STRESS-STRAIN BEHAVIOR OF BLUE MARLS FROM THE GUADALQUIVIR RIVER BASIN IN SPAIN

NAPETOSTNO DEFORMACIJSKI ODZIV MODRIH LAPORJEV IZ POVODJA GUADALQUIVIRJA (ŠPANIJA)

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Keywords

Guadalquivir blue marls, sedimentary clay, triaxial test, undisturbed and remolded samples, lime stabilization, stress-strain behavior

Abstract

This paper describes the geotechnical behavior of the Blue Marls from the Guadalquivir River Basin in Southern Spain, defined as high-plasticity clays that behave as a stiff, over-consolidated clayey soil. These Blue Marls are, in general, classified as an inadequate material for reuse in various earthworks. In this study the comparison between the geotechnical properties of its natural and compacted remolded state, with and without additives, is studied based on different laboratory tests. A great variety of laboratory tests were performed, including triaxial tests under consolidated undrained conditions. Three types of samples were tested in triaxial tests to define different stress-strain behaviors: undisturbed and remolded samples of the in-situ clay material, as well as remolded clay samples mixed with lime. Lime stabilization is frequently used to improve the geotechnical properties of clayey soils for application in different earthworks. The back-analysis of the slope stability is performed for a comprehensive assessment of the condition of the slopes consisting of these remolded materials mixed with lime as well as without lime. The results of the retrospective analysis of man-made slopes permit an analysis of the operational geotechnical strength parameters necessary in the design of slopes as well as its comparison with the results of the triaxial consolidated undrained tests. The improvement of the strength parameters for the slope-stability analysis is confirmed under remolded conditions with and without the addition of the small amount of lime.

Ključne besede

Guadalquivirski modri lapor; sedimentirana glina; triosni preizkus; neporušeni in pregneteni vzorci; stabilizacija z apnom; odziv napetost-deformacija

Izvleček

V članku je opisano geotehnično obnašanje modrih laporjev iz porečja reke Guadalquivir (južna Španija), ki so opredeljeni kot gline z visoko plastičnostjo in se obnašajo kot trdna prekonsolidirana glinasta zemljina. Obravnavani modri laporji so na splošno opredeljeni kot neustrezni material za njihovo ponovno uporabo v različnih zemeljskih delih. V tej študiji smo na podlagi različnih laboratorijskih preiskav preučili primerjavo med geotehničnimi lastnostmi njenega naravnega in zgoščenega pregnetenega stanja z dodatki in brez njih. Izvedle so se številne laboratorijske preiskave, vključno s triosnimi preizkusi v konsolidiranih nedreniranih pogojih. Da bi določili različno obremenitveno-deformacijsko obnašanje, smo v triosnih aparatih preizkusili tri vrste preizkušancev: neporušene in pregnetene preizkušance »in situ« glinastega materiala, kot tudi pregnetene preizkušance gline, pomešane z apnom. Stabilizacija z apnom se pogosto uporablja za izboljšanje geotehničnih lastnosti glinastih tal za uporabo v različnih zemeljskih delih. Za celovito oceno varnosti pobočij, sestavljenih iz teh predelanih materialov, zmešanih z apnom in brez apna, so bile izvedene povratne stabilnostne analize. Rezultati retrospektivne analize takšnih umetnih pobočij omogočajo analizo dejanskih geotehničnih parametrov strižne trdnosti, ki so potrebni pri načrtovanju pobočij ter primerjavo z rezultati triosnih konsolidiranih nedreniranih preizkusov. Izboljšanje parametrov strižne trdnosti v stabilnostni analizi pobočij je bila potrjena za pregnetene pogoje, tako z kot brez dodatka majhne količine apna.

1 INTRODUCTION

The Guadalquivir Blue Marls were studied at different points along the Guadalquivir River Basin in Southern Spain by different authors for the construction of various geotechnical structures and after a lot of damage that occurred in these materials after having this material as a foundation for specific structures. It was studied in relation to underground works associated with the construction of the subway for the city of Seville and for many slope-stability problems that happened during the construction of infrastructures (e.g., the slope-stability problem at Almodóvar del Rio at the high-speed railway Madrid–Seville) [1,2,3]. The study of these marls was a crucial part of the analysis of the 1998 failure of the Aznalcollar tailing dam, which was founded on this formation and caused one of the major environmental disasters in Spain [4,5,6,7]. These marls were also studied for the slope-stability analysis at the Cobre Las Cruces open pit mine [8,9]. This material is characterized by fragile shear strength and degradation after drying and wetting processes [4,8,10] that could provoke a sudden geotechnical failure in these materials. For that reason these Blue Marls are usually not suitable for reuse in the construction of different earthworks such as embankments, earth dams, pavement bases, etc. according to the Spanish standard PG-3 [11].

These marls represent a fine-grained soil with an average percentage of the clay fraction ranging from 50 to 60%, classified as high-plasticity clay (CH) with a high carbonate content. Its behavior is like a stiff soil, defined as over-consolidated clays [4,8,9,14].

This study is a comparison of the behavior of the undisturbed blue marls and compacted remolded samples with and without additives that are analyzed in order to quantify the improvement of the geotechnical properties. The improvement of the geotechnical properties by lime is studied. Lime is one of the most commonly used binders for an improvement of the geotechnical properties of clayey soils, due to its effect on the modification of soil particle packaging, soil plasticity, workability, dispersity, permeability, swelling and shrinkage properties, compressibility, etc. [12]. It is widely used for the soil stabilization of different types of structures, such as a foundation base, slope protection, embankments, highway and railway sub-grade, etc. due to its low cost and ease of application in construction [13].

For this paper, the observational method is conducted over man-made slopes constructed in these Blue Marls over a period of 10 years, to deduce the resistance parameters based on a slope-stability back analysis. These values are compared to laboratory strength parameters deduced from the triaxial consolidated undrained (CU) tests performed over undisturbed and remolded samples (with and without the addition of lime) to compare the stress-strain behavior of the undisturbed and remolded samples of Blue Marls.

This paper emphasizes the importance of the compacted remolded state of the material to be introduced in the earthworks in order to improve an inadequate clay material, such as blue marls (highly plastic and expansive) with and without lime for its application in different earthworks. In general, this kind of expansive clay can be encountered worldwide, and this subject could be of a great importance for the construction of different earthworks.

According to [15], slopes and cut-offs in blue marls have undergone instabilities despite its behavior as a soft rock/stiff soil. A wide range of factors affect its instability, making it very challenging to select the most suitable stabilization measures once the instability has occurred, as well as processes for its mitigation. Some of the factors that affect its instability is its great weathering, which is increased due to decompression during excavation, attributed to the existence of micro-discontinuities with low resistance and strain-softening behavior that is increased during the process of humidity draught (i.e., a rainfall period), in this way exhibiting a great variability in behavior with time. The effect of the drying and wetting cycles process on the changes of macro- and microstructure of undisturbed Guadalquivir blue marls were studied by [10].

2 RESEARCH METHODOLOGY

The investigation was divided into three stages, as described in Fig. 1.

During the first stage (5-year duration), a field research campaign was carried out based on a study of 41 slopes with different heights and inclination angles, on the unit of Guadalquivir Blue Marls. The geotechnical campaign was then supplemented by the rotary drilling of mechanical boreholes with the continuous taking of undisturbed samples. The samples were taken in the winter period after a long period of drought. These samples were taken during a wet season in which the area had received significant precipitation.

During the second stage, a laboratory-test campaign was carried out on 89 samples for the identification of properties (i.e., sieve analysis (wet-sieve analysis and sedimentation analysis), natural moisture content, Atterberg

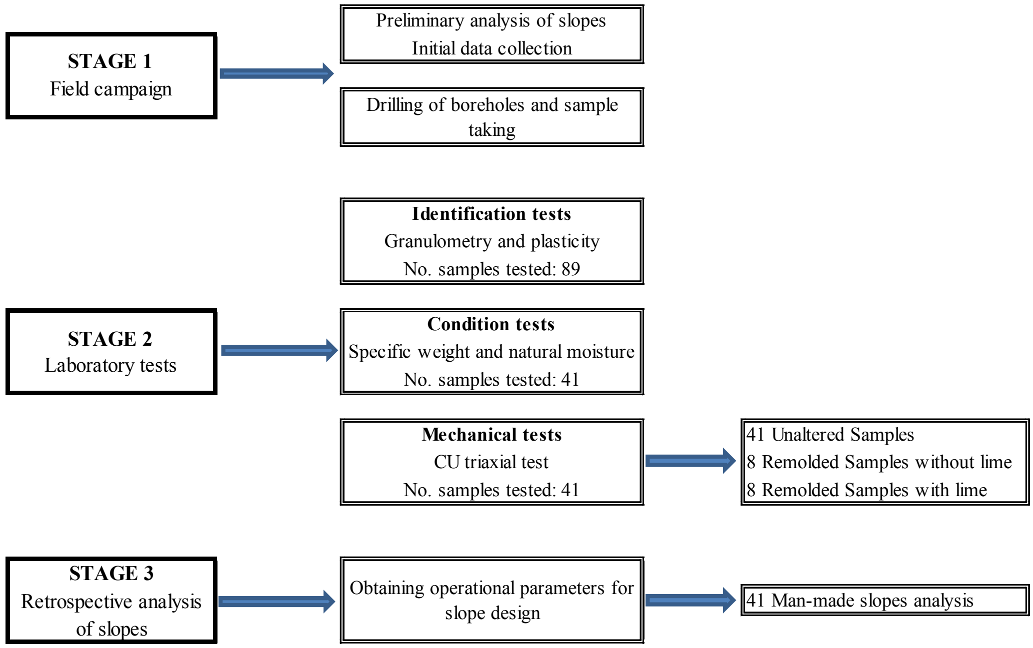

Figure 1. Research methodology.

limits, dry unit weight, unit weight of solid particles, etc.). Mostly, the samples were taken at shallow depths (down to 4 meters from the surface) due to its application for the possible reuse in the construction of man-made slopes. In order to study the stress-strain behavior, 57 triaxial tests were performed on: undisturbed samples (41), remolded samples (8) and remolded samples mixed with lime (8). The purpose of the tests carried out on remolded samples with and without lime was to study the improvement of their geotechnical behavior regarding strength properties (friction angle and cohesion) for its possible use as a material for the construction of different geotechnical structures (man-made slopes, pavement base, earth dams, embankments, etc.). The small amount of lime (2% of the weight) was added to the mixture of remolded samples in order to study its influence on the geotechnical parameters.

Finally, stage 3 is the retrospective analysis of the slopes studied during the first stage that makes it possible to reach conclusions regarding operational geotechnical strength parameters used for slope design, comparing them with the results obtained by laboratory tests (i.e., triaxial consolidated undrained tests).

3 GEOGRAPHIC AND GEOLOGICAL CLASSIFICATION OF THE GUADALQUIVIR BASIN

The Guadalquivir Basin occupies a large area in southern peninsular Spain. It takes the form of an elongated wedge running ENE–WSW, with the Guadalquivir River flowing through it. Geographically, to the north it is bordered by the terrain of the Sierra Morena, to the south by the terrain of the Baetic Range, and to the west by the Gulf of Cádiz. Although its topography is very gentle, there is a gradual decline in altitude from the eastern sector (800 m) to the west (sea level) [16].

In geological terms, it is a Tertiary exoreic basin which was formed during the Neogene. The northwestern edge of the basin is represented by the Iberian Massif, with very clear contact in a SW–NE direction as well, made up of materials from the Paleozoic Era (600–250 My) [17]. The southern edge of the depression, whose boundaries are not as well defined, is represented by materials from the Mesozoic Era (approximately 250–90 My), part of the Bética Range (Fig. 2) [18].

This basin began filling more than 10 My, the result of the erosion of the mountainous terrain bordering it. The northwestern edge always remained stable (without significant tectonic movements), providing a continuous supply of sediment to the basin from the stripping of the terrain. In contrast, the southeastern edge was constantly rising, with frequent movements and slides, supplying a smaller amount of sediment.

The largest amount of sediment was supplied by the erosion of the northwestern edge, with the deposits being more significant due to their representativeness: clayey or carbonated marls, in some cases slightly silty, bluish-gray in color (when they are intact) with zero stratification, and massive in appearance with concho-

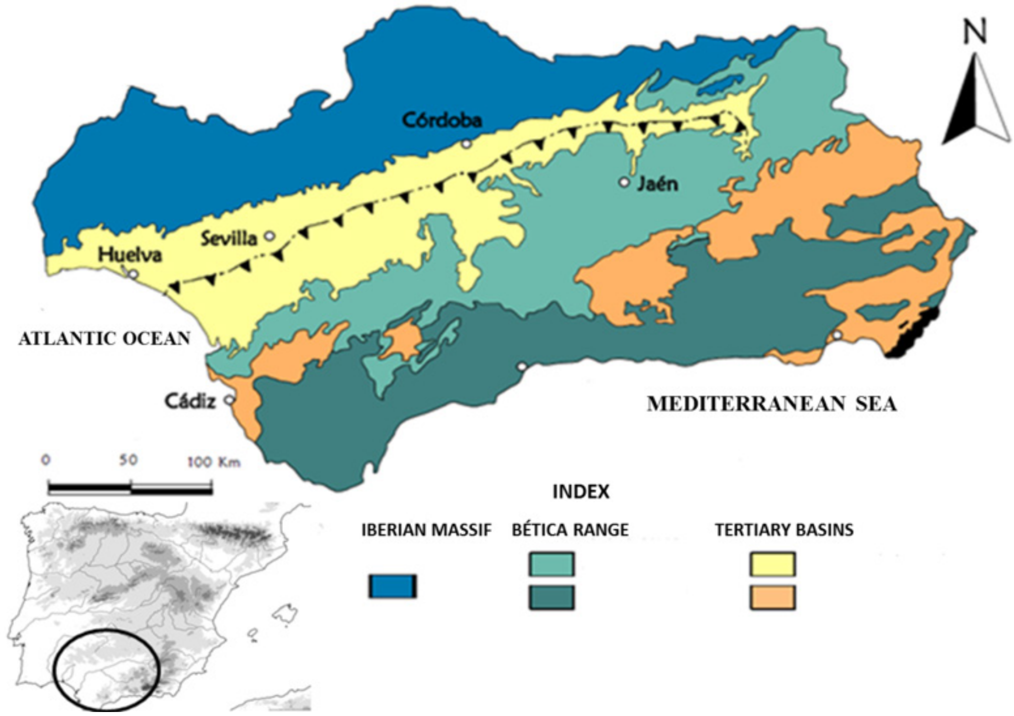

Figure 2. Geographic and geological locations of the Guadalquivir Basin (modified from [18]).

idal fracture. In an altered state (weathered), they take on a brown and yellowish gray-brown color due to the presence of iron oxides. Material is predominantly phyllosilicates (more than 65%). The rest of its components are carbonates and quartz. The clay minerals are formed mainly by illite and smectite. The presence of gypsum may also occasionally be observed.

There is extremely abundant microfauna, which has made it possible to date them to the Upper Miocene, specifically, the Messinian (6.3–5.2 My). This subject has already been a study of [18]. Due to their color (bluish--gray, when fresh), they are described in the geological and geotechnical literature as Guadalquivir Blue Marls. These deposits outcrop along some 800 km, from the province of Huelva, at the mouth of the Guadalquivir River, to the province of Jaén. The unit is present in the subsoil of major metropolitan areas such as the city of Seville.

4 GEOTECHNICAL CHARACTERIZATION OF THE GUADALQUIVIR BLUE MARLS

The geotechnical properties of Guadalquivir blue marls were extensively defined by different authors [2,4,8]. According to identification tests performed over 89 samples for this study, the material is primarily of a clayey nature, with over 80% of material passing through the No. 200 ASTM sieve mesh. The liquid limit values vary from 40 to 70%, while the plasticity index ranges from 15 to 40%. Therefore, these materials fall within the CH to CL category, according to the ASTM classification [19]. The Casagrande plasticity chart is given in Fig. 3, also indicating the suitability of the application of this material for the construction of highway subgrades according to the Spanish Code PG-3 [11]. Due to the nature of this material, classified as marginal to tolerable, the compaction is performed in order to study the behavior of remolded samples with and without the addition of lime.

The specific dry weight ranges from 14 to 16 kN/m^3, and the specific weight of the particles ranges from 25 to 27 kN/m^3. Regarding the carbonate content, most tested samples contain 20–55% $CaCO_3$, thus defining them as clayey marls and marls (Fig. 4).

Regarding the state conditions, Fig. 5 shows the initial moisture content and unit dry specific weight of both undisturbed and remolded samples. It is observed how the dry specific density is hardly modified with the remolding process. The unit dry weight is generally within a relatively narrow range from 14 to 16 kN/m^3, while the range of values for the initial natural moisture content is somewhat broader and mostly from 20 to 30%. It can be observed that these materials can be defi-

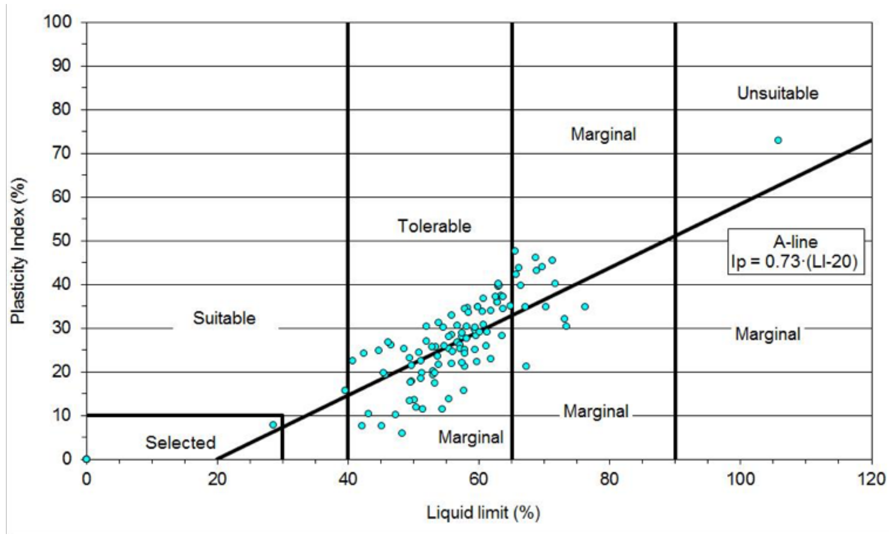

Figure 3. Plasticity chart of the studied undisturbed samples of blue marls.

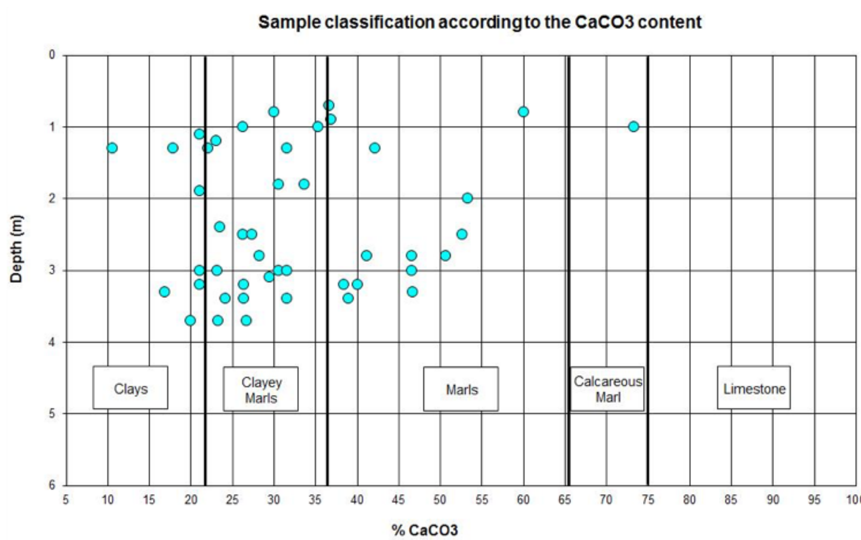

Figure 4. Relationship between % $CaCO_3$ and the depth of the undisturbed samples.

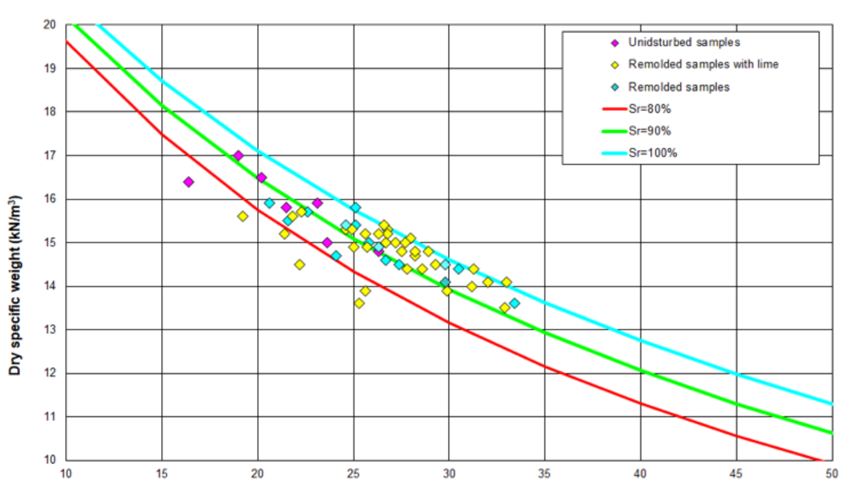

Figure 5. Initial state of the samples tested in the triaxial test (initial moisture content vs. specific dry weight).

ned between 80 and 100 % saturated, being closer to the full saturation the remolded samples with and without the addition of lime.

Of the 89 samples taken during the field research campaign, and tested for defining the identification properties, 57 were selected for testing in the triaxial apparatus under consolidated undrained conditions (CU) with a measurement of pore-water pressure according to the ASTM standard [20]. The following sets of samples were measured: 41 undisturbed samples, 8 remolded samples and 8 remolded samples mixed with lime. All the samples were consolidated under pressure ranging from 50 to 300 kPa. The minimum consolidation period for each tested sample was 24 hours, providing that the strains are stabilized during this period under the load application speed of 0.04 mm/min during the failure stage. The failure stage was conducted for the strains reaching a maximum of 20%. The outputs of these triaxial tests are discussed in the following sections.

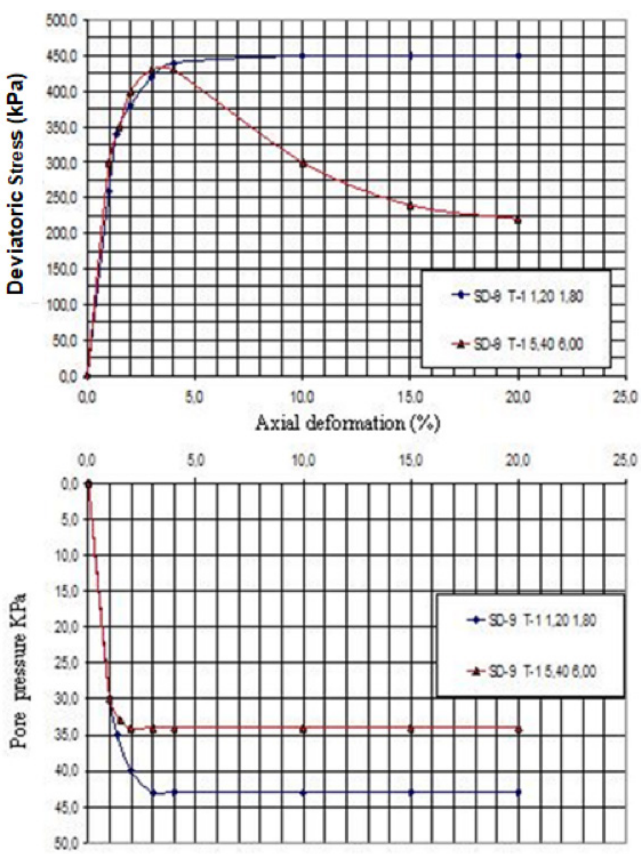

Figure 6. Triaxial test results on the undisturbed samples: deviatoric stress and pore pressure vs. axial deformation.

5 SHEAR-STRENGTH CHARACTERISTICS OF THE UNDISTURBED MARL SAMPLES

The tests performed on undisturbed samples show two different stress-strain behavior patterns under the same consolidation pressure, as can be observed in Fig.6. These two figures show a general trend of the stress--strain behavior for all the tested undisturbed samples.

Both behavior patterns presented in Fig. 6 reach almost the same maximum deviatory stress at approximately same strain level (1–3%), presenting after that different behavior. For the first case, the behavior is defined as an elasto-plastic one, where after reaching the maximum stress, with a relatively small increase in the deviatoric stress the strain continues its increase up to 20%, when the test is stopped. In this mode of ductile fracture, the tested sample takes on a barrel shape, so that the diameter of the central area increases without the appearance of failure surfaces. The second stress--strain type of behavior represents the strain softening behavior after achieving a peak deviatory stress for a strain level between 1 and 3 %. After reaching its peak value, the deviatoric stress decreases with the continuing increase of the strains until reaching its residual value (considered in this case at the end of the test). This mode of brittle failure is associated with the appearance of failure planes in the test sample. The elastic modulus ranges from 25 to 30 MPa for different failure patterns presented in Fig. 6, ductile and brittle respectively, under the same consolidation pressure [21]. The pore-water pressure increases during the failure stage for both types of behavior (brittle and ductile) till reaching its maximum value at the maximum level of deviatoric stress corresponding to the axial strain level of 2–3%, and after that remaining constant until failure.

Plotting the results of the triaxial tests in terms of Lambes variables on a *p-q* diagram the stress path is analyzed [22]. These Lambe parameters represent the following: $p=(\sigma_1' + \sigma_3')/2$ and $q=(\sigma_1' - \sigma_3')/2$. Fig. 7 shows the stress path reaching the $q = p/3$, being typical of materials with dilatant behavior or for over-consolidated clays. Plotting the failure points on *p-q* axes makes it possible to define a geometric location where the failure occurs (see Fig. 8).

Failure is considered to be the point where the deviatoric stress stops increasing with small strains ranging between 1 and 3% in this case. This geometric location is approximately a straight line, corresponding to the Mohr-Coulomb parameters:

- Cohesion 10 kN/m^2
- Angle of internal friction 25º

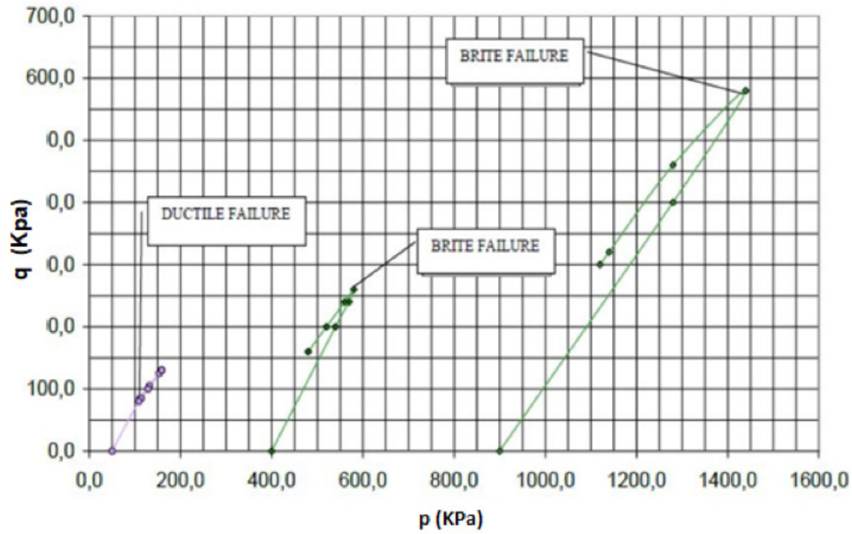

Figure 7. Stress paths of the undisturbed samples in the *p*-*q* diagram.

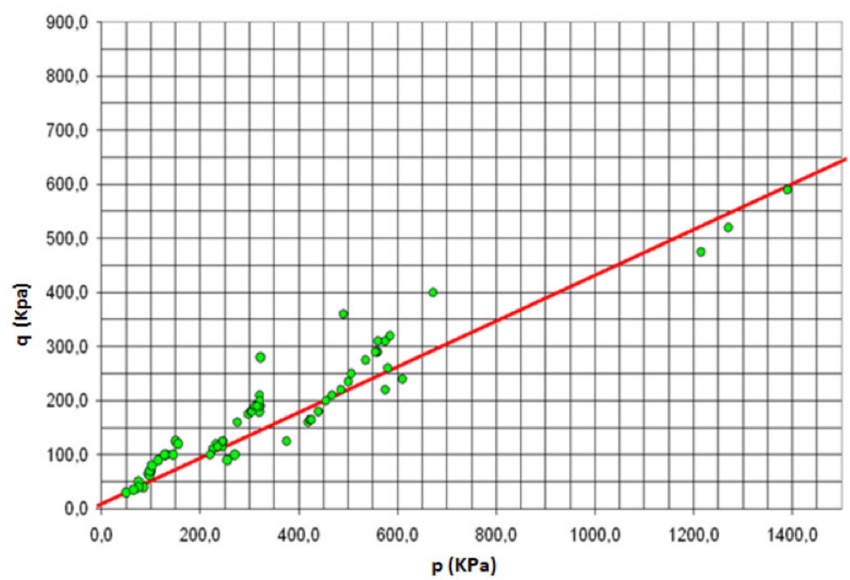

Figure 8. Failure criteria of the undisturbed samples.

6 SHEAR-STRENGTH CHARACTERISTICS OF THE REMOLDED MARL SAMPLES

Similar analyses to those described in Section 5 for undisturbed samples were performed on two types of remolded samples:

a) Eight remolded samples compacted to 100% of their normal Proctor density according to the ASTM standard [23] with moisture levels close to their initial moisture content. In this case, there is only one stress-strain behavior mode corresponding to the elasto-plastic one (ductile behavior). All the tested samples reach a given deviatoric stress at 1 to 5% of the axial strain, corresponding to a consolidation pressure of 50 and 300 kPa. After reaching these values of the axial strain level, a small increase can be observed until reaching the maximum strain of 20% when the test is stopped. Both curves for different consolidation pressures (50 and 300 kPa) present a similar elastic modulus (10 MPa) [21]. The pore-water pressure relationship represents an increase in the same range of axial strain (1 and 5% respectively), after which it shows the general tendency of remaining constant till the end of the test, as was already observed for the undisturbed samples, Fig. 9.

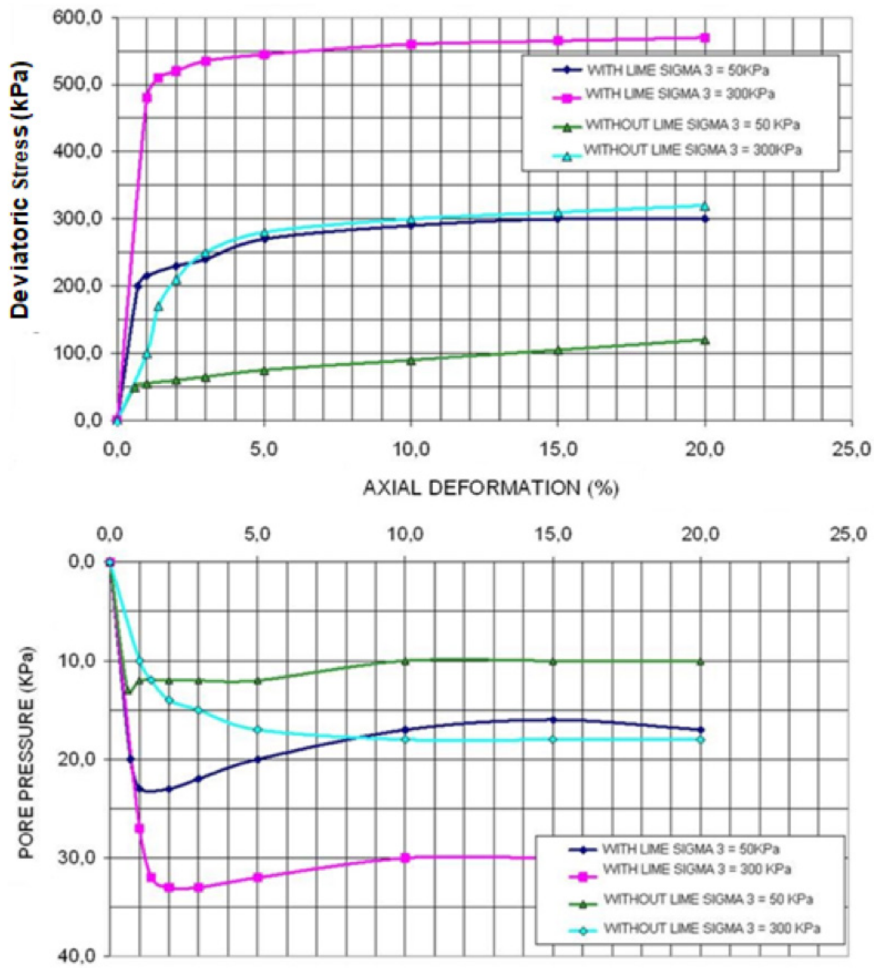

Figure 9. Stress-strain relationship for the remolded samples with and without lime.

b) Eight samples mixed with slake lime ($Ca(OH)_2$), 2% lime by weight of the dry soil, and then remolded and compacted to 100% of their normal Proctor density (15.2 kN/m^3) with moisture levels close to optimum (27%) (see Fig. 5). Samples had a maturation period of about 24 hours before testing. The tendency of the relationship curves is the same as for the remolded samples of the natural material, representing a greater deviatoric stress under the same confinement stress level necessary for the failure, as expected. The lime-treated samples again display the behavior pattern observed on undisturbed samples. The elastic stress-strain behavior is observed reaching axial strains at approximately 1%, and after that showing the small increase in deviatoric stress until the failure is reached (the test was stopped at 20% of the strain level). The elastic modulus [21] obtained is 25 and 48 MPa for different consolidation pressures of 50 and 300 kPa, respectively. These values of the initial elastic modulus are greater than the ones obtained for the natural material tested as a remolded sample under the same consolidation pressure. The pore-water pressure represents the contractive behavior until reaching the maximum strain level, after that representing slightly dilatant behavior until reaching the constant value until the end of the test (see Fig. 9).

The stress paths of both types of remolded samples in turn follow paths similar to those of the undisturbed samples (see Fig. 10). These stress paths are typical of over-consolidated clays [24].

Lastly, plotting the failure points, the geometric location of the failure is established in order to obtain the Mohr--Coulomb model parameters on the *p-q* diagram (see Fig. 11). These are:

- Remolded samples without lime:
  - Cohesion 15 kN/m^2
  - Angle of internal friction 28°

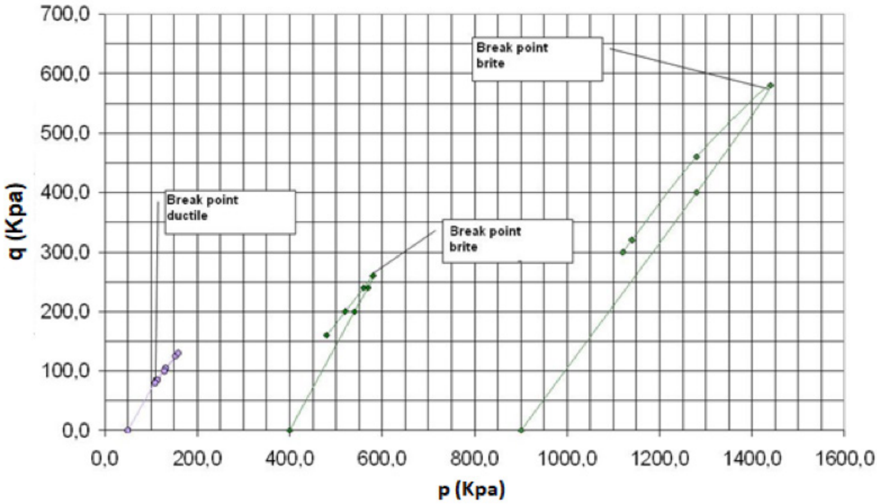

Figure 10. Stress paths of the remolded samples with and without lime.

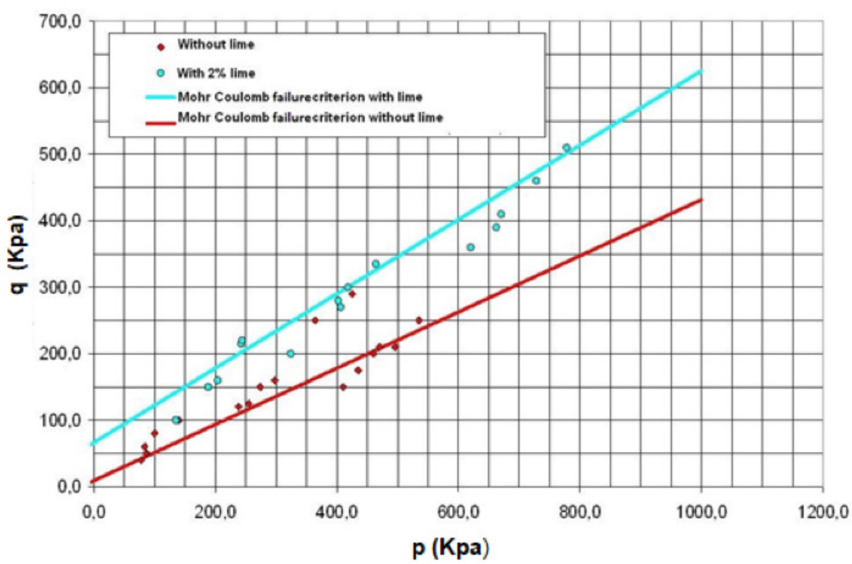

Figure 11. Failure line of the remolded samples with and without lime.

- Remolded samples with 2% lime:
  - Cohesion 80 kN/m^2
  - Angle of internal friction 34º

7 COMPARISON OF RESULTS FOR SAMPLES TESTED BY TCU

A comparison of the results for the three sets of tests described above allows us to reach several conclusions. First of all, undisturbed samples show greater unit dry density and lower initial moisture content than the remolded samples. The remolded samples with lime show a greater initial moisture content and a lower unit dry weight than the undisturbed and remolded samples. The undisturbed samples are stiffer, and they can show brittle and ductile behavior. Both types of remolded samples (with and without lime) display relatively similar stress-strain paths. The failure points are at the approximately same geometric location, representing the lowest strength parameters for undisturbed samples, as was expected.

The upper layers of the Blue Marls' formation are slightly over-consolidated deposits. Therefore, it is possible to conclude that the remolding and compaction process in a Proctor mold, and by extension, the compaction process in embankments on a real scale is equivalent

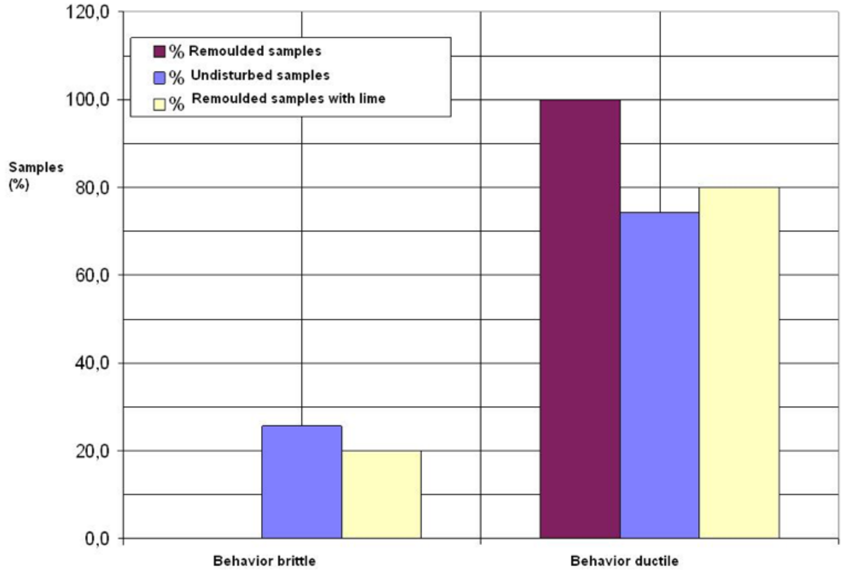

Figure 12. Relationship between the ductile and brittle behaviors for different samples.

to putting a light consolidation pressure on the spread material.

Fig. 12 summarizes the type of failure (brittle or ductile) according to the type of samples. A portion of undisturbed and remolded samples with lime displays brittle behavior, while the remolded samples of a natural material without any additive always display ductile behavior. This brittle behavior may be related to defects in the microstructure, which cannot be seen by the simple naked eye and should be the subject of further detailed analysis regarding the influence of the microstructure on the strength-strain behavior.

The remolded samples with a lime mixture constitute a material with different physicochemical conditions. The transformation of the clay when it is mixed with lime affects its mineralogical composition by replacing its exchangeable ions, as well as the presence of chemical compounds in proportions different to those in the original sediment. Therefore, the lime-treated clay is a new material. The most significant aspect of the comparison between the behavior of three types of samples, undisturbed, remolded and remolded with lime mixture, is that the remolded samples with lime mixture show a considerable improvement in the strength (cohesion and friction angle) and the deformation properties.

The lime mixture in the remolded samples also adds a certain brittleness to the material. Specifically, 20% of the samples remolded with lime tested by TCU display brittle behavior. The origin of this brittle behavior might be related to an unequal distribution of the lime within the test piece, which allows the properties of both types of materials to coexist.

8 RETROSPECTIVE ANALYSIS OF SLOPES IN GUADALQUIVIR BLUE MARLS

These Blue Marls have high plasticity, medium-high expansion and low strength parameters (angle of internal friction and cohesion). The typical residual values can be of the order from 10º to 15º for the angle of internal friction and from 0 to 5 kN/m^2 for the cohesion [16]. Under natural conditions, they evolve gravitationally, even with stable angle orders of magnitude on very low gradients (1V:2.5H and even 1V:3H) (see Fig. 13).

Figure 13. Long-term slopes in one of the studied area of the Guadalquivir basin.

Of the factors that trigger instability, the most important is usually the occurrence of a period of heavy precipitation, which significantly increases the pore-water pressure [2,25]. Nonetheless, these materials are subject to sudden instability, generally attributable to excavation processes, including elements re-excavated due to repairs.

The retrospective analysis of permanent slopes makes it possible to define certain operational geotechnical parameters with a safety coefficient that represents an acceptable risk. When the analysis is based on the limit equilibrium method with circular failures, this safety coefficient is of the order of 1.5 under permanent conditions.

Measurements were made of the height and inclination angle of 41 man-made slopes at the location where the samples for the identification and triaxial tests were taken. The results of these measurements, along with the results of the retrospective analyses, are shown in Fig. 14, which highlights the following:

- Points representing the observed man-made slopes in terms of height and slope angle.
- Line resulting from the retrospective analysis with a safety coefficient equal to 1.5 (red line). The design parameters used in the analysis are the values obtained for undisturbed samples:
  - Bulk density 20 kN/m^3
  - Angle of friction 25º
  - Cohesion 10 kN/m^2
- Line resulting from the retrospective analysis with a safety coefficient equal to 1.0 (green line).

This study indicates that the operational strength parameters used in the retrospective analysis are the same or greater than those deduced from the laboratory triaxial CU tests on undisturbed samples.

9 DISCUSSION AND CONCLUSIONS

The behavior of compacted soil is of special interest for its application in geotechnical structures such as embankments, pavement bases, earth dams, etc. A comparison of the results for undisturbed and remolded samples indicates that that they are similar materials with similar mechanical parameters, even though the undisturbed material is stiffer and sometimes shows brittle behavior.

The retrospective back-analysis study of the stable man--made slopes makes it possible to obtain mechanical operational strength parameters for the upper layer of the Blue Marls' formation. These operational parameters, when dry conditions are considered, are similar to the ones obtained by the triaxial tests performed on undisturbed samples. Therefore, engineering fills build with this material can be designed with a similar batter slope that the steepest ones observed in the surrounding landscape, as long as a dry condition for the embankment can be guaranteed. It was observed that landslides usually occur through existing failure surfaces or when water pressures build up within the slope, which is a reasonable consequence when considering the previous result. Therefore, again, slope cuts in this material can be designed with the steepest observed slopes as long

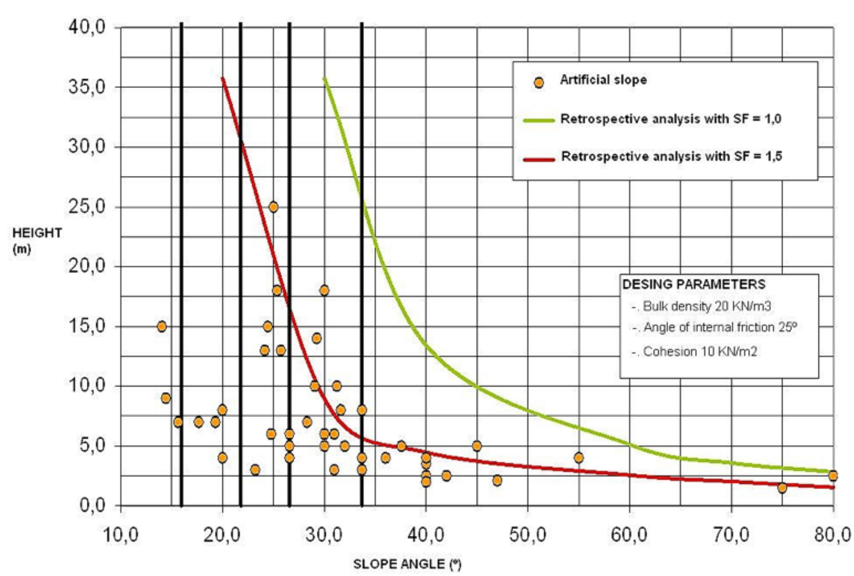

Figure 14. Retrospective analysis results.

as the drainage conditions are under control. Existing landslides require a separated approach. Some of the factors that affect its instability are the presence of a fault in its internal structure that is not easily detected during the site investigation. The observation of the stress-strain behavior in a triaxial test may be a clue to detect these internal faults.

The remolded samples mixed with lime drastically alter the form and chemical composition of the sediment and therefore result in different mechanical parameters. The improvement of the geotechnical strength parameters by the compaction of the sample with and without lime is emphasized, thus making this material adequate for its application in geotechnical structures. A small percentage of the lime content is enough for the improvement of the strength characteristics.

A comparison of the triaxial test results performed on undisturbed and remolded samples makes it possible to define the following conclusions: a) the behavior of undisturbed samples presents both ductile and fragile behavior, while the b) remolded samples undergo only a ductile stress-strain relationship and c) the remolded samples mixed with lime represent both fragile and ductile behavior.

The retrospective analysis of the stability of man-made slopes shows the failure line for the strength resistance characteristics being of same order as obtained with the triaxial tests.

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