A Rational Interpretation of Laboratory Direct Shear Test Results for Soils

Samuel Laura Huanca[1(✉)], Julio Cesar Laura Huanca[2], and Russel Allidren Lozada Vilca[2]

[1] Universidad Privada del Norte, Cajamarca, Peru
samuel.laura@upn.pe
[2] Universidad Nacional de Juliaca, Juliaca, Peru
{jc.laura,ralozadav.doc}@unaj.edu.pe

Abstract. An important property of soils is the shear strength, which guarantees the stability of geotechnical structures. This property is represented by two parameters: internal friction angle and cohesion, obtained from shear testing in the field and laboratory. The direct shear test is the most popular and intensively used for determining shear strength parameters. The aim of this paper is to present a rational procedure to interpret the results of the laboratory direct shear test for defining the strength parameters of soils. Two series of direct shear tests under consolidated and drained conditions (ASTM D3080) were carried out with samples of a wet well-graded sand (SW) compacted to a dense state, from Cutimbo's bank of aggregates, and saturated soft clay (CL and CH), from lacustrine deposits of Puno city. The procedure was applied to the results, for two soils, and the strength parameters were determined considering typical response curves and validity ranges of normal stresses for application purposes. Calculated strength parameters values were consistent with reported values in several publications and reduces the uncertainty of the reported values from direct shear tests.

Keywords: Shear strength · Direct shear testing · Interpretation procedure · Strength parameters

1 Introduction

Shear strength is one of the most important properties of soils [1–7] because the safety of any geotechnical structure (foundations, embankments, retaining structures, dams, slopes, among others) mainly depends on this soil property [2, 3, 6, 8, 9]. This property allows the soil to resist sliding across the internal surfaces of a soil mass [3, 5, 6]. The failure (or slide) of the soil mass occurs as a result of the mobilization of the maximum shear stress that it can support, so understanding shear strength is essential to understand part of the behavior of soils [2, 3, 6, 10–12].

The parameters that define the soil strength can be obtained by various methods, including field and laboratory tests [2, 9, 13, 14]. In the laboratory, the direct shear test is the most popular and intensively used test by engineers in different works to determine

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the shear strength parameters of soils, mainly due to its speed of execution and low cost [3, 5, 12, 15, 16].

The aim of this study is to present a rational procedure to interpret the results of the laboratory direct shear test and define the shear strength parameters of soils. The described procedure is applied to the results obtained from laboratory tests, carried out according to standardized procedures, and then compared with reported values taken from the available bibliographic references.

2 Shear Strength of Soils

To adequately interpret the shear strength of soil, based on the results of direct shear tests, a failure criterion must be considered [5, 9, 17, 18]. The Mohr-Coulomb law of failure is the criterion commonly used for interpreting the results of laboratory strength tests [2, 3, 10–12, 14], and the expression of the shear strength τ_f can be expressed, with modern symbols, by the following equation [19]:

$$\tau_f = c + \sigma^{'} tan\, \phi \tag{1}$$

where σ' is the effective normal stress on the analyzed plane, c is the cohesion, and ϕ is the angle of internal friction or, simply, the friction angle of the soil, the last two are "constant" for a soil [3, 5, 6, 8].

This equation defines a linear failure envelope and allows us to evaluate that for shear stress, on a certain plane less than τ_f, the deformations will be limited, but if these shear stresses reach the value of the resistance τ_f, the shear deformations will be unlimited, indicating shear failure [3, 5, 10, 12, 14]. The cohesion, c, indicates that even when the normal stress is zero, certain shear stress is needed to produce a shear failure [5, 10].

For soils, Eq. 1 must be expressed in terms of effective stresses, because the stresses that act in the contacts between the solid particles determine an eventual landslide. For this reason, soil properties are denoted as c' and ϕ', to highlight that these magnitudes refer to effective stresses [2, 3, 5, 6, 8].

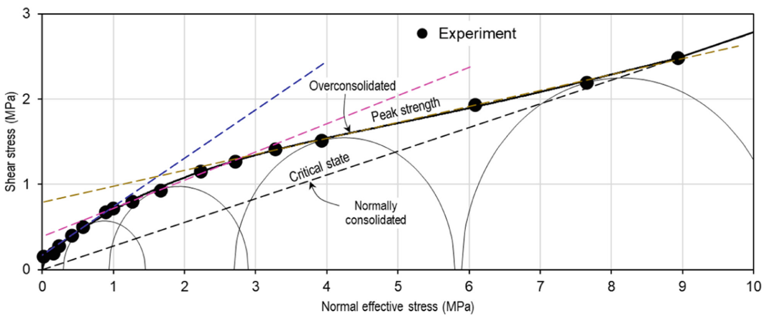

Fig. 1. Shear strength envelopes of undisturbed London clay in the $\sigma^{'} - \tau$ plane [10, 20].

Typical experimental results for the shear strength of soils plotted in the $\sigma^{'} - \tau$ space in Fig. 1, for a very large range of stresses, show that the failure envelope of an overconsolidated clay, the same as in dense sand, initially has a curved shape until it reaches the condition of normally consolidated, or a critical state strength [9, 10, 16].

To apply the Mohr-Coulomb criterion (Eq. 1) we must consider that the range of stresses applied to the soil mass, due to the applied loads from the engineering works is small. For common applications, the estimated stress ranges are below 1 MPa, for which the Mohr-Coulomb criterion is fully applicable, as shown in Fig. 1 [10, 21].

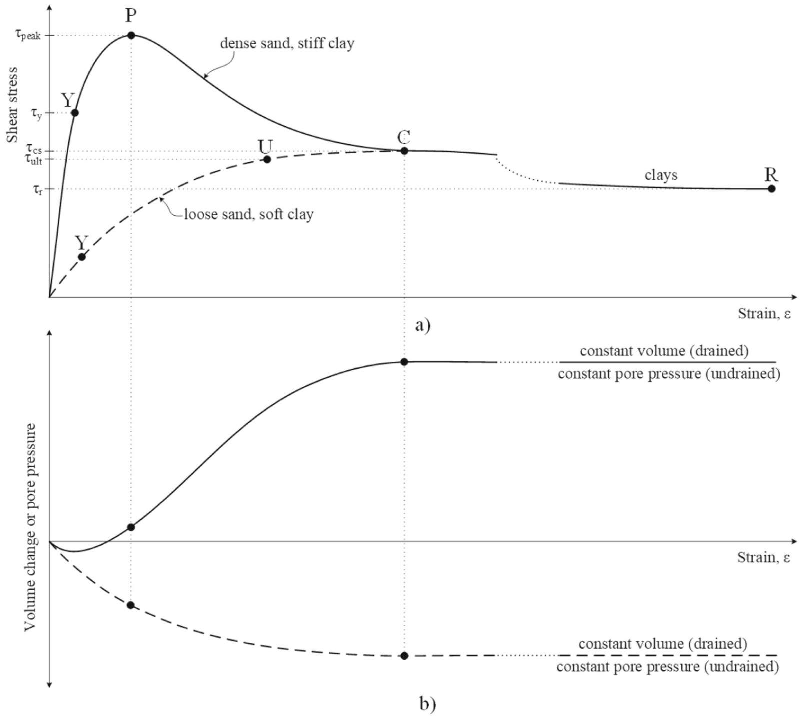

Fig. 2. Types of soil response, defined by: a) plot of shear stress-strain; b) plot of volume change or pore pressure–strain [14, 17, 18].

The behavior of soils can be observed through their stress-strain curves, in which different points can be recognized at which a soil can be considered to have failed. Figure 2 shows stress-strain curves for dense, loose, normally consolidated and overconsolidated soils, showing the points at which the soil fails, which define different criteria that can be adopted [3, 5, 6, 9, 18], which can be:

1. **Yield (Y):** Although it is not the maximum shear stress available for the soil, it represents the point where the curve ceases to have elastic behavior to experience elastoplastic behavior. Beyond this point, higher stresses will cause deformations, and ground movements are considered a failure [18].
2. **Peak shear strength (P):** Corresponds to the maximum shear stress that the soil can support, commonly present in dense sands and rigid or overconsolidated clays.

It can be dangerous to rely on this value because the soil rapidly loses strength if it deforms beyond this point [17, 18].

3. **Ultimate strength (U):** For loose sands and soft clays, can increase the stress, due to soil hardening, to the ultimate shear stress. The ultimate strength value is usually limited to shear (horizontal) strain between 10% and 20% [17, 18], related to the behavior of the soil structure.
4. **Critical state strength (C):** Sometimes can also be called ultimate strength. It is the shear stress for when the soil reaches a constant volume state (due to dilatancy or compression) or constant pore pressure [18], continuing the soil shear. It is sometimes called constant volume strength.
5. **Residual strength (R):** Sometimes it is also known as ultimate strength. It occurs after considerable deformation, on the slip surface, and is the lowest value of strength that the soil can support. This strength is very important in the analysis of the reactivation of old landslides [18].

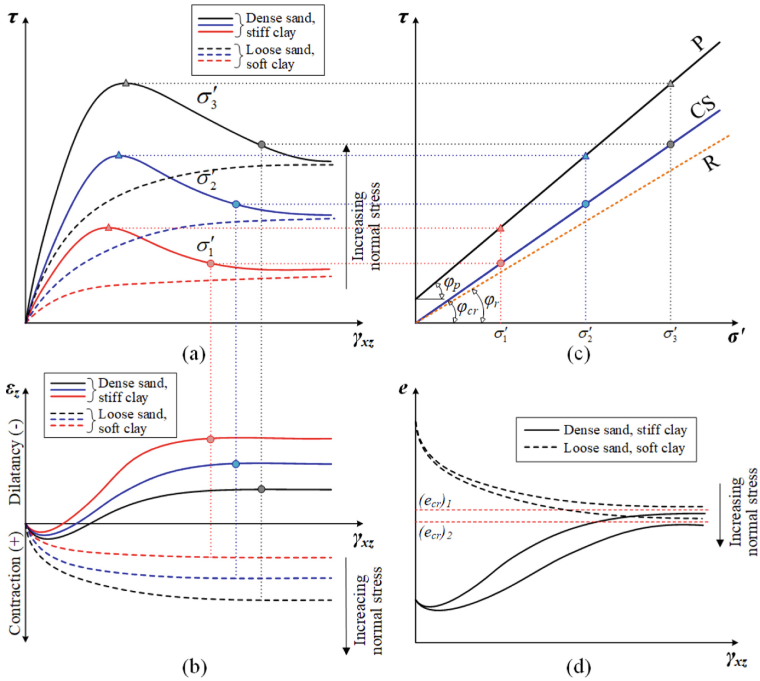

Fig. 3. Typical curves on the effect of increasing normal stress in soil behavior against shear stress [9, 20, 22].

Figure 2 shows typical curves, for single normal stress, for two large groups of soils. In a series of three or more direct shear tests with different applied normal stresses, different typical behavior curves will be produced, as shown in Fig. 3 [9, 22]. As a result of the repetition of the direct shear test procedure, the results are taken into diagrams shear stress – horizontal or shear strain (Fig. 3a) and volumetric strain – horizontal strain (Fig. 3b). Depending on the adopted criterion to define the shear strength of soil, the corresponding pairs (σ', τ) are transferred to the normal stress – shear stress plane (Fig. 3c) that allows a plot of corresponding failure envelope (P – Peak strength, CS – Strength at a critical state, R – Residual strength). The volumetric deformation - horizontal deformation diagram allows us to observe the variation of the soil void ratio (Fig. 3d), and it can also be verified that the critical void ratio is dependent on the magnitude of the normal effective stress [9, 23, 24].

3 Materials and Methods

For this study, a qualitative and quantitative analysis of the rational procedure for interpreting the results of direct shear tests under consolidated and drained conditions is carried out, to determine the parameters of the shear strength of soils.

Results of direct shear tests of two typical soils of Puno city are considered for the application of the interpretation procedure proposed in this paper. One soil is a clean well-graded sand (SW) compacted to a dense state, from Cutimbo's bank of aggregates normally used in works in this city. The other soil is a soft clay of medium to high plasticity (CL and CH) with the presence of organic material, characteristic of the lacustrine zone of this city.

The procedure described below is based on the approaches proposed by Morilla [25]. Then, the rational procedure proposed, for the interpretation of results of direct shear tests, assumes that to obtain the values of shear strength parameters (ϕ' and c') the soil already has these 'true' values, therefore we must follow:

1. Carry out a series of three or more direct shear tests with the same soil sample, in each test: shear stresses (τ), horizontal deformations (δ_h), and vertical deformations (δ_v) must be measured for each normal stress: $\sigma_1' < \sigma_2' < \sigma_3' < \ldots < \sigma_n'$.
2. Plot the results of readings in two graphs: horizontal strain (by shear) versus shear stress ($\epsilon_h - \tau$) and horizontal strain versus volumetric strain ($\epsilon_h - \epsilon_v$).
3. Determine the type of response or failure criterion is considered to determine the corresponding parameters, according to Fig. 2. The adopted criterion must be indicated when submitting the final results.
4. Determine the pairs (σ', τ) for each test, determining the shear stresses according to the type of response determined.
5. Write Eq. 1 for each test performed, in an equation system, as follows:

   – Eq. 1 (specimen 1): $\tau_1 = c' + \sigma_1' \tan\phi'$
   – Eq. 2 (specimen 2): $\tau_2 = c' + \sigma_2' \tan\phi'$
   – Eq. 3 (specimen 3): $\tau_3 = c' + \sigma_3' \tan\phi'$
   – Equation n (specimen n): $\tau_n = c' + \sigma_n' \tan\phi'$

6. Determine various values for the angle of friction (ϕ') and cohesion (c'), corresponding to the combination of each pair of the last equation system.

7. If the test was carried out following the standardized procedure (ASTM D3080), the results of ϕ' and c', from each pair of equations, must be very close so that finally a statistical procedure can be carried out (average, regression, etc.) to determine their final values. In addition, graphs $\epsilon_h - \tau$ and $\epsilon_h - \epsilon_v$ of the same soil should be observed, which should indicate a similar typical behavior, according to what is shown in Figs. 2 and 3.
8. Finally, in a checking way, the values obtained for the resistance parameters (ϕ' and c') must be compared with those typical values reported in the literature.

4 Results and Discussion

Figure 4 shows direct shear test results of wet dense sand ($\gamma = 18.3\,\mathrm{kN/m^3}$) and a saturated soft clay ($\gamma = 14.5\,\mathrm{kN/m^3}$), performed in a 60 mm × 60 mm shear box and a specimen of 30 mm and 20 mm thickness respectively. The dense sand was subjected to six different normal stresses, with two values above the common (13.6; 27.2; 54.5; 109.0; 163.4, and 217.9 kPa), and shear stresses in peak and critical state were identified, according to the behavior of this type of soil. On the other hand, the soft clay was subjected to four normal stresses within the common range (13.6; 27.2; 54.5, and 109.0 kPa) and ultimate shear stresses were identified for a horizontal strain of 15% (3 mm). This completes the first three steps of the procedure described above.

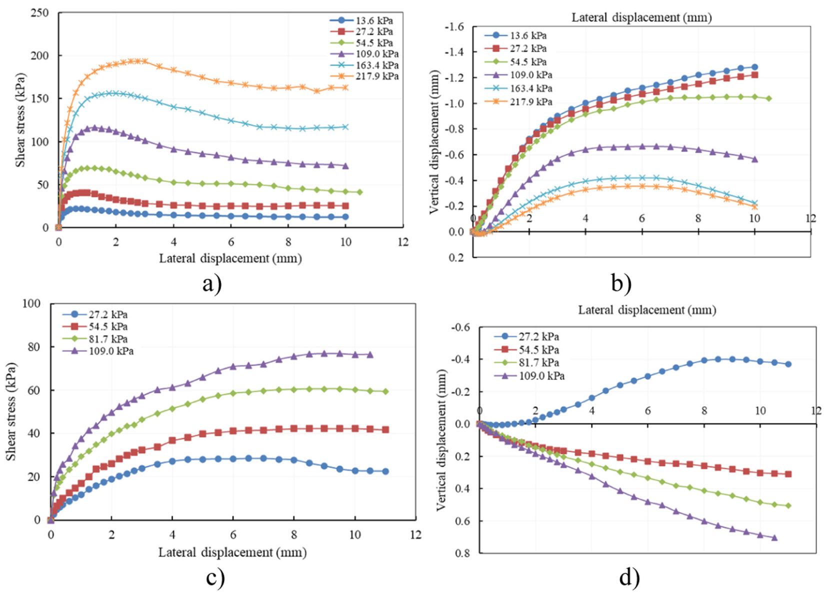

Fig. 4. Direct shear test results: wet dense sand (a and b), and saturated soft clay (c and d).

Then, in step 4, the pairs (σ', τ) are identified and determined for the adopted criteria that were indicated for each type of soil. In Table 1 and Fig. 5, it can be seen that for dense sand, six pairs (σ', τ_p) were determined for peak strengths, corresponding to the six tests carried out, and four pairs (σ', τ_{cs}) for strengths in a critical state, which correspond to the last four tests that show the trend to constant volume, while the first two tests continue with the increase in the volume of the test specimen. On the other hand, Table 1 and Fig. 5 show that four pairs (σ', τ_{max}) and four pairs (σ', τ_{ult}) corresponding to the four tests performed were determined for soft clay.

Table 1. Pairs of points (σ', τ) from failure criteria for wet dense sand and saturated soft clay.

Normal stress (σ')	**Wet dense sand**		**Saturated soft clay**	
	Peak shear stress (τ_p)	**Critical state shear stress (τ_{cs})**	**Maximum shear stress (τ_{max})**	**Ultimate shear stress (τ_{ult})**
kPa	*kPa*	*kPa*	*kPa*	*kPa*
13.6	22.0	-	28.4	23.9
27.2	40.8	-	42.3	32.5
54.5	69.2	44.1	60.6	46.3
109.0	116.4	84.1	76.9	57.3
163.4	156.2	128.4	–	–
217.9	193.7	170.6	–	–

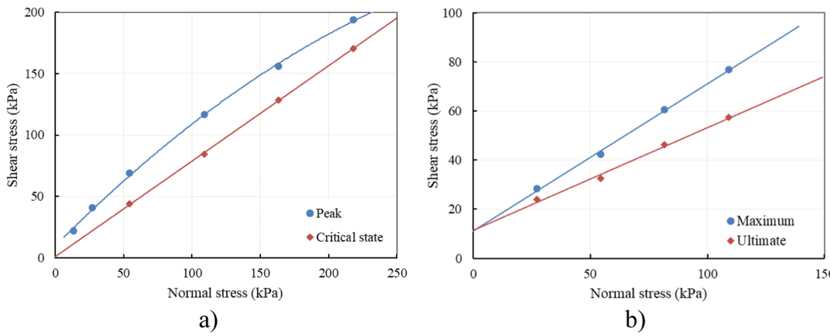

Fig. 5. Shear strength envelopes obtained by regression (commonly), according to failure criteria for a) wet dense sand and b) saturated soft clay.

In Fig. 5a, it can be seen that an error would be made if a linear regression of the pairs (σ', τ_p) was performed for the peak strengths of the dense sand because, in reality, the peak failure envelope is a non-linear curve, therefore it must be interpreted by segments, in which the Mohr-Coulomb failure criterion is valid, which in this case can be: 25–125 kPa and 100–225 kPa. On the other hand, the critical state failure envelope shows the existence of cohesion, which does not correspond to the critical state failure criterion in which the cohesion must be zero.

In the case of soft clay, Fig. 5b shows that both maximum strength and ultimate strength envelopes apparently can be obtained by linear regression, obtaining values of shear strength parameters without qualitative analysis of the tests, which also leads to a wrong interpretation.

Thus, for results shown in Table 1, the equations for each pair of values for each soil can be written, considering as an example of criteria the peak strength for wet dense sand and ultimate strength for saturated soft clay. Then, according to step 6 described above, the values of ϕ' and c' are calculated for each combination of the equations.

According to step 7 of the procedure described above, the results obtained are analyzed. For wet dense sand, the first segment of normal stresses between 25 and 125 kPa, the valid results to determine the values of ϕ' and c' are those corresponding to specimens 2, 3, and 4, with the corresponding combinations of equations. For this stress range, Fig. 6a shows that the values obtained are relatively close, noting that the combination of 1 and 2 shows high values of the angle of friction and low of cohesion, therefore the result of a resulting weighted average is $\phi_p{}' = 42.7°$ and $c_p{}' = 17.2\,kPa$. In this case, the result is practically the same as that which would be obtained through a linear regression with $R2 = 0.9978$ (42.5° and 17.2 kPa), due to the good quality of the procedure performed and the results obtained from the direct shear test.

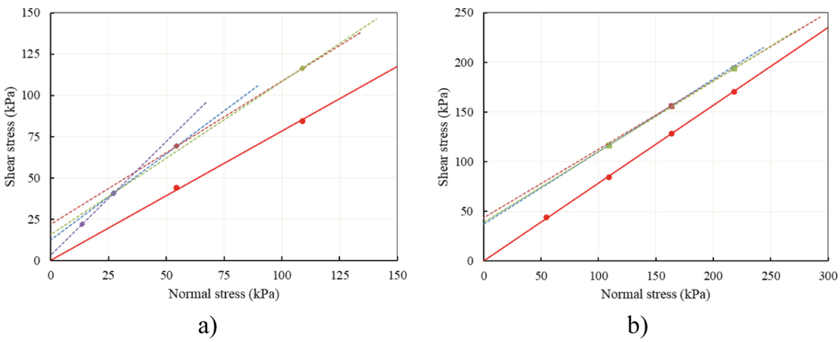

Fig. 6. Trend lines of combinations of direct shear test results for wet dense sand: a) normal stress between 25 and 125 kPa, and b) normal stress between 100 and 225 kPa.

Proceeding in the same way for the interval between 100 and 225 kPa, for the combinations related to specimens 4, 5, and 6, values of the shear strength parameters of $\phi_p{}' = 35.4°$ and $c_p^{'} = 39.6\,\text{kPa}$ are obtained (see Fig. 6b). Again, the results are practically the same as those obtained by linear regression with $R2 = 0.9996$ (35.4° and 39.4 kPa). The results obtained for wet dense sand correspond to reported values in the bibliography [2, 9, 25–27] for shear strength parameters in sands.

For soft clay, considering that the test was carried out for common normal stresses, a linear failure envelope must be considered, for which the pairs (σ', τ) for maximum and ultimate strengths must correspond to a straight line. Figure 7 shows the combinations that can be obtained from the specimens subjected to testing. In Figs. 4c and 4d, it can be seen that specimen 1 should be discarded because it does not correspond to the results of the rest of the test specimens since it shows a peak resistance and volume increase (dilatancy) that does not correspond to soft clay. Therefore, for this case, the combinations related to specimens 2, 3, and 4 must be considered. Thus, the ultimate strength parameters are determined to be $\phi'_{ult} = 24.5°$ and $c'_{ult} = 8.4\,\text{kPa}$, results are practically the same as those obtained from linear regression with $R2 = 0.9959$ (24.5° and 8.1 kPa), which is due to the good quality of the tests carried out, except with specimen 1. These values of drained shear strength parameters for soft clay are consistent with those reported by various authors [2, 9, 26].

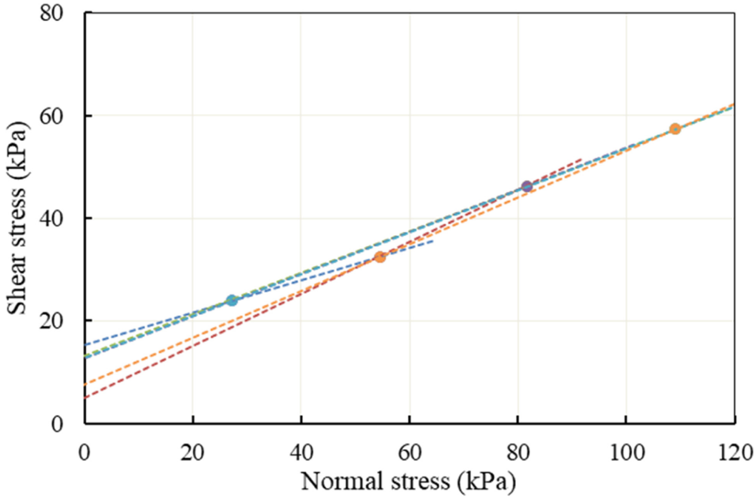

Fig. 7. Trend lines of combinations of direct shear test results for saturated soft clay.

5 Conclusion

The procedure to interpret the results of the direct shear test (in drained consolidated condition) was presented and explained, with considerations previously established by various authors. The results of direct shear tests carried out with samples of wet dense sand and saturated soft clay, characteristic of the city of Puno in Peru, were interpreted. The results obtained, with the criteria adopted and the observation of the response curves of the soils, were consistent with the values reported in the available bibliography. Therefore, the proposed procedure allows obtaining results that reduce the uncertainty of the reported values, selecting the valid results (points or specimens) and the validity ranges for the determined parameters for application purposes. In the future, similar procedures must be carried out with other laboratory tests such as triaxial compression, carried out in accordance with the corresponding standards.

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