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Mechanical parameters of soil-rubber mixtures from oedometer and direct shear tests

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Technical Note

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Oedometer tests
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Abstract
In Brazil alone, 12.23 million tires were manufactured in the first quarter of 2024. The inadequate disposal of rubber waste from scrap tires is a globally recognized problem. The incorporation of this solid waste into geotechnical projects can serve to mitigate the environmental impact of its disposal. This paper presents complementary results previously published by Abrantes et al. (2025). This first publication dealt with the following procedures applied to the soil and soil-rubber mixtures: specimen preparation, characterization, standard compaction tests and compaction tests with damping ratio measurement, CIU Triaxial tests and Dynamic Triaxial tests. The current publication (Part 2) presents results and discussions about the following tests performed in soil and soil-rubber mixtures: oedometer tests (consolidation and elastic parameters), oedometer tests (permeability) and direct shear tests (strength parameters). The tests were conducted with pure soil and with soil-rubber mixtures in proportions of 2.5%, 5.0%, 7.5%, 10.0%, 12.5%, and 15.0% of rubber weight in relation to the weight of the pure soil. Based on present study, the rubber from shredded scrap tires can be used in applications such as: a) compacted embankments; b) soil walls reinforced with geosynthetics. Nonetheless the use of rubber mixed with soil is not recommended in clay liners for sanitary landfills.

1. Introduction

This paper consists of a complementation of the study conducted by Abrantes et al. (2025) regarding soil-rubber mixtures mechanical behavior. This study has been previously published in the Journal Soils and Rocks under the title “Mechanical parameters of soil-rubber mixtures for sustainable geotechnical projects”. This current publication presents results and discussions about the following tests performed in soil and soil-rubber mixtures: oedometer tests and direct shear tests.

The permeability coefficient remains largely unchanged when rubber is added to the soil, as demonstrated by Özkul & Baykal (2007). Conversely, the compressibility of the soil tends to increase with the addition of rubber to the soil, as reported by Edil & Bosscher (1994) and Sellaf et al. (2014).

Venkatappa & Dutta (2006) performed oedometric tests on rubber-sand mixtures and observed an increase in compressibility with increasing rubber content. Lee et al. (2010) performed oedometric tests on rubber-sand mixtures and observed an increase in vertical deformation with increasing rubber content.

Ghazavi (2004) performed direct shear tests on pure sand and sand-rubber mixtures and reported an increase in friction angle of up to 13.0% with the addition of up to 15.0% rubber to the loose sand. The author also reported a slight increase of about 2.7% in the mixtures with compacted sand. As for the friction angle, the results presented in the study for clay soil are more similar to those obtained for compacted sand, according to the results presented by Ghazavi (2004).

Cetin et al. (2006), when performing direct shear tests under unsaturated conditions on predominantly pure clay soils and soil-rubber mixtures, observed a significant increase in the shear strength of the soil as rubber was added. Cohesion tended to increase to 40.0% rubber content in the soil. On the other hand, the friction angle tended to decrease up to that content.

2. Materials and methods

The rubber content used in the studies were 2.5%, 5.0%, 7.5%, 10.0%, 12.5%, and 15.0% of the rubber weight in relation to the weight of pure soil. Laboratory tests were conducted on pure soil and soil-rubber mixtures. The

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methodology and standards employed in the tests performed, both on pure soil and soil-rubber mixtures, are explained in detail by Abrantes et al. (2025).

2.1 Oedometer consolidation and permeability tests

Seven compression oedometer tests were performed on the pure soil and the soil-rubber mixtures. The tests were conducted in accordance with the recommendations of Brazilian Standard NBR 16853 (ABNT, 2020). The objective of the tests was to determine the following geotechnical parameters: E_{oed} = oedometric modulus; E = elastic modulus; K_v = vertical permeability coefficient; C_c = compression index; C_s = swelling index and c_k = rate of variation of the void index with permeability (a parameter from the Plaxis software for numerical modeling).

The values of E were calculated for each loading stage using Equation 1, and the values of E_{oed} were calculated directly from the specific deformation (ε) versus vertical effective stress where the specific deformation is a function of the void ratio (e). The Poisson's ratio (v) was assumed to be equal to the average Poisson's ratio obtained from triaxial tests with the soil and the rubber content mixtures of 10.0% and 15.0%. Therefore, the value of 0.234 was used to representv in Equation 1.

$$E = E_{oed}\frac{\left(1+\right)\left(1-2\right)}{1-} \quad (1)$$

where E = elastic modulus; E_{oed} = oedometer modulus; v is the Poisson's ratio; $\nu = K_o/(1+K_o)$ and $K_o = 1 - \sin \phi'$. K_o is the coefficient of earth pressure at rest and ϕ' is the effective friction angle of the soil.

The specimens were molded by driving a steel ring onto the previously compacted soil in the compaction cylinder.

2.2 Direct shear tests

A series of direct shear tests were conducted on pure soil and soil-rubber mixtures. The tests were conducted under both saturated and unsaturated conditions, applying normal stresses of 12.5, 25, 50, 100, 200 and 400 kPa. One test was also performed on pure rubber under saturated conditions. The tests were carried out according to the recommendations of ASTM D 3080-98 (ASTM, 2003) and the applied strain rate was 0.055 mm/min. The main objective was to determine the shear strength parameters (cohesion and angle of friction) of the pure soil, the mixtures, and the rubber. The specimens were molded using a procedure similar to that used in the oedometer tests. A total of 84 direct shear tests were performed.

3. Results and discussion

3.1 Oedometer tests – consolidation and elastic parameters

Figure 1 shows the void ratio (e) versus vertical effective stress (σ'_v) curves obtained for the seven specimens tested.

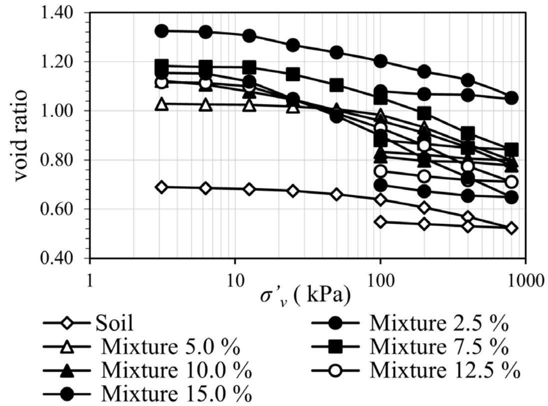

Figure 1. Vertical effective stress versus void ratio curves for pure soil and soil-rubber mixtures.

Figure 1 also shows that, in general, the compressibility of the material increases as the rubber content increases. This behavior is observed during both loading and unloading of the specimens. It should be noted that the C_c values range from 0.13 to 0.26 for mixtures with rubber content between 0.0% and 15.0%. In this instance the incorporation of 15.0% of rubber into the soil resulted in a 100% increase in compressibility. The C_s values remained between 0.029 and 0.080 for rubber contents ranging from 0.0% to 15.0%. The behavior of the compressibility coefficient (C_s) is also consistent, with the incorporation of 15.0% rubber resulting in an increase of 176%.

Figure 2a shows the variation of the compression index (C_c) with rubber content, while Figure 2b shows the variation of the swelling index (C_s), also in relation to the rubber content (0.0% to 15.0%). Both parameters were calculated for a vertical effective stress interval (σ'_v) of 200 to 800 kPa. This stress interval was chosen because the curves exhibit linearity within this stress range. In addition, consideration of higher stress levels provides values that can be considered conservative and on the side of safety.

Figure 2a shows that the compression index (C_c) value typically increases with increasing rubber content. Consequently, when an external load is applied, the deformations will be greater in the mixtures with the highest rubber content. Figure 2b shows that the swelling index (C_s) increases in direct proportion to the rubber content, exhibiting a linear growth pattern. Therefore, the elastic response of the material, in terms of strain, increases with increasing rubber content following the removal of the external load.

Figure 3a shows the variation of the oedometer modulus (E_{oed}) with vertical effective stress (σ'_v) for the loading stages applied to the specimens. Figure 3b shows the elastic modulus (E) values versus effective vertical stresses (σ'_v).

Figure 3 shows that as the rubber content increases, the oedometer (E_{oed}) and elastic modulus (E) decrease. The decrease in E_{oed} and E with increasing rubber content is less pronounced from $\sigma'_v \approx 200$ kPa, indicating that the addition of rubber increases the deformability of the material, making it more ductile.

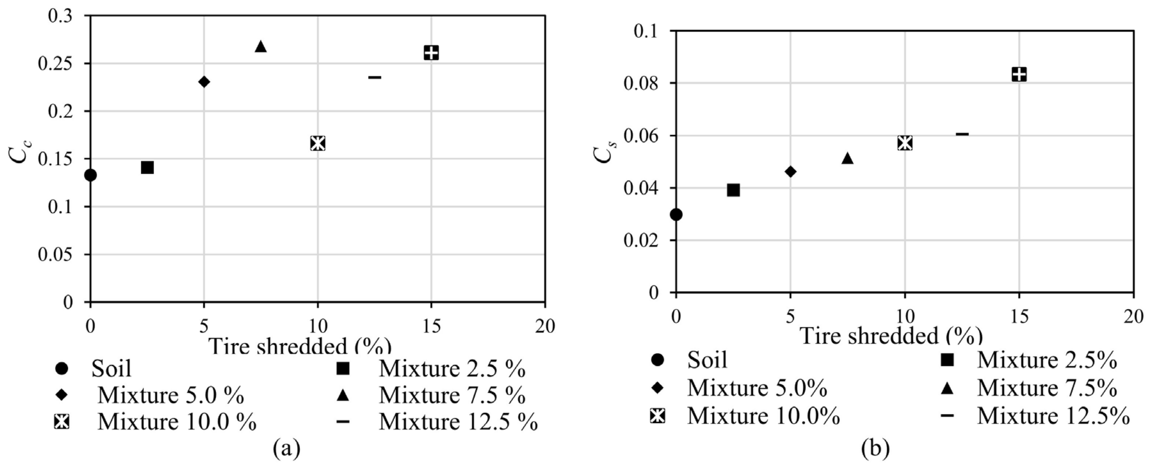

Figure 2. Compressibility parameters: (a) variation of C_c with σ'_v; (b) variation of C_s with σ'_v.

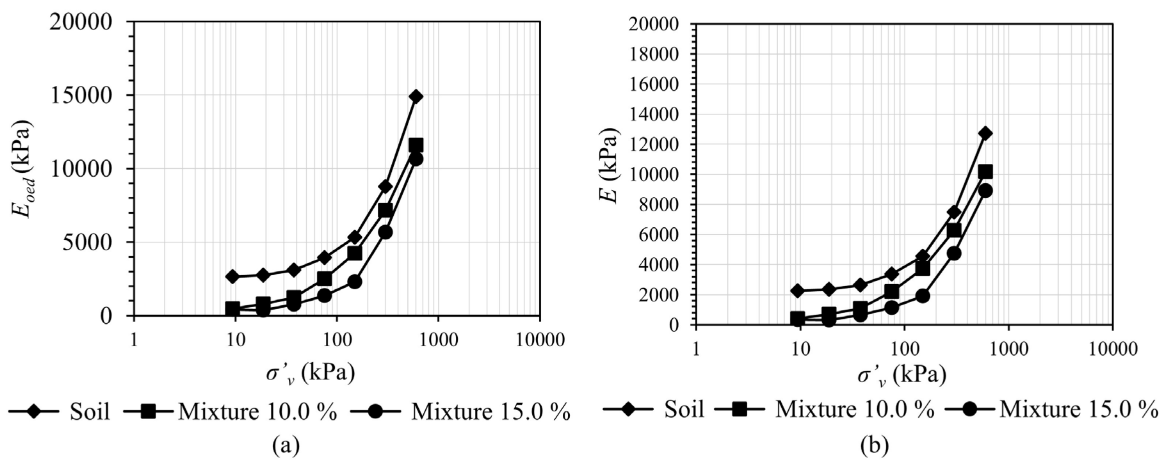

Figure 3. Elastic modules: (a) variation of E_{oed} with σ'_v; (b) variation of E with σ'_v.

3.2 Oedometer tests – permeability

The variation of the permeability coefficient (K_v) as a function of the variation of the effective vertical stress (σ'_v) of pure soil and soil-rubber mixtures is shown in Figure 4.

As expected, Figure 4 shows a decrease in the permeability coefficient with increasing effective vertical stress. This behavior occurs for both pure soil and mixtures, regardless of rubber content. With respect to the permeability coefficient (K_v), the highest values are generally associated with the highest rubber content used in the mixtures. Lower rubber content (up to 7.5%) slightly changes the K_v value. The observed behavior shows that rubber particles can create a preferential flow path that increases the K_v value. For example, at an effective vertical stress of 100 kPa, the pure soil has a permeability of $1 \cdot 10^{-4}$ cm/s, while at a rubber content of 15.0%, the permeability increases by 700% to a value of $1 \cdot 10^{-4}$ cm/s.

Equation 2 translates the variation of the coefficient of permeability as a function of the void ratio. This relationship is essential if the intent is to model the material with a K_v update related to the deformations that have occurred in that material. Table 1 shows the c_k values (rate of variation

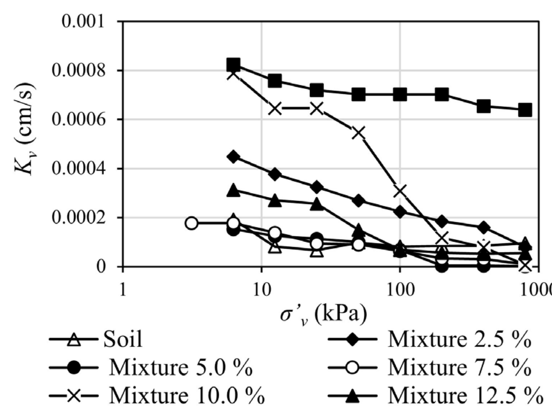

Figure 4. Coefficient of permeability versus effective vertical stress curve.

Table 1. Values of c_k as a function of rubber content.

Rubber content	0.0 (%)	2.5 (%)	5.0 (%)	7.5 (%)	10.0 (%)	12.5 (%)	15.0 (%)
c_k [-]	0.55	0.36	0.12	0.27	0.16	0.53	0.46

of the void index with permeability) for pure soil and soil-rubber mixtures.

$$c_k = \frac{\Delta e}{\log\left(\frac{k_v}{k_{vo}}\right)} \quad (2)$$

where: Δe = void ratio variation, K_{vo} = initial coefficient of permeability (first loading stage), and K_v = coefficient of vertical permeability (subsequent loading stages). Loading stages refer to the oedometer compression tests.

Table 1 shows that c_k ranges from 0.12 to 0.55 for the mixtures with rubber content between 0.0% and 15.0%. No discernible trend of increase or decrease in c_k was observed with each increase in rubber content.

3.3 Direct shear tests

This section presents the results of the investigation of the shear strength parameters of the pure soil, rubber, and soil-rubber mixtures. The percentages of rubber content were 2.5%, 5%, 7.5%, 10%, 12.5%, and 15.0%. These parameters were obtained from direct shear tests conducted under both saturated and unsaturated conditions. Figures 5a to 5h show the strength envelopes obtained from the tests. Figure 6a shows

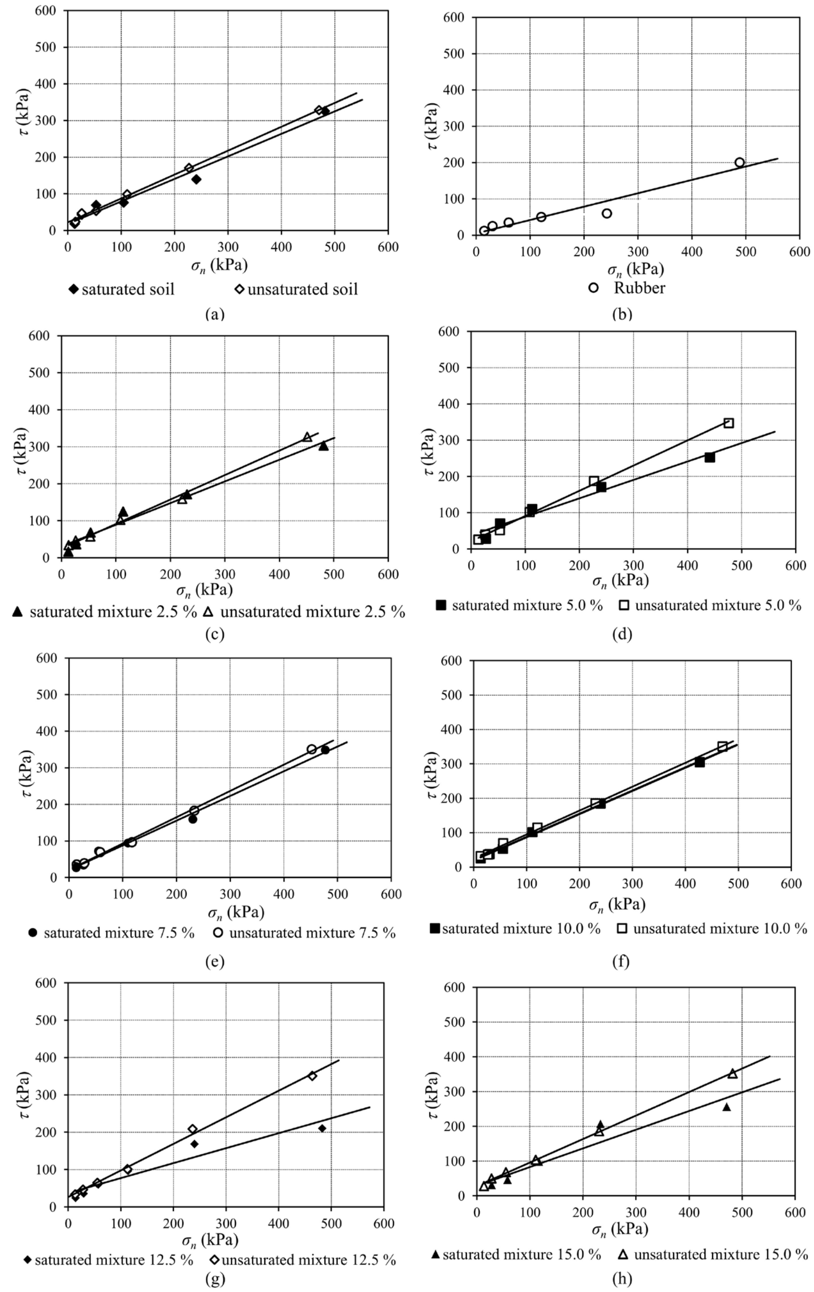

Figure 5. Strength envelope under saturated and unsaturated conditions: (a) pure soil; (b) pure rubber; (c) mixture 2.5%; (d) mixture 5.0%; (e) mixture 7.5%; (f) mixture 10.0%; (g) mixture 12.5%; (h) mixture 15.0%.

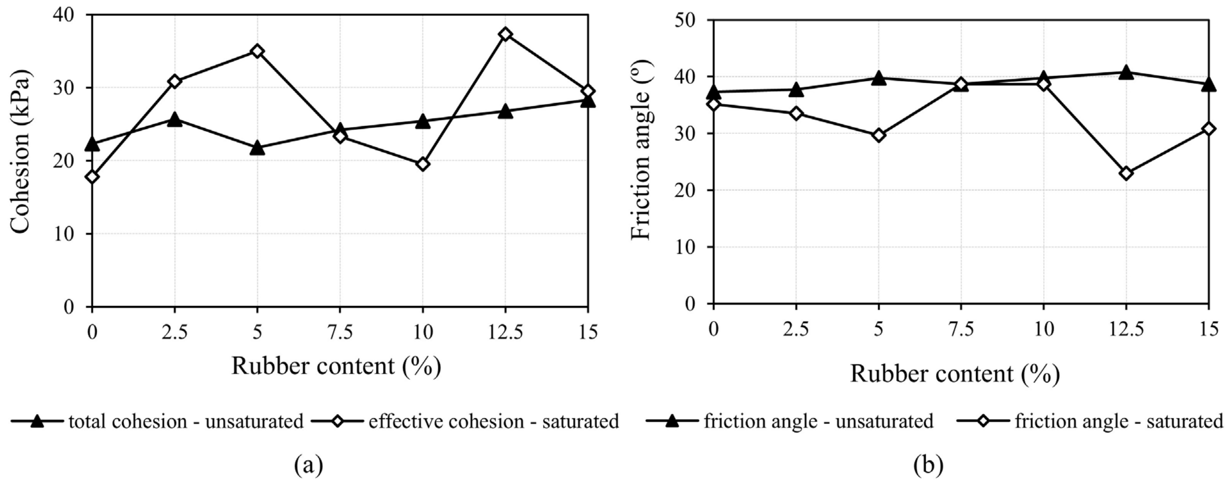

Figure 6. Variation of shear parameters (a) variation of cohesion; (b) variation of the friction angle.

the variation of effective cohesion (c') and total cohesion (C) with rubber content under saturated and unsaturated conditions. The results shown in Figure 6b illustrate the variation of the effective friction angle as a function of the rubber content applied, considering the envelopes for both saturated and unsaturated conditions.

Total cohesion (C) is defined by the following Equation 3, which is based on the classic statement by 0 regarding the shear strength of unsaturated soil.

$$C = c' + \left(u_a - u_w\right) \cdot tg\,\phi^b \quad (3)$$

where C = total cohesion; c' = effective cohesion; $(u_a - u_w)$ = matric suction; tg ϕ^b = relationship between shear stress and matric suction; u_a = pore air pressure; u_w = pore water pressure.

According to Figure 6, for the unsaturated condition, there was a slight tendency for the total cohesion to increase with increasing rubber content. In unsaturated conditions, the friction angle remained largely unchanged, regardless of the rubber content. Therefore, for the unsaturated condition, as found in compacted soil-rubber mixtures in the field, the addition of rubber does not cause a decrease in the shear strength parameters.

In the saturated condition, there was an increase in the cohesion intercept for the mixtures with up to 5.0% rubber content. However, a decrease in cohesion was observed for the mixtures between 5.0% and 10%. For mixtures with more than 10% rubber content, the effective cohesion increased again, followed by a subsequent decrease. The effective cohesion and friction angle exhibited oscillatory behavior in the saturated condition. In the saturated condition, which is critical for earthworks, there was generally no decrease cohesion, except for the 10.0% rubber content mixture. Conversely, the friction angle decreased for all the rubber content mixtures, except 7.5% and 10.0% due to saturation.

4. Conclusions

1. From the oedometer tests it can be concluded that: a) the highest permeability values are associated with the highest rubber content used in the mixtures. Lower rubber content (up to 7.5%) slightly changes the K_v value. The observed behavior shows that rubber particles can create a preferential flow path, increasing the K_v value; b) the compression index, C_c, and the swelling index, C_s, decrease as the amount of rubber in the soil matrix increases; c) the oedometer modulus (E_{oed}) and the elastic modulus (E) decrease as the rubber content increases;
2. The results of the direct shear tests indicate that for the unsaturated condition there is a slight tendency for the cohesion to increase as the rubber content increases. For the saturated condition, an oscillation in the cohesion value was observed as the rubber content increase. The friction angle related to the unsaturated condition remains the same regardless of the amount rubber. The friction angle related to the saturated condition presents oscillations as the rubber content increases;
3. Based on this study, the rubber from shredded scrap tires can be used in applications such as: a) compacted embankments; b) soil walls reinforced with geosynthetics. The first application is highly useful in terms of sustainability because the construction of embankments involves a very amount of material. The use of the soil-rubber mixture is not recommended in clay liners for sanitary landfills, because the rubber produces an increase in soil permeability.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have reviewed and affirmed the content of the paper and there is no financial interest to report.

Authors' contributions

Mario Vicente Riccio Filho: supervision, validation, writing – review & editing. Lorena Gomes Abrantes: conceptualization, data curation, formal analysis, investigation, methodology, software, writing – original draft. Claudio Fernando Mahler: validation, writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

c'	Effective cohesion
c_k	Coefficient of variation of the permeability with void ratio
e	Void ratio
u_a	Pore air pressure
u_w	Pore water pressure
$(u_a - u_w)$	Matric suction
C	Total cohesion
C_c	Compression index
CIU	Consolidated, isotropic, and undrained triaxial test
C_s	Swelling index
E	Elastic modulus
E_{oed}	Oedometer modulus
K_o	Coefficient of earth pressure at rest
K_v	Coefficient of permeability
K_{vo}	Initial coefficient of permeability (first loading stage)
W_o	Optimum moisture content
γ	Unit weight
ε	Specific deformation
ν	Poisson's ratio
σ'_v	Vertical effective stress
ϕ'	Effective friction angle of the soil
tg ϕ^b	Relationship between shear stress and matric suction
Δe	Change in void ratio

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