimal mixing ratio. The results support the combined use of these materials for more effective and sustainable stabilisation [23].

Neo Soil is mainly made from volcanic ash, but there is no specific research on Neo Soil for soil stabilisation or other areas; however, there are studies on volcanic ash, the material from which Neo Soil is derived [13]. For example, in Iran, the Department of Civil Engineering investigated Ground Granulated Blast Furnace Slag (GGBS) combined with alkalis and volcanic ash to stabilise clay soils, evaluating compressive strength and durability under moisture-dry and freeze-thaw cycles, finding significant improvements in these properties and a low associated carbon footprint [24]. Similarly, in that country, they confirmed that volcanic ash is an effective substitute for Portland cement in sandy soils, increasing compressive strength when combined with alkaline solutions [25]. In another Iranian study, the addition of 6% cement and 15% volcanic ash increased Unconfined Compressive Strength (UCS) and CBR index by 83% and 126% respectively, at 28 days [26]. In addition, volcanic ash has been used to remediate lead-contaminated soils in Iran, reducing leaching by 91%, which decreases the mobility of the contaminant and the risk of groundwater contamination, while increasing Unconfined Compressive Strength (UCS) by 600% with the addition of 15% volcanic ash [27]. Finally, in Egypt, volcanic ash, rich in iron oxides, silica, and alumina, as well as minerals such as feldspars, quartz, kaolinite, and montmorillonite, has been shown to improve soil fertility and the productivity of crops such as potatoes, without causing nutritional deficits in plants or their tubers [28].

After reviewing various studies, it has been shown that polyacrylamide offers significant benefits for soil stabilisation, although its use is still limited. However, there is no previous research on the application of Neo Soil for this purpose, which makes this study particularly relevant, as it explores an innovative alternative with the potential to improve the behaviour of unconventional soils and expand the options in geotechnical engineering. In this context, the soil was characterised using granulometry, Atterberg limits, and moisture content tests to determine its physical properties. Mixtures were then prepared with different proportions of Neo Soil (0%, 1.5%, 3%, 4.5%, 6%, 7.5% and 9%) and polyacrylamide (0%, 0.15%, 0.30%, 0.45%, 0.60% and 0.75%), which were compacted according to the modified Proctor method and evaluated using the CBR test to analyse how these additives influence the behaviour and bearing capacity of the soil when used as subgrade.

3. Materials and Methods

3.1. Rigid Floor

Rigid pavement is a structure consisting of hydraulic concrete slabs designed to receive traffic loads and transmit them efficiently to the foundation soil [29]. Therefore, its proper construction is essential to ensure the safety and continuity of vehicular and pedestrian traffic. In this context, Figure 1 shows the deterioration of a section of rigid pavement located in the district of Chilca, corresponding to one of the main access avenues to the centre of Huancayo. As can be seen, items (a), (b), and (c) show longitudinal cracks, surface detachments, and joint failures, caused mainly by heavy traffic and the lack of regular maintenance. This shows that, even in the case of strategic roads for urban connectivity, rigid infrastructure can fail prematurely when design and maintenance conditions are inadequate.

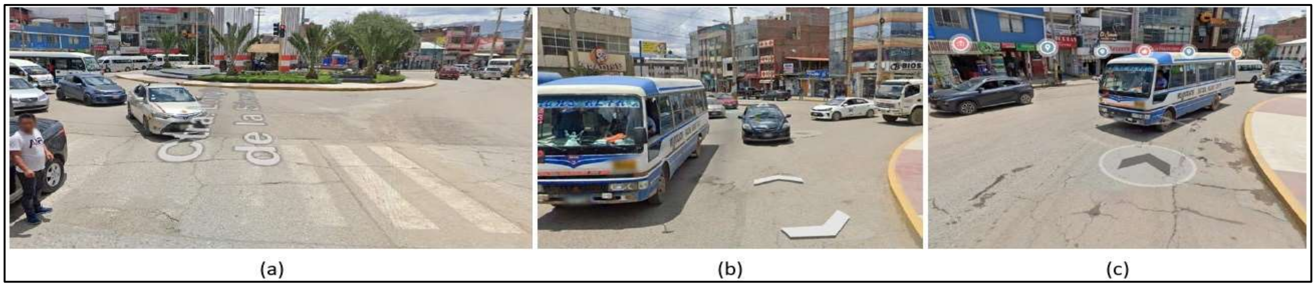
(a) (b) (c)

Fig. 1 Rigid pavement in poor condition

3.1.1. Structure of Rigid Pavement: Layers and Functions

Rigid pavement consists of several layers that work together to distribute the loads applied by vehicular traffic and ensure the stability and durability of the road [30]. Figure 2 shows a cross-sectional diagram of a car on the pavement, with arrows indicating the progressive transfer of load to the lower layers. First, the concrete slab directly resists traffic, provides a safe driving surface, and protects the internal layers from the elements [31]. Below, the base acts as an intermediate element that dissipates loads to the subsoil [32]. Granular materials are further down in the sub-base, which helps improve the overall drainage of the system and moisture retention as well as drainage and moisture retention of the system as well as the overall drainage of the system [33]. Lastly, the subgrade is the unprocessed earthen materials, which are the last load support of the whole system and whose proper preparation, in addition to compaction, is fundamental [34]. This illustration is an example of how the different layers have different performance capabilities that are, in turn, interrelated to provide an adaptable road system.

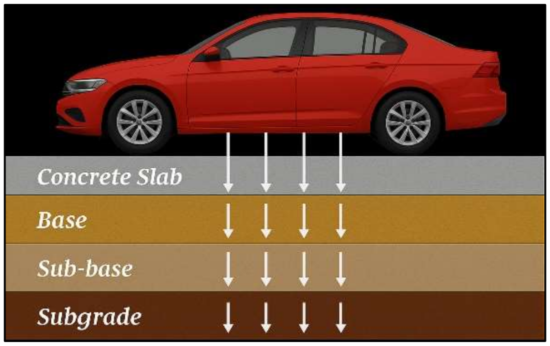

Fig. 2 Rigid pavement structure [31]

3.1.2. Influence of Climatic Conditions

The functionality of rigid pavements relies on both the structural and the environmental factors to which a pavement and its base are exposed [35]. In order to understand the integrated climatic factors with the pavement and its base as a composite system in the design, refer to Figure 3.

For a given precipitation, water can infiltrate, evaporate, or run off excessively. Prolonged water standing in a system can lead to a reduction in the flooring system and create a weak subgrade. Monolithic slabs of concrete pavements shelter subgrade and detain early seasonal weathering on the pavement surface, which may, in time, develop patterns of abrasion and crack geoforms. However, water-positive subgrade and weak subgrade lead to geoforms on the pavement surface, which are often referred to as alligator cracking, with protruding edges of the geoforms, carrying water.

Due to being perched at an elevation of 3,259 metres above sea level, the city of Huancayo experiences an increase in solar radiation and accelerated evaporation, intensifying the local environmental conditions of the area [36]. The city receives the majority of its precipitation from December to March, where it receives a yearly average of 700 mm of precipitation, and experiences the local environmental conditions of the area, which are extremely variable between the drying and wetting of moisture in the soil. Added to this is a marked temperature range, with temperatures varying between 7 °C and 21 °C, causing considerable gradients in the surface layers of the soil [37]. These variations can reach depths of 20 to 50 cm in a daily cycle and up to 10 m in a seasonal cycle.

The combination of water saturation and thermal gradients produces repeated processes of expansion, contraction, wetting, and drying that accelerate the deterioration of rigid pavement. In this context, the subgrade, as the foundation layer, is the most vulnerable to external conditions, and its weakening is the main cause of the failures observed in the slab, such as longitudinal cracks, surface detachments, and joint failures, as shown in Figure 1.

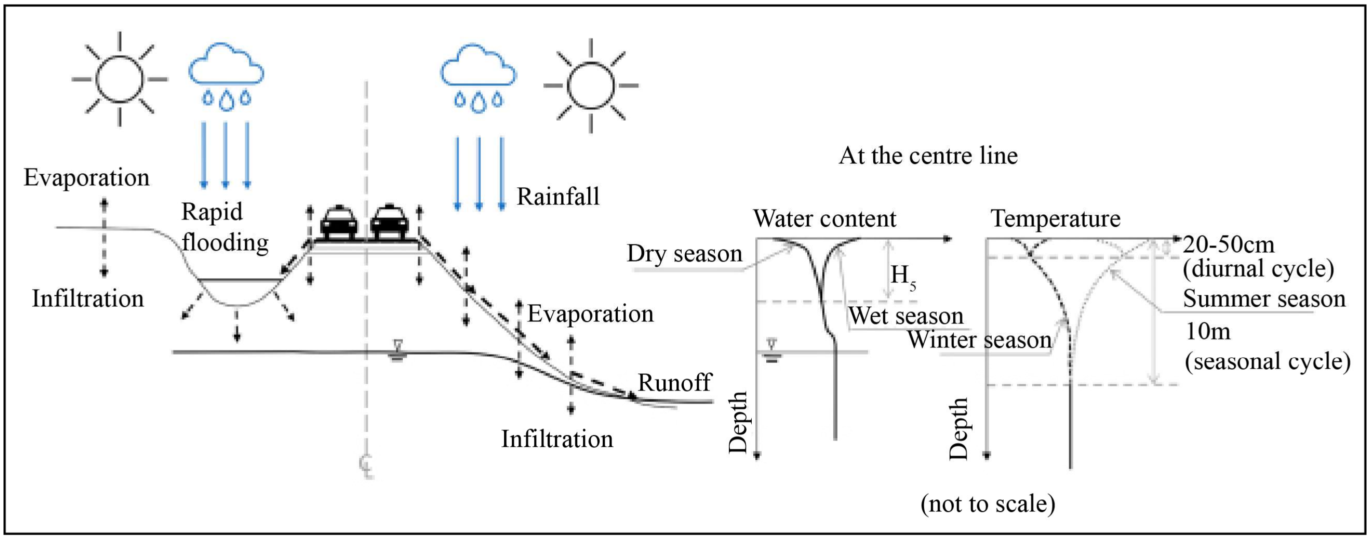

Fig. 3 Hydrological and thermal dynamics in road infrastructure during seasonal cycles [38]

Table 1. Chemical properties

Neo Soil	
Components	Content
Volcanic material	50-60%
Fermented organic matter	10-15%
Nitrogen	0.4-0.8%
Phosphorus	0.3-0-6%
Potassium	0.5-1.0%
Iron	0.1-0.3%
Calcium	1.5-2.5%
Magnesium	1.5-2.5%
pH	5.5-6.5

3.2. Neo Soil

Neo Soil is a light brown to grey artificial substrate with a homogeneous granular texture, composed of inorganic materials such as expanded ceramics, volcanic minerals and clay, as well as organic compounds such as compost, coconut fibre, rice husks, biochar and peat, which are integrated to form a balanced medium that promotes plant development, providing physical support, organic matter, and suitable conditions for biological activity within the substrate itself [13].

Table 1 presents the chemical properties of Neo Soil, a product that combines between 50% and 60% volcanic material with 10% to 15% fermented organic matter, promoting soil fertility and biological activity. Its main nutrients include nitrogen (0.4-0.8%), phosphorus (0.3-0.6%) and potassium (0.5-1.0%), essential for the development of plants and microorganisms, as well as micronutrients such as iron (0.1-0.3%), calcium (1.5-2.5%) and magnesium (1.5-2.5%), which improve soil chemical quality and promote biochemical processes. Its slightly acidic to neutral pH (5.5-6.5) is suitable for most crops and beneficial microorganisms, while its high concentration of active bacteria, mainly nitrifying and nitrogen-fixing bacteria such as Azotobacter and Nitrosomonas, plays a key role in nutrient transformation and soil health.

Figure 4 shows Neo Soil, a product that was applied to the soil in proportions of 1.5%, 3%, 4.5%, 6%, 7.5% and 9% in order to evaluate its effect on the properties of the subgrade.

Fig. 4 Neo soil

3.3. Polyacrylamide

Polyacrylamide (PAM) is a manmade polymeric compound with a general appearance of slightly beige or white powder or granules [39]. Fine and uniformly sized granules of PAM are composed of molecular chains of acrylamide [40]. This compound is hydrophilic and can create viscous solutions or gels depending on its concentration [41]. PAM can be cationic, anionic, or non-ionic, which describes its molecular interactions and reactions with other molecules [42]. PAM's durability with extreme temperatures and elements makes it versatile and useful in many situations and environments [43].

In Figure 5, the repeating units authorized as Polyacrylamides (PAM) are displayed with their characteristic chemical structure, displaying the Polyacrylamides' (PAM) characteristic chemical structure, displaying the Polyacrylamides' (PAM) characteristic chemical structure and repeating units, allowing for their continued hydrolysis. The structure has a CH_2 methylene and a carbon atom bearing a free radical (•) necessary for polymerisation. Also, forming polymer chains. The $CONH_2$ groups forming the polymer chains are hydrophilic amide groups that influence the structure as they are capable of forming hydrogen bonds. These free radicals portray the position of the amide group, which explains the difference in physical intermolecular interactions.

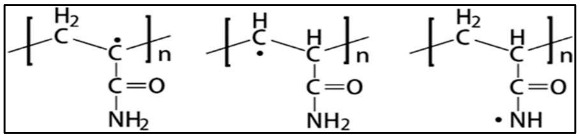

Fig. 5 Forms of polymeric radicals in polyacrylamide [44]

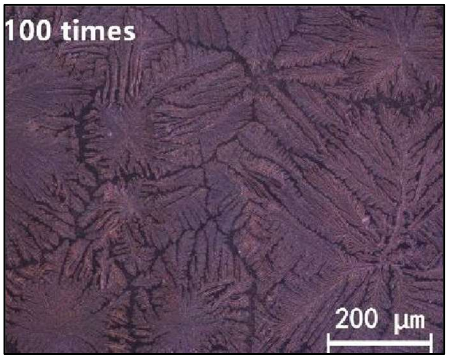

Fig. 6 Microscopic image of PAM [14]

Figure 6 shows an optical micrograph of the surface of Polyacrylamide (PAM), magnified 100 times, which allows its structural behaviour to be analysed in isolation. This image shows a branched surface morphology, with clearly distinguishable dendritic or filamentous formations emerging from central points, suggesting a spontaneous organisation pattern of the polymer chains once applied to a solid surface. As a result, it can be inferred that, during the drying or settling process, PAM forms an internal network with multiple branches, which, in turn, could contribute significantly to holding adjacent particles together. In this sense, the micrograph not only illustrates the surface distribution of the polymer but also highlights its intrinsic ability to generate retention, coating, or bonding effects, which are fundamental qualities in its application as a structuring agent.

A simplified diagram of how Polyacrylamide (PAM) interacts with soil particles is illustrated in Figure 7. The polymer chains are initially soluble in the medium. Then, upon meeting soil grains, they begin to adsorb onto the soil surfaces, i.e., they adhere to the surface and are immobilized due to Van der Waals intermolecular forces. Consequently, the PAM chains can attach multiple soil particles together, causing a bridging effect that holds together loose soil grains. Moreover, the long polymer chains can occupy the voids in the soil, thus contributing to a denser arrangement. These processes can lead to PAM-treated soils having greater cohesion, less erosion, and possibly better water retention. The diagram summarizes how PAM might alter the soil distribution pattern and the physical arrangement of soil particles. This is useful in dust suppression, soil stabilization, and improving soil physical properties.

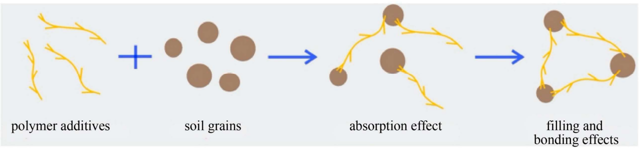

Fig. 7 Schematic diagram of interaction between soil and polyacrylamide [45]

Figure 8 shows the polyacrylamide product used in the research, presented as a fine, homogeneous white powder, which was applied to the soil in proportions of 0%, 0.15%, 0.30%, 0.45%, 0.60%, and 0.75%, following recommendations based on previous studies that have shown that polyacrylamide significantly improves the mechanical properties of the soil, such as compressive strength, cohesion, and bearing capacity, thus contributing to the stabilisation and durability of the treated structure [22].

Fig. 8 Polyacrylamide

3.4. Measurement Indicators

3.4.1. Particle Size Distribution

Granulometry is a method used to determine the size distribution of the particles that make up soil, and is a fundamental procedure in civil engineering for soil classification and the proper design of structures. Standard MTC E-107 [46] was used to perform this test. First, a representative soil sample was collected and subjected to a quartering process to ensure its homogeneity. Subsequently, the sample was washed with water through a No. 200 sieve to remove fine particles that could alter the accuracy of the analysis. On the other hand, washing continued until the water ran completely clear, which represented the effective removal of the finest fractions. The material retained in the No. 200 sieve was collected and placed on a tray to be dried in an oven at a temperature of 110 ± 5 °C for 24 hours. Once dry, a total of 1000 g was weighed, and the sieve column was prepared, from the largest aperture (such as the 1" sieve) to the finest (No. 200 sieve), including a lower tray to collect the material that passes through all the sieves. The sample was placed on the top sieve and manually sieved for 10 to 15 minutes. We then weighed the material retained in each sieve and added the retained weights to verify that the loss of material did not exceed 2%. Subsequently, we calculated the percentage retained in each sieve using formula 1. Next, we obtained the cumulative percentage retained using formula 2. We then found the percentage passing (or fine) using formula 3. With this data, we created the particle size distribution curve in Excel, plotting the particle size on the X-axis (logarithmic scale) and the percentage passing on the Y-axis.

$$\% \, Detained = \frac{Weigh \;\; retained\ on\ the\ sieve}{Total\ sample\ weigh} x100 \tag{1}$$

$$\% \, Cumulative\ retention = Sum\ of\ the\ percentages\ retained \tag{2}$$

$$\boldsymbol{\% \, that\ happens = 100\% \ cumulative\ retention} \tag{3}$$

3.4.2. Atterberg Limits

Atterberg limits refer to crucial parameters in soil mechanics for assessing different moisture-related soil consistency changes [47]. Some of these limits include the liquid limit and the plastic limit, which respectively define the change of state from the liquid to the plastic, and from the plastic to the semi-solid [48]. Consequently, the plasticity index, which distinguishes the moisture limits of the plastic state of the soil, is calculated and serves as an important criterion in its classification and geotechnical behaviour.

Liquid Limit

The Liquid Limit (LL) refers to the moisture content at which a soil transitions from a plastic to a liquid state [49]. The procedures outlined in standard MTC E-110 [46] were utilized for the execution of this test. For this purpose, a representative soil sample was taken using the quartering method and then passed through a No. 40 sieve, discarding the intact material. The soil fraction that passed through the sieve was mixed with incremental water additions until a smooth, homogeneous paste was obtained that did not contain any lumps. This paste was then placed in the cup of the Casagrande device, the surface was smoothed, and it was bisected with a spatula using the standard groove. The crank was then turned to drop the cup from a height of 10 mm, recording the number of blows required for both halves of the soil to join together over a 12 mm length. This procedure was repeated three times with different moisture contents. A portion was taken from each mixture to determine its moisture content, placing it in metal capsules that were dried in an oven at 105 °C ± 5 °C for 24 hours. Finally, the moisture content values were plotted against the logarithm of the number of blows in Microsoft Excel, and the liquid limit was determined from this curve using formula 4.

Liquid limit = moisture content corresponding to 25 beats (interpolated on the logarithm curve of beats vs. moisture) (4)

As mentioned, three data points were obtained and plotted, as shown in Figure 9. This figure presents the data for each sample, with the number of impacts on the X-axis and the corresponding moisture percentage on the Y-axis. For example, capsule A-23 recorded 16 blows with 27.62% moisture; capsule A-39 recorded 25 blows with 26.51% moisture; and capsule A-51, in two repetitions, recorded 35 blows with 25.92% moisture. From this curve, the moisture content corresponding to 25 blows was interpolated, thus determining the liquid limit of the analysed soil.

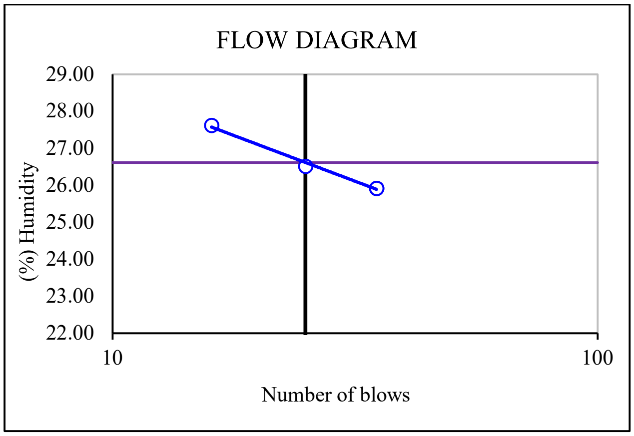

Fig. 9 Fluidity diagram

Plastic Limit

The Plastic Limit (PL) is defined as the moisture content at which the soil changes from a semi-solid to a plastic state [49]. This test was carried out in accordance with the provisions of standard MTC E-111 [46]. To do this, soil previously sieved through a No. 40 sieve was used, which was mixed manually with water until a plastic mass was obtained that did not stick excessively to the fingers or crumble. Next, portions of approximately 6 grams were taken and moulded on a smooth surface to form uniform strands 3 mm in diameter. If the strands broke or cracked when this thickness was reached, the soil was considered to have reached its plastic limit, as shown in Figure 10. This procedure was repeated at least three times to ensure consistency of results. The samples used were placed in metal capsules and dried in an oven at 105°C ± 5°C for 24 hours. Finally, the LP was determined as the average moisture content of the samples analysed.

Fig. 10 Plastic limit test

Plasticity Index

The Plasticity Index (PI) is a parameter that defines the range of moisture content in which a fine soil maintains its plastic behaviour [50]. In this context, the PI reflects the soil's ability to deform without fracturing within that moisture range [51]. This parameter is determined using formula 5:

$$PI = LL - PL \tag{5}$$

From a geotechnical standpoint, a low IP means the soil contains a low range of plasticity, comprising silts, and on the other hand, a higher IP means clay of a plasticity-bending type, such as expansive clay. Thus, this value was essential for soil categorization as per the Unified Soil Classification System (USCS) because, through its study, one was able to foresee its mechanical behaviour and thus, establish the level of its class in the system.

3.4.3. Moisture Content

Soil moisture content, in percentage, is the expression of the total amount of water a soil sample contains as compared to the weight of the sample soil in its dried condition [52]. To achieve this, the principles outlined in standard MTC E-108 were employed [46].

The initial stage involves drawing a representative soil sample using a quartering method to maintain the sample's homogeneity. After that, a target weight of 30–50 grams was taken, and this was inserted into a pre-tared metal capsule that was labelled before use, which means its weight, in an empty state, was recorded. The empty weight of such a capsule is measured before the capsule is filled. The weight of the capsule containing the moist soil is taken immediately.

After that, the capsule was put in an oven set to 105°C and left there for 24 hours. After drying, the capsule was taken out of the oven and placed in a desiccator to cool to avoid adsorbing water. After these capsules reached room temperature, the last weighing was done to determine the dry weight of the soil. If needed, the stability of the dry weight was checked by several weighings that should differ by 0.1 g at most, as the standard says. Using the resulting numbers, the moisture content was obtained with the help of equation 6.

$$W = \frac{Ph - Ps}{Ps} x100 \tag{6}$$

Where:
Ph = weight of wet soil
Ps = dry soil weight

The results obtained were documented in an electronic spreadsheet, along with the tare weight of the capsule, capsule weight with wet soil, and capsule weight with dry soil to maintain the traceability and reliability of the test. This step was necessary to ascertain the water content in the soil at the time of collection, which is critical in understanding the soil's properties and the status of the soil moisture.

3.4.4. Soil Classification

The ability to determine and analyze physical properties such as particle size and plasticity for soil samples enables the effective classification of soil found within the study area [46]. Granulometry (particle size) and Atterberg limits (plasticity) results were used to determine the soil classification within the area as per the SUCS classification.

Results of the tests were used to determine the physical properties of soil and are detailed in Table 2. For the soil sample, within the bounds of the granulometric analysis, it was found that silt contains particles that are smaller in size than 0.075 mm, while for the case of clay, it contains fine particles that are smaller than 0.002 mm. Clayey silt was found to combine both fractions, which was represented by minimal plasticity.

Plasticity index, on the other hand, has a range between 7% which corresponds with silt, and 26% in the high plasticity clay, as well as with the moisture content that ranged from 15.20% to 41.80%. As per these results, the soil was classified under the USCS as silt (ML), elastic silt (MH), low plasticity clay (CL), low plasticity clayey loam (ML-CL), and high plasticity clay (CH). Therefore, this characterization was vital in the understanding and further analysis of soil within the study area for the in situ stabilisation processes.

Table 2. Physical properties

Physical properties					
Essays	Soil types				
	1	2	3	4	5
Particle size distribution	< 0.075 mm	< 0.075 mm	< 0.002 mm	< 0.075 mm	< 0.002 mm
Classification (SUCS)	Lime (ML)	Elastic slime (MH)	Low plasticity clay (CL)	Low plasticity clay loam (ML-CL)	High plasticity clay (CH)
Plasticity index	7	9	21	6	26
Moisture content	15.20%	34.60%	29.30%	22.70%	41.80%

3.4.5. CBR

Modified Proctor

The modified Proctor test is designed to examine the relationship between the moisture content and the maximum dry density a soil can achieve under an elevated compaction load [53]. This test was conducted according to the specifications of standard MTC E-116 [46].

To begin with, a soil sample was obtained by the quartering method. This sample was then air-dried and sieved with a No. 4 sieve (4.75 mm). If the retained coarse material was greater than 30%, this sample was discarded to conform to the test's requirements.

After this, the fine material obtained was divided into different weight portions. Then the different weight portions were mixed to prepare sample sets with distinct moisture contents by the addition of water in increments. The different moisture content sample sets were then individually mixed by hand to achieve a uniform moisture distribution.

The sample sets were then placed, one at a time, into a cylindrical mould of a volume of about 1/30 cubic feet in five equal layers. Each of the five layers was compacted with 25 strikes from a 4.54 kg compaction hammer from a height of 45.7 cm and evenly spread across the layer.

After the five layers were compact, the surface was boxed off, and the mould was inverted. Then the compaction block was removed from the mould with care so that there was no damage to the compacted mass. Next, a small representative sample of the compacted soil was extracted and used to determine the moisture content using formula 7:

$$w = \frac{P_h - P_s}{P_s} x100 \tag{7}$$

Where:

- W = moisture content (%),
- Ph = weight of the wet sample (g),
- Ps = weight of the dry sample (g).

With the total wet weight of the compacted block (P) and the known volume of the mould (V), as well as the moisture content (w) obtained from the sample, the dry density was calculated using the formula:

$$p_d = \frac{P}{V\,x\,(1+\frac{w}{100})} \tag{8}$$

Where:
ρ_d = dry density (g/cm³ or kg/m³),
P = total wet weight of the compacted block (g or kg),
V = mould volume (cm³ or m³),
w = moisture content (%).

This procedure was repeated for each mixture with different moisture contents, allowing the maximum achievable dry density to be determined, as well as the associated optimum moisture content, for each of the soils evaluated.

The study population consisted of the soil used in the trials. The sample was obtained using a complete factorial design, in which the factors and their levels were defined in advance, as this type of design allows the researcher to establish them according to the objectives of the study [54]. The total number of combinations resulted from the product of these levels.

The factors considered were: Soil (5 levels: S1–S5), Dosage (6 levels: M1–M6), and Compaction (2 levels: 95% and 100%), yielding a total of k = 5 × 6 × 2 = 60 experimental combinations (cells). In this study, the experimental unit corresponded to each CBR test tube moulded at the optimum moisture content and maximum dry density determined by the modified Proctor test.

Therefore, following ASTM D1883, three CBR test tubes were prepared for each experimental combination, which determined the number of replicates r = 3 [55]. Consequently, the total sample size was N = k × r = 60 × 3 = 180 CBR specimens.

In this context:

- k represents the total number of experimental combinations (cells) generated by the factors and their levels.
- r corresponds to the number of replicates or specimens for each combination.
- N expresses the total sample size, calculated as the product of k and rN.

From this point onwards, we worked with different samples identified as M1 to M6, to which specific proportions of Neo Soil and polyacrylamide were assigned, as detailed in Table 3. To define these dosages, we took into account, on the one hand, the Neo Soil technical data sheet, which recommends an application range between 2% and 5% [56], and on the other hand, previous research reporting that a dosage of 0.4% polyacrylamide was adequate [18]. Based on this, the values used in this study were established.

Table 3. Dosages

Samples	Neo Soil (%)	Polyacrylamide (%)
M1	0.00%	0.00%
M2	1.50%	0.15%
M3	3.00%	0.30%
M4	4.50%	0.45%
M5	6.00%	0.60%
M6	7.50%	0.75%

The CBR (California Bearing Ratio) test is a laboratory test used to determine the bearing capacity of soil, a fundamental parameter for pavement design [57]. This test was carried out in accordance with the guidelines of standard MTC E-132 [46], using soil that had been previously characterised and conditioned to its optimum moisture content, determined using the Modified Proctor test (MTC E-116 [46]).

For sample preparation, Neo Soil was added in proportions of 0%, 1.5%, 3%, 4.5%, 6% and 7.5%, as well as polyacrylamide in concentrations of 0%, 0.15%, 0.30%, 0.45%, 0.60% and 0.75%. Subsequently, the soil was placed in a cylindrical mould and compacted in five layers, applying 56 blows per layer with a 4.54 kg rammer from a height of 457 mm. Once compaction was complete, the soil was levelled to remove excess soil and even out the surface.

Next, an expansion disc was placed on the compacted surface, and a 4.5 kg weight was applied to prevent swelling during the soaking process. Next, the mould with the soil was completely submerged in a container of water for 96 hours (four consecutive days), simulating saturation conditions.

After the soaking period, the excess water was leveled, and the mold was positioned on the CBR apparatus. A vertical load was added with a metal piston with a diameter of 50 mm at a constant velocity of 1.27 mm/min. During the test, the loads needed for the following penetrations: 0.625 mm, 1.25 mm, 1.875 mm, 2.5 mm, 3.75 mm, and 5.0 mm, were noted.

The subgrade classification was defined by Standard CE.010 (Urban Pavements). And is shown in Table 4. Based on this standard, a subgrade is defined as excellent if CBR is 17% and higher, good if the CBR is between 8% and 17%, fair if the CBR is between 3% and 8%, and poor if the CBR is less than or equal to 3%.

Table 4. Subgrade classification

Quality	CBR (%)
Excellent	≥ 17%
Good	8-17%
Regular	3-8%
Poor	≤ 3%

Thus, the CBR values from the tests can be compared with the reference ranges, defining whether the treated soil obtains good or excellent subgrade, which is a fundamental requirement to guarantee the proper structure performance in urban pavements.

4. Results

4.1. Lime

Figure 11 shows how the CBR value varies at 95% compaction in a silt-type soil when applying different dosages of polyacrylamide and Neo Soil, demonstrating their influence on the mechanical behaviour of the soil. Sample 1, which does not contain any additives, had a CBR of 3.10%, serving as a baseline reference for comparing the effect of the stabilisers. Starting with sample 2, with a dosage of 0.15% polyacrylamide and 1.5% Neo Soil, an improvement in CBR to 4.40% is observed, indicating that even a low dose of additive has a positive effect on soil strength.

This upward trend continued in sample 3, with a dosage of 0.3% polyacrylamide and 3% Neo Soil, where the CBR reached 5.12%, reflecting a considerable improvement over the untreated sample. Sample 4, treated with 0.45% polyacrylamide and 4.5% Neo Soil, continued its upward trend with a value of 7.30%. This indicates that with the increase in the amount, the soil acquires a higher resistance to shearing and to deformation. Sample 5, while incorporating 0.6% polyacrylamide and 6% Neo Soil, achieved the CBR value of 10.10%.

This amount represents the optimal value needed for the stabilization of loams, as it represented the highest increase of strength in comparison to the natural condition. Sample 6, with the dosages (0.75% polyacrylamide and 7.5% Neo Soil), high in value, resulted in a CBR value of 9.20%. This indicates that too many of the additives will bring about over-stabilization, thus having a negative effect on the soil. All of these results together represent that controlled proportions of Neo Soil and polyacrylamide enhance the silt's bearing capacity to a significant level, while also indicating the value of having a limiting (optimum) value of dosages after the stabilizing value of the soil decreases.

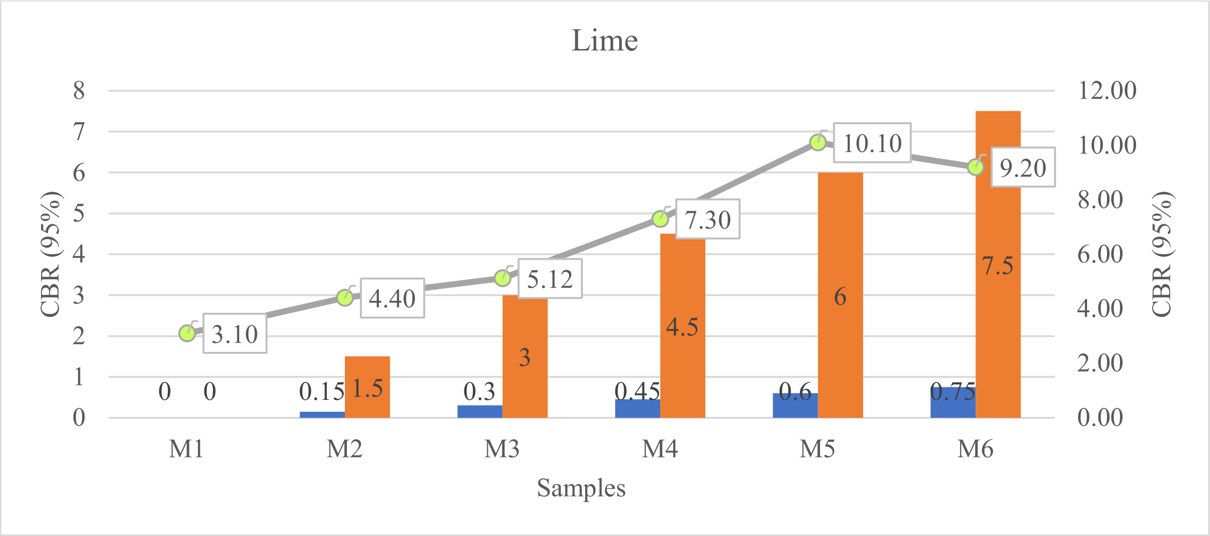

Fig. 11 Lime (CBR 95%)

The evolution of the CBR value at 100% compaction is shown in Figure 12 for silt-type soil treated with varying proportions of polyacrylamide and Neo Soil in an effort to assess its performance at maximum dry density. Sample 1, which has no stabiliser, of CBR 5.99% is the base condition of the natural soil. Sample 2 has 0.15% polyacrylamide and 1.5% Neo Soil CBR, which increased to 7.50% resultant for the first significant improvement of the area of interest. Sample 3 recorded a CBR of 9.26% which value continued to climb in midrange proportional polyacrylamide with 3% Neo Soil of 0.3% and thus a moderate reaction of the soil to the stabiliser. Sample 4 gained 12.50% and thus a substantial improvement in the soil's mechanical strength with a higher polyacrylamide at a 0.45% level, and Neo Soil 4.5%, cemented 0.6% and soil at level 6% Neo Soil. The optimum result in the area of interest is with sample 5, deducing 14.70% CBR cement and soil stabilising the value to 0.6%. All results are at maximum compaction.

To some degree, this is also the case in Sample 6, which had the dosage combination 0.75% polyacrylamide and 7.5% Neo Soil, where the CBR was 12.23%. This is likely a case of an excessive dosage severely causing adverse consequences, perhaps from the stabilising agent saturating the soil structure such that the agent's compaction potential is nullified.

In summary, the findings suggest that using a combination of polyacrylamide and Neo Soil has the potential to increase soil strength due to enhanced compaction at 100% effectiveness, but the correct dosage needs to be established to maintain optimal soil structure stability.

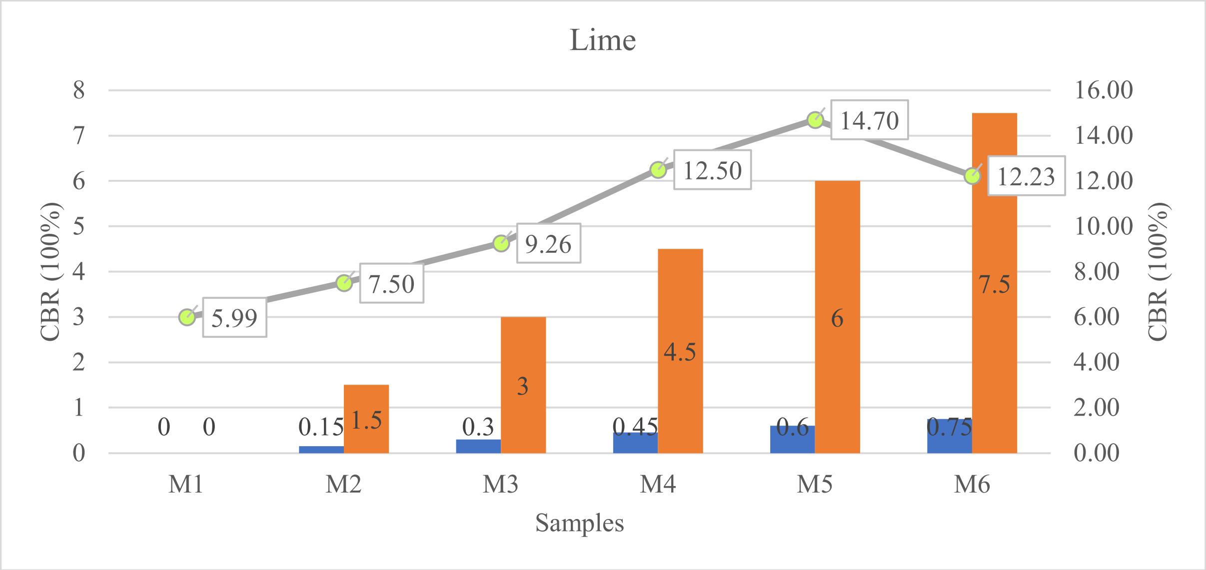

Fig. 12 Lime (CBR 100%)

4.2. Elastic Silt

The behaviour of the CBR in Figure 13 considers 95% compaction of soil in the elastic silt range treated with mechanical behaviour improvement of different doses of polyacrylamide and Neo Soil. Soil in sample 1 (no stabilisers) had an initial CBR value of 3.70% and with 0.15% polyacrylamide and 1.5% Neo Soil (sample 2), the CBR value increased significantly to 4.60, suggesting initial improvement to the soil strength. Sample 3 (0.3%, 3%) continued with the three-point upward trend with a CBR of 6.20%. Sample 4 (0.45% and 4.5% CBR 8.1) showed further improvement in optimum mechanical behaviour (progressive mechanical properties improvement). Sample 5 has 0.6% of polyacrylamide and 6% Neo Soil and showed the highest CBR of 11.60%, which is an indication that this mixture is a proficient combination since it significantly improved the bearing capacity. However, sample 6 (0.75% and 7.5%) CBR dropped to 9.10% suggesting that the highest dosed stabilisers may result in the loss of cohesion/internal structure of elastic silt.

In summary, the findings show significant enhancement in the shear strength of consolidated elastic silt at 95% compaction, showcasing the necessity of assessing the preferable dosage, in order to mitigate detrimental outcomes triggered by additional stabilizer.

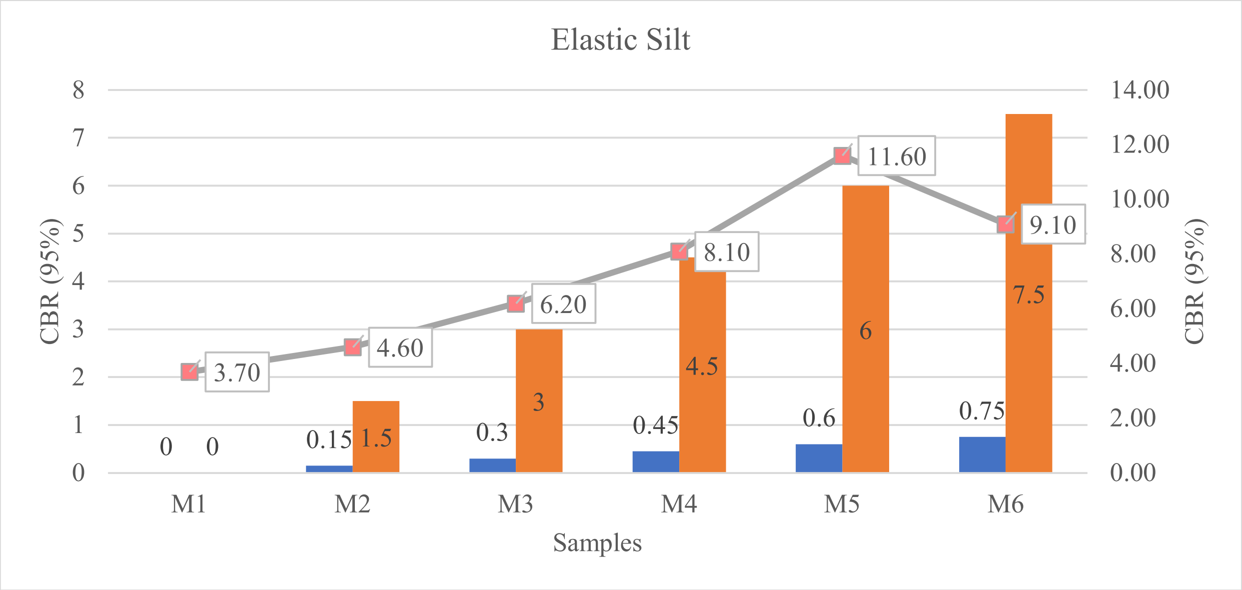

Fig. 13 Elastic silt (CBR 95%)

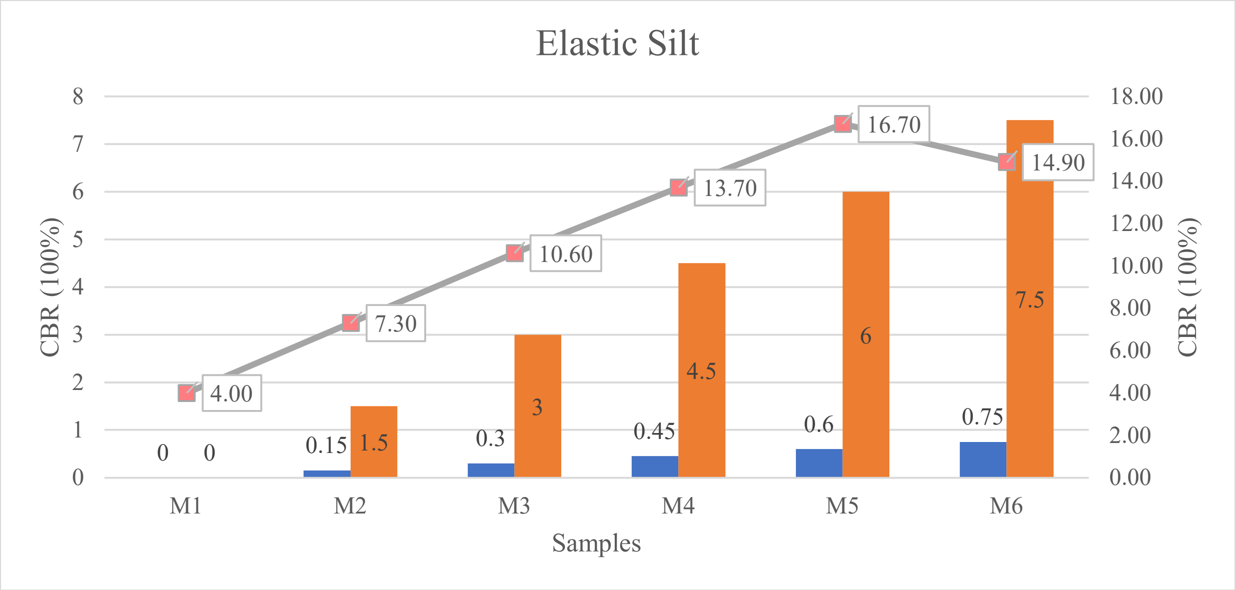

Fig. 14 Elastic silt (CBR 100%)

Figure 14 examines the CBR values obtained at 100% compaction on elastic silt soil due to the varying treatment combinations (soils + polyacrylamide + Neo Soil) used to improve the soil's engineering properties at maximum dry densities (MMD). For the base sample without stabilizers (Sample 1), CBR values recorded were 4.00%. The addition of a low stabilizer dose (Sample 2), 0.15% polyacrylamide + 1.5% Neo Soil, increased the CBR to 7.30% indicating an effective improvement. This trend continued in Sample 3 (0.3% + 3%), where CBR values were reported at 10.60% and Sample 4 (0.45% + 4.5%), 13.70 % where a significant increase in the soil was achieved and therefore bonded. The highest value of CBR of 16.70% was recorded in sample 5 on the soil bonded with 0.6% polyacrylamide + 6% Neo Soil, which is most probably the optimum dosage.

Nonetheless, in Sample 6, a 0.75 and 7.5% stabilizer dosage, the CBR dropped to a reduced 14.90%. This may indicate a level of stabilizer added may hamper the cohesiveness and or compaction of the soil due to the stabilizer saturating the soil or interacting with the soil material's internal structure. Overall, the results indicate the bearing capacity of elastic silt increased significantly, indicating the requirement for a specific dosage to obtain optimal value and reduced decreases in efficiency.

4.3. Low Plasticity Clay

Figure 15 examines the behaviour of the CBR at 95% compaction for the soil classified as a low plasticity clay, treated with varying dosages of polyacrylamide and Neo Soil, to assess the mechanical properties for suboptimal dry density. Sample 1, which is the soil case of 0% stabilisers, had a CBR value of 3.10%. At 0.15% polyacrylamide + 1.5% Neo Soil stabiliser (sample 2), the CBR value was 4.80% representing a significant improvement for low dosages of stabilisers. This increasing trend in CBR values continued with sample 3 (0.3% and 3%), CBR value of 6.20%, and sample 4 (0.45% and 4.5%), with a CBR value of in CBR 9.20%. This demonstrates improvement in the soil treated at every increment of the stabilisers in increasing CBR values. Sample 5 exhibited a stabiliser dosage of 0.6% polyacrylamide and 6% Neo Soil, with the CBR value of 10.60% resulting in the optimal dosage for the dry density to bearing soil structure being low. Contrastingly, sample 6, which had the highest dosage (0.75% and 7.5%), exhibited a drop in CBR value of 9.10%, which is interpreted as detrimental for the internal structure, or structure flow of the clay. To summarize, there is a marked improvement in the mechanical strength of low-plasticity clay modified at 95% optimum moisture content. Hence, it is crucial to determine the appropriate dosage to maximize the efficiency of the treatment.

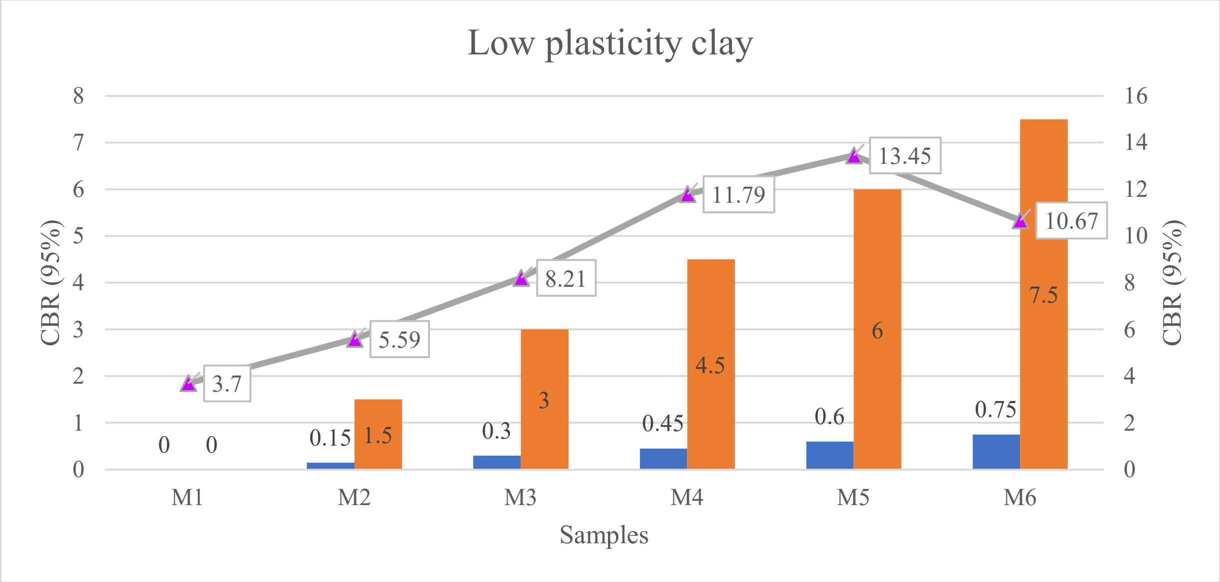

Fig. 15 Low plasticity clay (CBR 95%)

Figure 16 looks at the behaviour of the CBR at 100% compaction for the low plasticity clay subsoil treated with various polyacrylamide and Neo Soil additives for soil modifier tests at maximum dry density. Soil without stabilisers (Sample 1) had an initial CBR score of 4.60%. In Sample 2, with the addition of 0.15% polyacrylamide and 1.5% Neo Soil, the CBR showed an initial improvement to 7.60%. Sample 3 (0.3% polyacrylamide and 3% Neo Soil) yielded further improvement to 10.20% CBR, and Sample 4 (0.45% and 4.5%), an increment to 14.70%. There was continuing improvement to Sample 5 with the addition of 0.6% polyacrylamide and 6% Neo Soil, yielding a maximum of 17.30% CBR. This was indicative of an optimal admixture. Sample 6 with a resultant CBR of 15.80% (0.75% polyacrylamide with 7.5% Neo Soil) confirmed the observation that with excessive stabiliser, there could be a result of disrupting cohesion due to alterations of the internal structure of the clay.

To summarize, the findings are indicative of significant improvements with respect to the treatment of the bearing capacity of low plasticity clay with particular emphasis on the 100% compaction values, substantiating the necessity for suitable thresholds to be established for optimal treatment applicability.

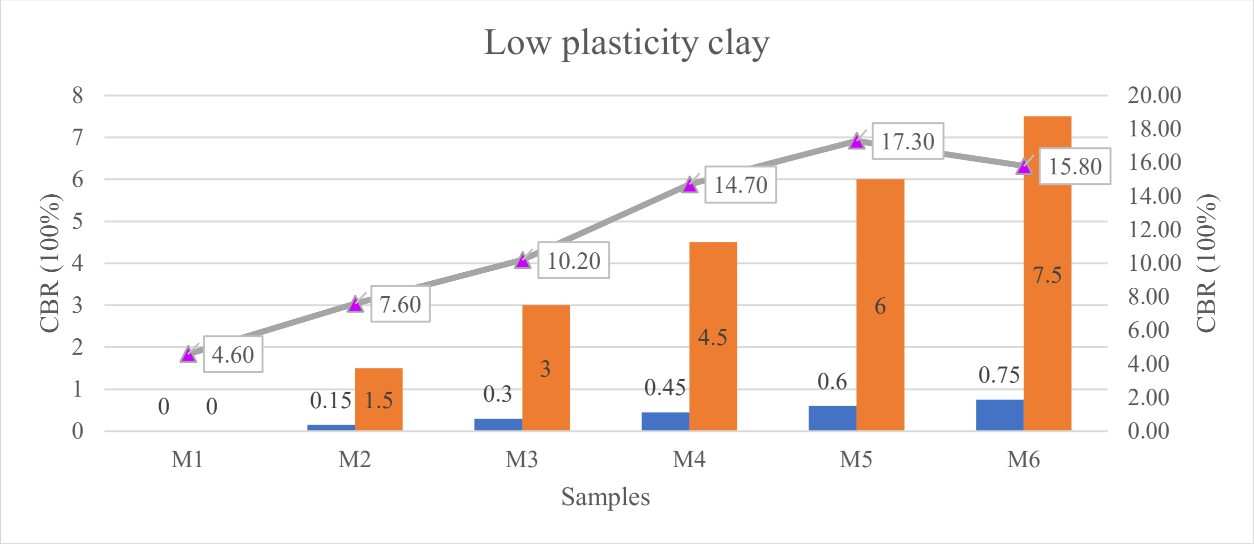

Fig. 16 Low plasticity clay (100%)

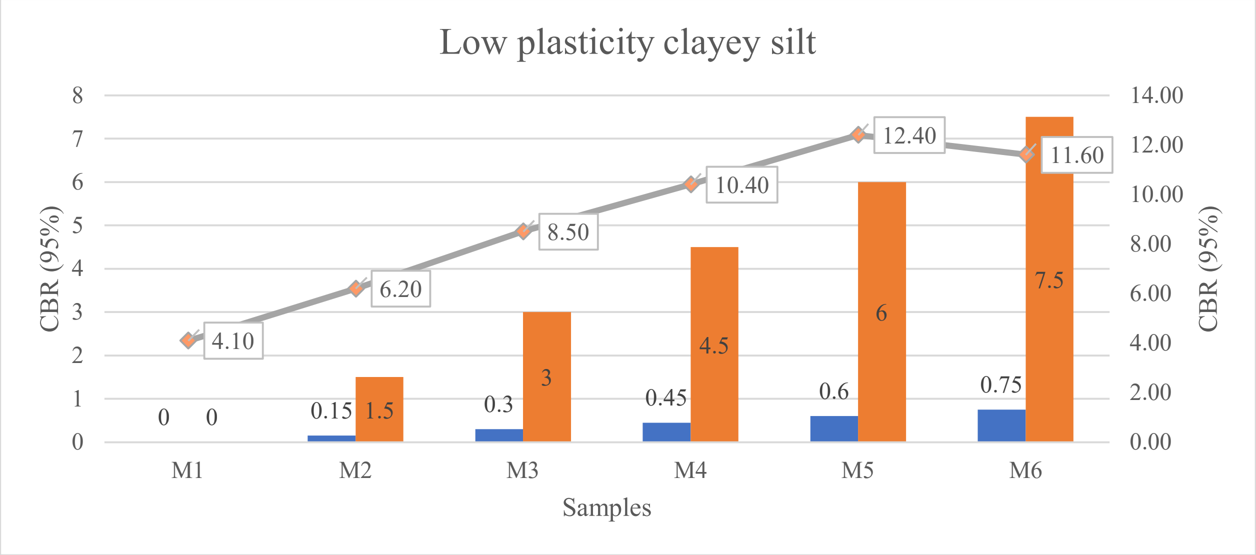

Fig. 17 Low plasticity clayey silt (CBR 95%)

4.4. Low Plasticity Clayey Silt

Figure 17 studies the behavior of the CBR at 95% compaction for a soil described as low plasticity clay loam for which various dosages of polyacrylamide and Neo Soil had been added in order to enhance its mechanical properties under the conditions of suboptimal compaction. Sample 1: The soil without stabilisers had an initial CBR of 4.10. However, with the addition of 0.15% polyacrylamide and 1.5% Neo Soil (sample 2), the CBR increased to 6.20, thus demonstrating a considerable enhancement with a minimal dosage. This trend of increasing strength continued with sample 3 (0.3% and 3%), with a CBR of 8.50, and with sample 4 (0.45% and 4.5%), with an even greater value of 10.40, a reflection of a continued optimisation in the strength of the treated soil. Sample 5, with a dosage of 0.6% polyacrylamide and 6% Neo Soil, produced the maximum CBR of 12.40, indicating that this ratio was possibly the optimal dosage for increased bearing capacity under these conditions. Sample 6 had the highest dosages of 0.75% and 7.5%, but it did not demonstrate that it increased CBR; in fact, it lowered the CBR to 11.60. This shows that excessive stabiliser might negatively impact the internal structure or compaction of the silt.

The outcomes of the study indicate that the mechanical strength of low-plasticity clayey silt treated at 95% compaction significantly improves, as well as the efficacy of the treatment and the need for adequate dosage.

Figure 18 examines the 100% compaction CBR value behavior of the low plasticity clay loam and different combinations of polyacrylamide and Neo Soil to best alter the soil mechanics that yield the maximum dry density. Soil alone in Sample 1 had a CBR of 7.00%. Sample 2 demonstrated that adding polyacrylamide 0.15%, Neo Soil 1.5% increased the CBR to 10.30% and showed that there can be solid advancement from a low dosage. Samples 3 and 4 (0.3%, 3%, 0.45, 4.5% respectively) had CBR values of 12.60 and 15.40. All of these ratios were showing a clear trend of improving the soil in soil mechanics, and the soil can be functional. Sample 5 had the highest value at 0.6% polyacrylamide and 6% Neo Soil of 18.30% and that value shows a plateau at that dosage. However, sample 6 had a decreased CBR value and high dosage of polyacrylamide 0.75% and Neo soil 7.5% with a value of 16.90% showing that there can be weaknesses in the soil at these ratios, and that means there can be deficiencies in the internal structure that keeps the soil in.

In summary, the data showed significant improvement in the bearing capacity of the low plasticity clayey silt treated at 100% compaction, highlighting the value of determining an exact dosage in order to optimally utilise the treatment.

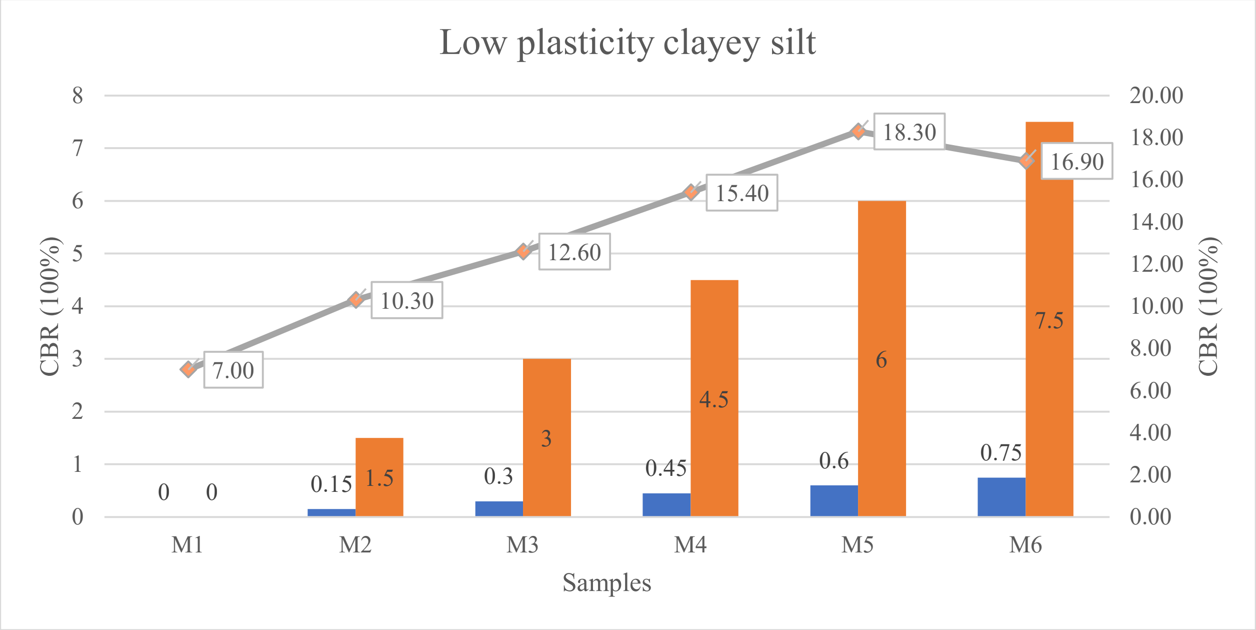

Fig. 18 Low plasticity clayey silt (CBR 100%)

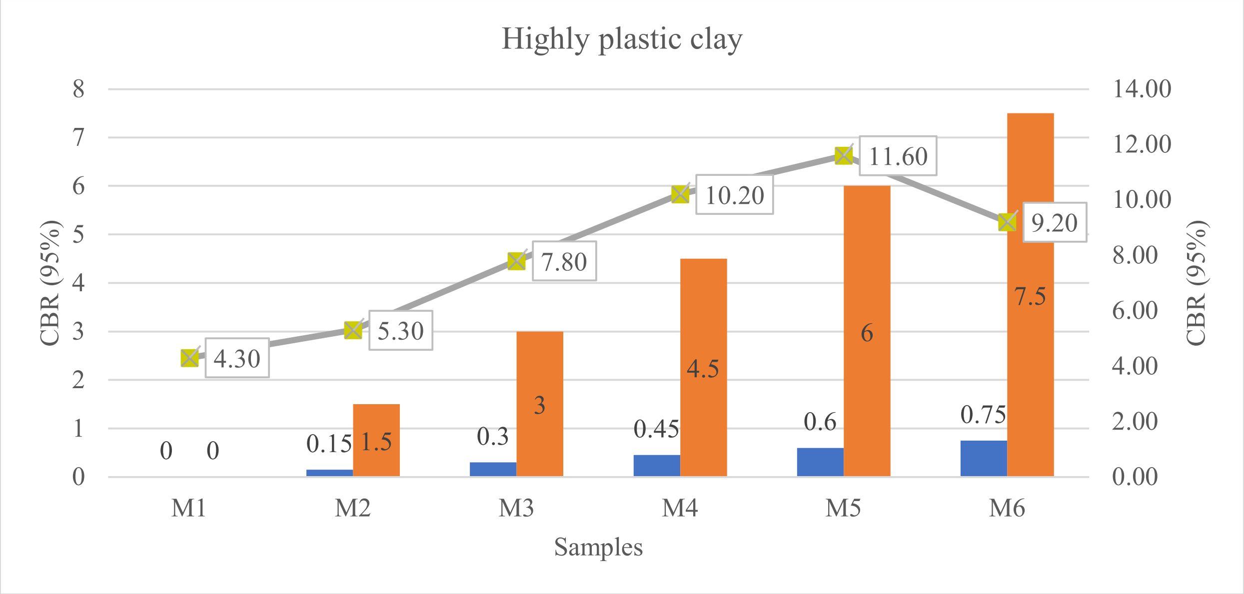

Fig. 19 Highly plastic clay (CBR 95%)

4.5. High Plasticity Clay

Figure 19 assesses the impact of different polyacrylamide and Neo Soil modifications on the values of the CBR of highly plastic clay at 95% compaction and its mechanical properties obtained from dry suboptimal compaction conditions. The CBR results for sample 1, which did not incorporate stabilisers at all, were 4.30% on the CBR scale. Subsequently, the CBR value of sample 2 for the range of 0.15% polyacrylamide and 1.5% Neo Soil exhibited an increase in CBR to 5.30%. This was the first of the stabilisers added. Modifiers in sample 3 of 0.3% polyacrylamide and 3% Neo Soil exhibited the highest CBR value and gave the sample a CBR value of 7.80%. Sample 4, which had 0.45% polyacrylamide and 4.5% Neo Soil, exhibited a CBR value of 10.20%. Because of the values of the CBR for sample 4, it was considered to be a significant contributor to the strength of the sample. Sample 5, which exhibited 0.6% polyacrylamide and 6% Neo Soil, had its value of the CBR raised to 11.60%. Sample 6 was the highest in the amount of stabiliser added to the sample, and its CBR value was decreased to 9.20%. The polyacrylamide and Neo Soil of 0.75% and 7.5% had an inverse relationship on the sample; hence, sample 6 obtained the lowest CBR value. This alludes to the point that clay is a cohesive compound and that more of the stabilisers are not added.

The findings demonstrate the mechanical strength of the highly plastic clay altered at 95% compaction, which achieved significant mechanical strength, and suggest how crucial it is to determine a suitable dosage to optimize the impact of the treatment.

Figure 20 examines the impact of various dosages of polyacrylamide and Neo Soil on the CBR at 100% compaction of a highly plastic clay while trying to enhance its mechanical properties at maximum dry density. Sample 1, which is the base case or 0% soil stabiliser, has a CBR of 5.00. Starting sample 2, which has 0.15% polyacrylamide and 1.5% Neo Soil, the CBR value of the sample increased to 8.50, indicating a very effective and significant positive response to the low dosage. Such a positive response at low dosage continued in sample 3, which has 0.3% and 3% as well as a CBR value of 12.60.

Sample 4, which has the 0.45% and 4.5% as well, resulted in a 15.30 CBR value, which shows to be a sequential or a continuum in the soil stabilisation and strength parameter. Sample 5 consists of the greatest CBR value, which is at 0.6% polyacrylamide and 6% Neo Soil as well. The CBR value of 17.50 indicated that this range is the most effective or the optimum dosage value under the soil and weather conditions for the obtained soil. Sample 6 has the CBR value of 14.20, and this sample has 0.75% and 7.5% dosage as well, indicating that too much polyacrylamide can be counterproductive to the soil cohesiveness.

To summarize the findings, there were undeniable positive modifications in the bearing capacity in clay that was highly plastic with the treatment at 100% compaction, indicating that determining the right dosage is critical to optimize the treatment effectiveness.

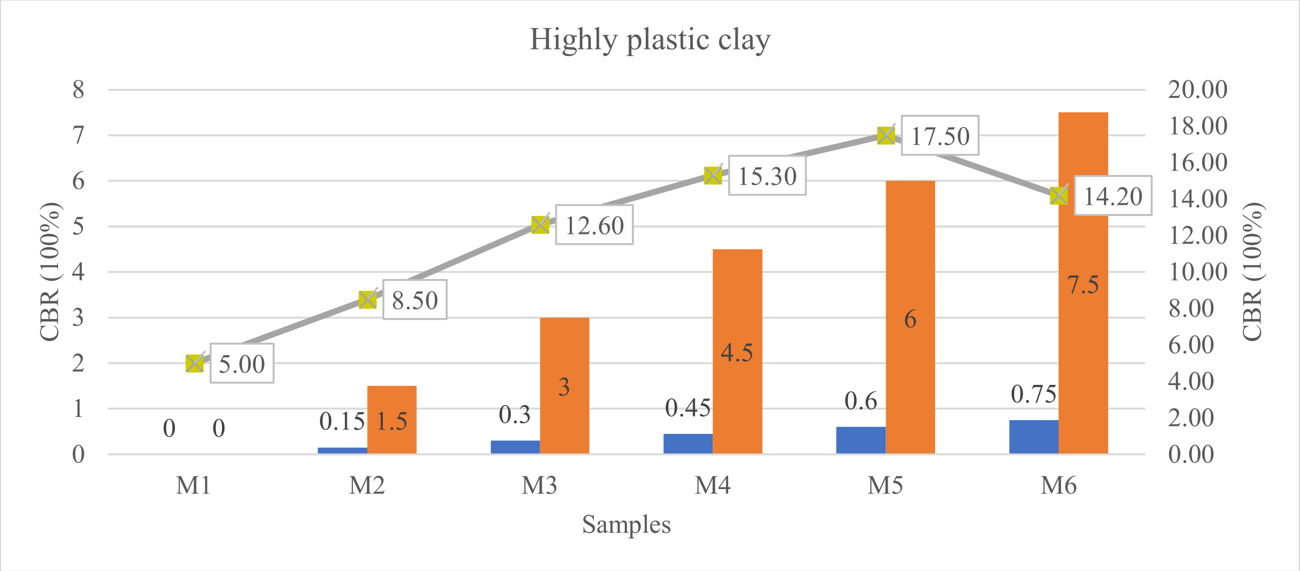

Fig. 20 Highly plastic clay (CBR 100%)

4.6. Statistical Analysis

4.6.1. CBR 95%

Table 5 shows the results of the Shapiro-Wilk normality test applied to the CBR index values obtained at 95% Modified Proctor compaction, corresponding to the five soil types (silt, elastic silt, low plasticity clay, low plasticity clay loam and high plasticity clay) treated with six increasing combinations of Polyacrylamide (P) and NeoSoil (NS), as indicated in Table 3. This statistical test allows verification of whether the data for each treatment follows a normal distribution, a necessary condition for using parametric analyses such as ANOVA and Tukey. In all treatments, the p-value obtained was greater than 0.05, which means that the hypothesis of normality is not rejected. In other words, the data is considered to be sufficiently close to a normal distribution. In technical terms, a p-value within the range of 0.05 to 1.00 is interpreted as statistically acceptable for assuming normality. Even treatment T6 (0.75% P + 7.5% NS), which obtained a relatively low p-value (0.08), still meets this criterion. Therefore, it is concluded that the CBR data for all treatments can be validly analysed using parametric tests without the need for additional adjustments.

Table 5. Shapiro wilk

Treatment	Shapiro-Wilk statistic	Shapiro p
M1	0.943	0.685
M2	0.954	0.762
M3	0.889	0.354
M4	0.94	0.666
M5	0.968	0.862
M6	0.799	0.08

Table 6 shows the results of the Analysis Of Variance (ANOVA), which allows us to determine whether there are significant differences between the mean values of the CBR index recorded in the five soil types (silt, elastic silt, low plasticity clay, low plasticity clayey silt and high plasticity clay) treated with six increasing combinations of Polyacrylamide (P) and NeoSoil (NS), as indicated in Table 3. The analysis yielded an F value of 31.532 with an associated p-value of 8.44E-10, indicating that the differences observed between treatments are statistically significant at 95% confidence. In other words, the variability in the CBR results is not attributable to chance, but rather to the actual effect of the different proportions of polyacrylamide and NeoSoil applied. This confirms that the application of these additives significantly influences soil strength as measured by the CBR index.

Table 6. ANOVA

Source	Square Sum	gl	F	p-value (PR(>F))
C(Treatment)	235.586	5	31.532	8.44E-10
Residual	35.863	24	-	-

Table 7 presents the results of Tukey's multiple comparison test, used to identify statistically significant differences between pairs of treatments. The data show that treatment M1 (no additives) does not differ significantly from M2 (0.15% P + 1.5% NS), suggesting that this initial dose does not generate a considerable improvement in the mechanical behaviour of the soil. However, starting with treatment M3 (0.30% P + 3.00% NS), significant differences from M1 and M2 are evident, indicating that from that point on, the additives begin to produce a real positive effect. The comparisons M3-M4, M3-M5, and M3-M6 are also significant, reinforcing this trend. However, between treatments M4 (0.45% P + 4.5% NS), M5 (0.60% P + 6.0% NS) and M6 (0.75% P + 7.5% NS) there are no statistically significant differences, suggesting that from M4 onwards a level of stabilisation or saturation is reached, beyond which increases in the additive dose do not produce additional statistically verifiable improvements in the CBR index.

Table 7. Tukey

Comparison	Average difference	p-adjusted	Confidence Interval	Significant difference
M1 - M2	1.438	0.449	No	No
M1 - M3	3.386	0.0025	Yes	Yes
M1 - M4	5.778	1.43E-06	Yes	Yes
M1 - M5	8.05	3.16E-09	Yes	Yes
M1 - M6	6.174	4.55E-07	Yes	Yes
M2 - M3	1.948	0.1579	No	No
M2 - M4	4.34	0.0001	Yes	Yes
M2 - M5	6.612	1.33E-07	Yes	Yes
M2 - M6	4.736	3.37E-05	Yes	Yes
M3 - M4	2.392	0.0498	Yes	Yes
M3 - M5	4.664	4.22E-05	Yes	Yes
M3 - M6	2.788	0.0158	Yes	Yes
M4 - M5	2.272	0.0692	No (limit)	No
M4 - M6	0.396	0.9952	No	No
M5 - M6	-1.876	0.1869	No	No

Figure 21 shows the CBR index fragility curves at 95% compaction for five soil types: silt (M1), elastic silt (M2), low plasticity clay (M3), low plasticity clayey silt (M4) and high plasticity clay (M5), considering both the untreated condition and the progressive application of Polyacrylamide and Neo Soil, according to the six dosages defined in Table 3. It can be seen that Soil 4 consistently maintains the highest probability of exceeding most of the thresholds analysed, which shows a more favourable mechanical behaviour under loads. In contrast, Soil 2 has the lowest curve, reflecting its lower bearing capacity and greater structural susceptibility. Soils 1, 3, and 5 show intermediate trajectories, with Soil 5 standing out for its proximity to the performance of Soil 4 in medium load ranges. These curves show how the incorporation of stabilisers gradually improves resistance.

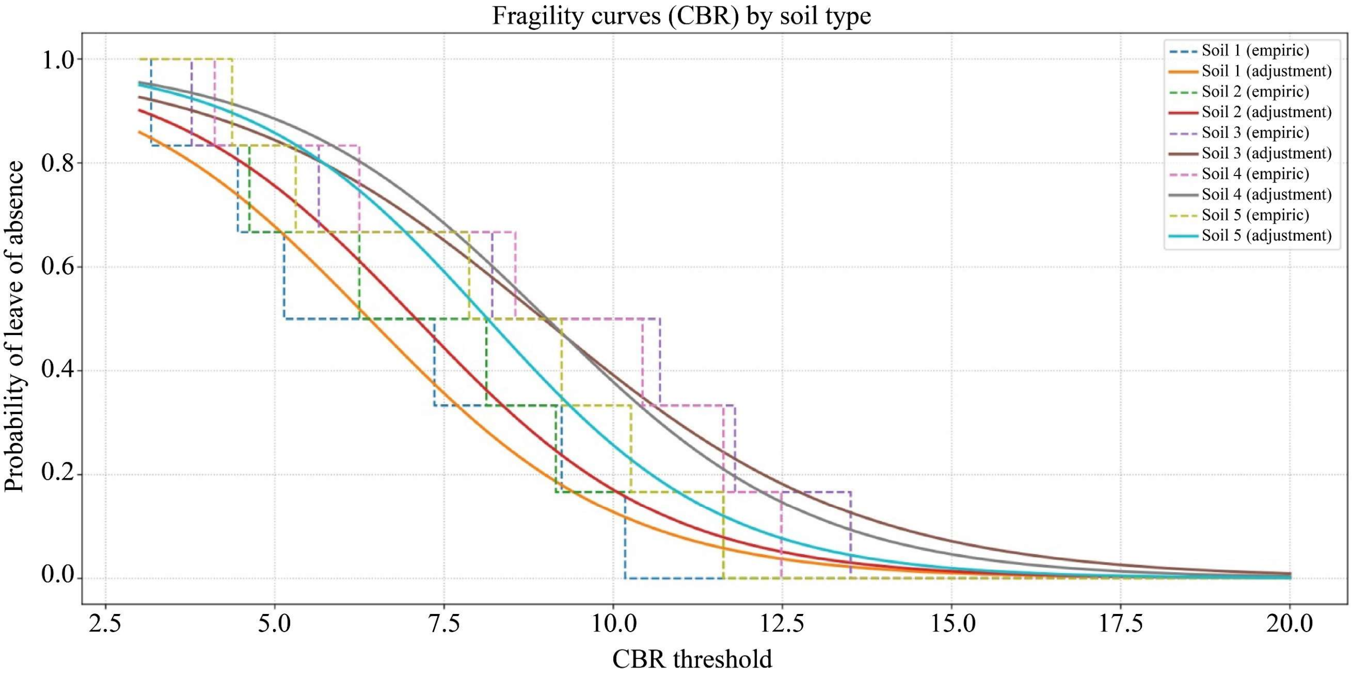

Fig. 21 Fragility curve (CBR at 95%)

4.6.2. CBR 100%

Table 8 shows the results of the Shapiro-Wilk normality test applied to the CBR index values obtained under 100% compaction, corresponding to the five soil types (silt, elastic silt, low plasticity clay, low plasticity clayey silt, and high plasticity clay) treated with six increasing combinations of Polyacrylamide (P) and NeoSoil (NS), as indicated in Table 3.

Table 8. Shapiro wilk

Treatment	Shapiro-Wilk statistic	Shapiro p
M1	0.963	0.829
M2	0.812	0.101
M3	0.877	0.796
M4	0.897	0.393
M5	0.908	0.458
M6	0.984	0.952

The objective of this test is to determine whether the data for each treatment conforms to a normal distribution, which is essential for applying parametric statistical tests such as ANOVA and Tukey. All treatments have p-values greater than 0.05; therefore, the hypothesis of normality is not rejected in any of the cases. This indicates that the data is adequately distributed for parametric statistical analysis. Treatment T6 (0.75% P + 7.5% NS) obtained the highest p-value (0.952), which reinforces its fit to normality. In technical terms, a p-value within the range of 0.05 to 1.00 is considered statistically acceptable, and all treatments meet this criterion.

Table 9 shows the results of the analysis of variance (ANOVA), which allows us to identify whether there are statistically significant differences between the mean CBR index values recorded in the five soils for each of the six treatments. The result shows an F value of 49.951 with a p-value of 6.59E-12, indicating that at least one treatment differs significantly from the rest. This difference is not random, but rather the result of the actual effect that different concentrations of polyacrylamide and NeoSoil have on soil strength. This finding validates the direct and measurable impact of the additives on improving the CBR index at 100% compaction and justifies the multiple comparison analysis.

Table 9. ANOVA

Source	Square Sum	gl	F	p-value (PR(>F))
C(Treatment)	483.207	5	49.951	6.59E-12
Residual	46.433	24	—	—

Table 10 presents the results of Tukey's multiple comparison test, which details between which pairs of treatments there are significant differences in CBR index values. Unlike the results observed with 95% CBR, in this case, the treatments show more significant contrasts. Treatment T1 (without additives) differs significantly from all others, including T2, suggesting that even a small amount of additive significantly improves the soil's resistance to maximum compaction. Similarly, treatment T2 also shows significant differences from all other treatments, indicating a progressive improvement.

However, from treatment T4 (0.45% P + 4.5% NS) onwards, there are no longer any significant differences with T5 or T6, suggesting that a point of saturation or stability in the soil response has been reached again. In other words, adding more additives beyond T4 no longer generates statistically significant improvements in the CBR at 100%, which has direct implications for optimising resources in the design of stabilised mixtures.

Table 10. Tukey

Comparison	Average difference	p-adjusted	Confidence Interval	Significant difference
M1 - M2	2.922	0.0302	0.202 – 5.642	Yes
M1 - M3	5.734	1.32E-05	3.014 – 8.454	Yes
M1 - M4	9.002	4.45E-09	6.282 – 11.722	Yes
M1 - M5	11.582	2.57E-11	8.862 – 14.302	Yes
M1 - M6	9.488	1.57E-09	6.768 – 12.208	Yes
M2 - M3	2.812	0.0398	0.092 – 5.532	Yes
M2 - M4	6.08	5.21E-06	3.36 – 8.8	Yes
M2 - M5	8.66	9.47E-09	5.94 – 11.38	Yes
M2 - M6	6.566	1.46E-06	3.846 – 9.286	Yes
M3 - M4	3.268	0.0122	0.548 – 5.988	Yes
M3 - M5	5.848	9.68E-06	3.128 – 8.568	Yes
M3 - M6	3.754	0.0032	1.034 – 6.474	Yes
M4 - M5	2.58	0.097	-0.14 – 5.3	No
M4 - M6	0.486	0.9932	-2.234 – 3.206	No
M5 - M6	-2.094	0.2027	-4.814 – 0.626	No

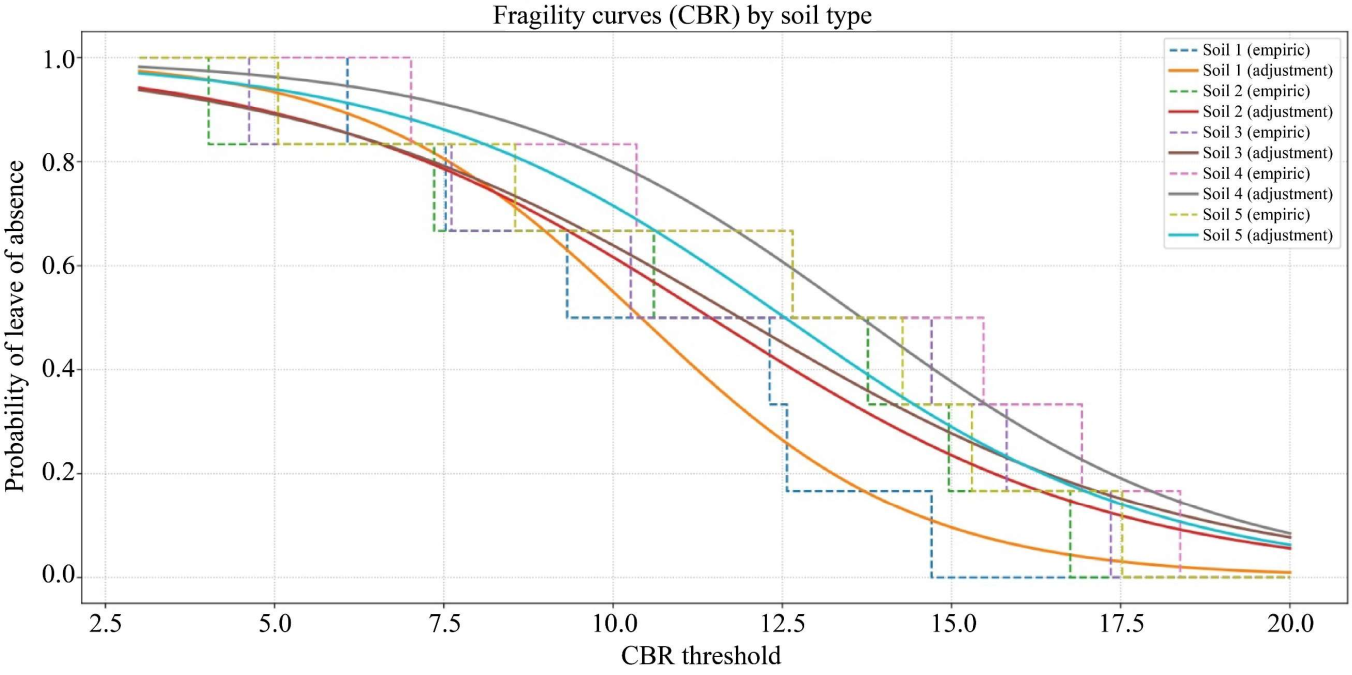

Fig. 22 Fragility curve (CBR at 100%)

Figure 22 shows the CBR index fragility curves at 100% compaction for five types of soil evaluated: silt (M1), elastic silt (M2), low plasticity clay (M3), low plasticity clayey silt (M4) and high plasticity clay (M5), considering both the condition without stabilisation and with the progressive addition of polyacrylamide and Neo Soil, in accordance with Table 3. In this context, it can be observed that Soil 4 consistently maintains the highest probability of exceeding most thresholds, which shows better mechanical performance compared to the other soils when stabilisation is applied. In contrast, Soil 2 has the lowest curve, reflecting lower bearing capacity and greater structural vulnerability. Soils 1, 3, and 5 show intermediate trajectories, with Soil 5 standing out for its proximity to the behaviour of Soil 4 in medium load ranges. These curves clearly show the cumulative effect of the treatments on the mechanical behaviour of each soil, which is useful for comparing their relative efficiency and guiding technical decisions in urban pavement stabilisation.

5. Discussion

According to Shengquan et al. [22], in the improvement of expansive soils through the addition of polyacrylamide, it was determined that a concentration of 0.6% was optimal for increasing shear strength, while 0.8% achieved a compressive strength of up to 410 kPa, demonstrating a significant strengthening of the soil. Complementarily, Dewi et al. [18] studied the modification of cohesive soil with polyacrylamide and concluded that the addition of 0.4% significantly improved its bearing capacity. Comparing these findings with the results of the present investigation confirms that the most efficient dosage in the CBR test corresponded to the combination of 0.6% polyacrylamide and 6% Neo Soil, achieving a substantial increase in bearing capacity, especially in low-plasticity clay loam, where the CBR increased by 169.77% at 95% compaction and by 250% at 100%. This behaviour can be explained by the fact that polyacrylamide, being a long-chain polymer with charged groups, adheres electrostatically to soil particles, which promotes flocculation, understood as the binding of particles into more stable clusters, and bridging, whereby polymer chains link different particles to form an internal network of strong bonds [45]. As a result, a more compact, cohesive, and durable mass is generated, which explains the increase in bearing capacity.

On the other hand, in a research on the improvement of low plasticity clay soils through the use of Neo Soil, determined that the optimal dosage was 5%, with which the CBR reached 19.20%, compared to 8.12% recorded without addition, both under 95% compaction, which demonstrated the effectiveness of the treatment. This result is relevant to the present research, since when using 0.45% polyacrylamide and 4.5% Neo Soil, the latter dose being close, CBR values of 15.30% were obtained compared to 5% recorded in the sample without additions, which also shows a significant improvement. This increase is attributed to the action of Neo Soil, which, being an adhesive biopolymer, adheres to individual soil particles, forming a surface coating that reduces their dispersion and promotes their bonding. In this sense, the coating promotes the agglomeration of fine particles into larger, denser structures, which facilitates the creation of a compact and stable matrix. This increases cohesion, reduces deformability, and optimises bearing capacity, as reflected in the increases obtained in the CBR tests.

In conclusion, the reviewed research supports the results obtained, demonstrating that the addition of polyacrylamide in appropriate concentrations, together with Neo Soil, significantly increases the strength and bearing capacity of cohesive and expansive soils, confirming the validity and relevance of the findings for their application in soil improvement projects.

6. Conclusion

In conclusion, stabilising the five soil types through the controlled incorporation of polyacrylamide and Neo Soil significantly increased their bearing capacity, achieving CBR values between 8% and 17%, a range that allows them to be classified as good sub-bases in accordance with standard CE.010 (Urban Pavements).

At a compaction degree of 95%, the optimal dosages varied according to soil type. In silt, the combination of 0.60% polyacrylamide and 6% Neo Soil achieved a CBR of 10.10%, while in elastic silt, dosages of 0.45% and 4.5% yielded a CBR of 8.10%. In low-plasticity clay and low-plasticity clay loam, a dosage of 0.30% and 3% was sufficient, achieving CBRs of 8.21% and 8.50%, respectively. In the case of high plasticity clay, a proportion of 0.45% and 4.5% achieved a CBR of 10.20%. These results show that, even with 95% compaction, it is possible to optimise bearing capacity by adjusting dosages to the type of soil, thus favouring the construction of more stable sub-bases and reducing the risk of premature settlement in urban roadways.

Upon reaching 100% compaction, the dosages were further optimised, achieving better structural performance with lower stabiliser consumption. In silt, the ratios of 0.45% and 4.5% achieved a CBR of 9.26%, while in elastic silt, the dosages of 0.30% and 3% reached 10.60%. Similarly, in low-plasticity clay, this same ratio achieved a CBR of 10.20%. In contrast, in low plasticity clayey silt and high plasticity clay, a dosage of 0.15% and 1.5% was sufficient, reaching CBRs of 10.30% and 8.50%, respectively. These findings demonstrate that achieving 100% compaction not only increases the structural performance of subgrades but also reduces the consumption of stabilisers, generating savings in intervention costs and facilitating the allocation of resources to maintenance, expansion, or improvement of the urban road network.

When analyzing CBR results from 5 different soil types with 6 incremental dosages of polyacrylamide and NeoSoil, the 95% and 100% CBR compactions showed consistent results. Customary statistical tests, such as ANOVA and Tukey, can only be performed if the results come from a normal distribution. Thus, the parametric tests performed are justified because all the treatments returned $p > 0.05$ with the Shapiro-Wilk normality tests. ANOVA results showed that treatments do, in fact, have different effects on the strength of soils, with some treatments containing the additives and others not. Tukey showed that for the CBR at 95% compaction, treatments M4, M5, and M6 had no significant differences; thus, a saturation point was achieved with at least 0.45% P + 4.5% NS. For CBR at 100%, there were more differences between treatments M1 and M2, and M2 and M3. However, the same stabilisation behaviour that was observed previously was confirmed between M4, M5, and M6, supporting this as a technical efficiency limit. Figures 21 and 22 rounded off the anomalies observed in the soil strength ranking for CBR 95 and CBR 100, respectively. They showed clearly that Soil 4 most likely exceeded the strength threshold, closely followed by Soil 5, while Soil 1 exhibited the most brittle behaviour and thus exceeded the soil strength threshold. Therefore, this statistical analysis further strengthens and complements this study's technical findings and increases confidence in determining appropriate dosages and in providing unambiguous parameters for the determination and design of urban pavements.

Among the limitations of this study is the limited range of dosages evaluated, as only six specific levels of polyacrylamide and Neo Soil (from 0% to 0.75% / 7.5%) were analysed, without considering intermediate or higher dosages, which could conceal optimal points or undetected adverse effects. In addition, the CBR tests were conducted under controlled laboratory conditions of compaction and humidity, which differ from actual field conditions, where factors such as climatic variability, dynamic loading, and drainage can influence the behaviour of the stabilised soil. Nor was the long-term durability of the treated soil evaluated in relation to moisture-dry cycles, freeze-thaw cycles, or repeated loads, which are essential aspects for validating the stability of the material over time. The study focused on silts with different plasticities and low- and high-plasticity clays, without including other types of soils such as sands, gravels, or organic soils, which could respond differently to the stabilisers used. Finally, the analysis did not delve into the chemical or physical interaction between polyacrylamide, Neo Soil, and the minerals present in the soil, which could influence the effectiveness of the treatment.

For future research, it is recommended to expand the range and combinations of dosages, exploring finer or higher doses that allow for more accurate identification of the optimal interval and avoid over-stabilisation. It would also be necessary to conduct pilot-scale or real-world tests that simulate dynamic loads and climatic variability in order to validate the applicability of the treatment on urban pavements. One of the goals of this research is to submit a thorough proposal to the Colorado Department of Transportation that details potential soil stabilization methods. This includes relocating soil off-site and treating it with chemical binding agents before reintroducing it to the desired location. In the stabilization proposal, the soil additives that are commercially available to the construction industry will be detailed. Dry and wet sieved soil analysis will reveal a soil's mineralogical and geological formation. Moisture and dry cycles, accelerated aging, and climate cyclic testing will correlate to the field to evaluate performance. Microstructural testing, chemically and Ash X-Ray Diffraction, will reveal the stabilization mechanisms and their potential. Concluding, the proposal will recommend soil additive applications with other soil types to evaluate the treatment of the construction industry's applications. Sustainable and economical outcomes are to be anticipated to recommend a proposal for the construction industry soil stabilization.

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