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Tensile strength of compacted clays

La résistance à la traction d'argiles compactées

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ABSTRACT: Tensile strength of soils is often considered negligible for engineering applications, being small or equal to zero. Nevertheless its evaluation and comparison with other geotechnical parameters can be interesting. This paper presents split-tensile and double-punch tests results carried out on compacted cohesive samples. Relationships among tensile strength, degree of saturation, unconfined compression strength, water content, plasticity index of cohesive samples are shown.

RESUME: La résistence à la traction des sols n'est pas souvent prise en considération dans les application professionnelles, vu qu'elle est généralement nulle ou de valeur très modeste. Malgré ce la, son estimation et son analyse par rapport à d'autres paramètres géotechniques peuvent être intéressantes. Cet article présente toute une série de résultats expérimentaux que nous avons obtenus à travers des expériences du type brésiliennes et à travers le double-poinçonnage (double-punch) d'échantillons de terrain cohésif compacté et de plasticité variable. Ici nous chercons à illustrer les correlations existantes entree la résistance à la traction, le dégré de saturation, la résistance à la compression simple, l'humidité et l'indice de plasticité.

1. INTRODUCTION

Soil strength usually decreases with increasing water content, because bonds, holding the particles together in structural units, are weakened by increasing amount of adsorbed water. Strength is due to the bonds acting among clay particles, including van der Waals forces, surface attraction, organic matter and inorganic cements. The bonds strength is reduced by the softening of cements and by the increasing separation of particles, when water is adsorbed. Furthermore soil can be strengthened by a negative pore water pressure, while can be weakened by cracking as it dries.

Experimental evidences show that the effect of suction on intergranular stress and hence on the shear and tensile strength of soil can be considerable, but limited in dry soils by the onset of cracking. Snyder and Miller (1985) affirmed that the maximum tensile stress to be expected from the capillarity forces in unsaturated soil is about half of the suction. Mullins and Panayiotopoulos (1984), using mixtures of different plasticity, made by sand and kaolin, demonstrated that intergranular stress, induced by suction, was largely responsible for strength at suctions greater than 10 kPa and that strength increased with suction to a maximum at some suction greater than 100 kPa. The maximum tensile strength was 30 kPa for a mixture having 8% of kaolin.

Though tensile strength of soil is often considered negligible for engineering applications, being small or equal to zero, its evaluation can be interesting. In the present paper several laboratory test results, obtained by means of split-tensile and double-punch apparatuses are shown. Correlations among tensile strength of compacted cohesive samples and their degree of saturation, unconfined compression strength, water content and plasticity index are shown.

2. SPLIT-TENSILE TEST

The split-tensile or Brazilian test (BT) was developed in the 1950s for evaluating the tensile strength of concrete. Later the same test apparatus was used for rocks and cemented, or compacted, soils. The test is carried out on cylindrical samples (with height h and diameter d), loaded along two opposite generatrices by means of two parallel rigid platens. When a brittle sample is tested, failure is reached along the diametrical vertical plane, connecting the two loading strips.

Let us assume horizontal the X-axis, vertical the Y-axis and the loading plane, and denote with P the vertical testing load; the elasticity theory shows vertical stress σ_y (acting along X-axis) is always compressive, ranging from a maximum value (+6P/πhd) at the centre to zero at the circumference, while horizontal stress σ_x ranges from a tensile value of (-2P/πhd), at the centre, to zero at the circumference. Horizontal stress tensile σ_x (acting along Y-axis) shows a constant value of -2P/πhd, while vertical compressive stress σ_y ranges from +6P/πhd, at the centre, to ∞ at the circumference. These infinite value can be strongly reduced applying the test loads by means of two distribution strips (with width a).

If the test sample presents high compression strength, failure will be reached for exceeding the tensile strength at the middle part of the vertical loaded diameter. Tensile stress σ_t is equal to:

$$\sigma_t = \sigma_x = \left(\frac{1 - d \cdot (\alpha - \sin\alpha)}{2a}\right) \cdot \frac{2P}{\pi \cdot h \cdot d} \qquad (1)$$

For evaluating angle α see the Fig.1.

3. DOUBLE-PUNCH TEST

The Double-Punch test (DPT), developed at Lehigh University around 1970, is carried out on cylindrical samples; two rigid punches penetrate both the top and bottom surfaces of

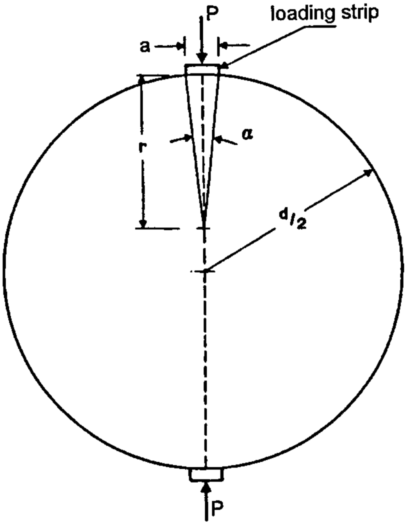

Figure 1: Schematic section of a sample loaded in a split-tensile apparatus.

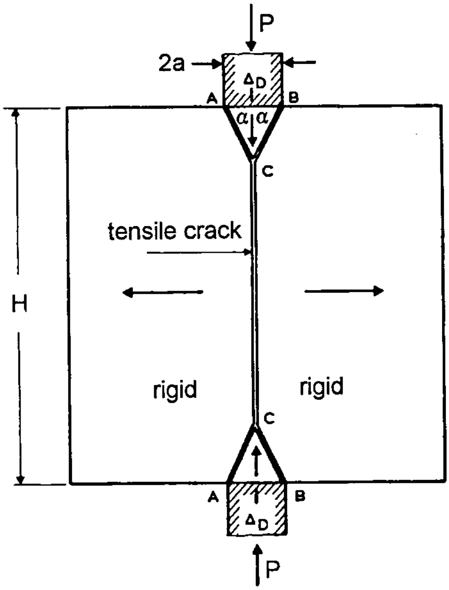

Figure 2: Schematic section of a sample loaded in a double-punch apparatus.

the sample, until tensile failure is reached along radial vertical planes (Fig.2). Theoretical approach is due to Chen and Drucker (1969), which applied the upper bound theorem of the limit analysis. Two fundamental assumptions were made:

1. sufficient local deformations in tension and compression must occur for application of limit analysis method to the investigated soils, idealised as perfectly plastic materials;
2. a modified Mohr-Coulomb failure surface in compression and a small but non-zero cut-off is postulated as a yield surface for the investigated soils (Fig.3).

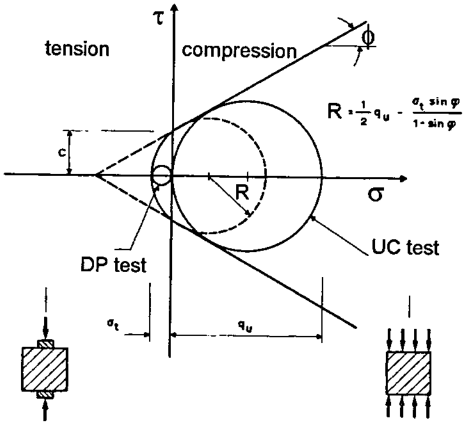

Figure 3: Modified Mohr-Coulomb failure criterion, considering tensile strength of soil.

Chen and Drucker proposed the following expression for tensile strength σ_t:

$$\sigma_t = \frac{P}{\pi \cdot (k \cdot rh - a^2)} \tag{2}$$

where a and r are the radius of punches and sample respectively, P is the vertical load, h the length of the sample and k is empirical value close to unit.

4. LABORATORY INVESTIGATION

Test samples were prepared in laboratory mixing two different soils: a medium plastic kaolin and a highly plastic bentonite. The main chemical compounds and the index properties of the natural soils and the testing mixtures are summarised in tables 1 and 2.

Table 1: chemical compounds of soils.

chemical compounds	**kaolin**	**bentonite**
	percentages	
SiO_2	54.50	51.50
Al_2O_3	43.25	25.20
Fe_2O_3	1.95	13.60
TiO	0.05	3.80
CaO	0.05	3.40
Na_2O	0.20	2.50

Table 2: Main index properties of the natural soils and the testing mixtures.

natural soils	**G**	**w_l (%)**	**I_p (%)**
kaolin (K)	2.63	61	23
bentonite (B)	2.89	449	362
testing mixtures			
(1) k100%	2.63	61	23
(2) k80%-b20	2.68	101	65
(3) k60%-b40%	2.73	186	137

Cylindrical samples, 103 mm wide and 115 mm high, were prepared by compaction according to Standard AASHTO procedure. Compaction curves are reported in Fig.4, while Optimum Water Content (OWC) and Maximum Dry Unit Weight (MDW) corresponding to each mixture are summarised in Tab. 3. MDW values decrease with increasing plasticity of soils, while the degree of saturation at MDW decreases with increasing plasticity of soil.

Table 3: Optimum Water Content and Maximum Dry Unit Weight of the mixtures

mixtures	**OWC (%)**	**MDW(kN/m^3)**
1	25.5	15.25
2	28.1	14.25
3	26.5	13.70

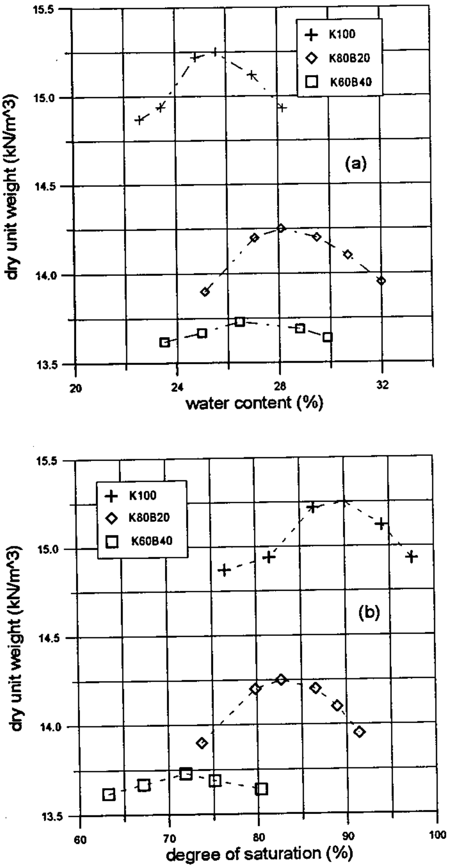

Figure 4: Standard AASHTO compaction curves of the investigated mixtures (a) water content vs. dry unit weight γ_d; (b) degree of saturation vs. γ_d.

After the determination of the Optimum Water Content (OWC) for each mixture Brazilian, Double-Punch and unconfined compression tests were performed on samples wetted and compacted at their corresponding OWC.

Fifteen Brazilian tests, thirteen Double-Punch tests and thirteen unconfined compression tests were carried out in undrained conditions, using a rate of vertical displacement of 0.5 mm/min.

Generally for reaching tension failure condition, wider displacements were necessary in DP tests rather than in Brazilian ones.

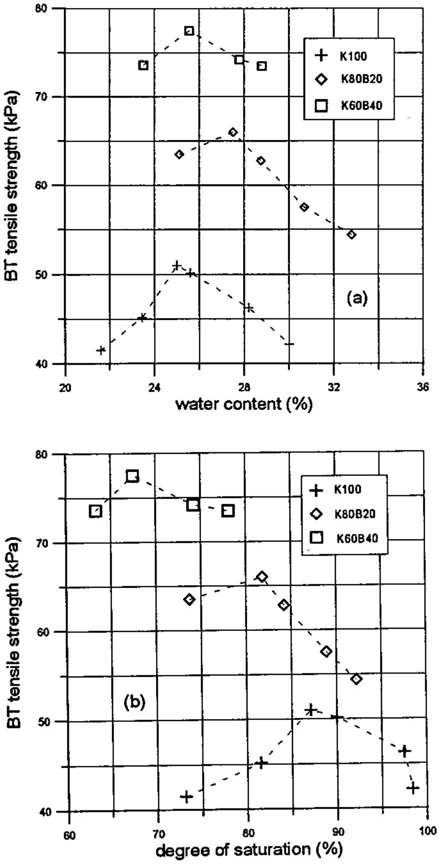

Figure 5: Split-Tensile tests: (a) tensile strength vs. water content; (b) tensile strength vs. degree of saturation.

Tensile strength and water content or degree of saturation are plotted, for both tests, in Fig.5 and 6. Maximum tensile strength always occurs as critical water content (CWC) and degree of saturation (CDS) have reached; CWC values always are a little bit lower than corresponding OWC. A sharp decrease of the tensile strength was noticed for water content higher than CWC. Maximum tensile strength increases with increasing soil plasticity.

An empirical coefficient k is within the tensile strength expression (2), proposed by Chen and Drucker; this coefficient is often assumed equal to 1. Comparing experimental results, derived from both laboratory procedures (DPT and BT), the best fitting

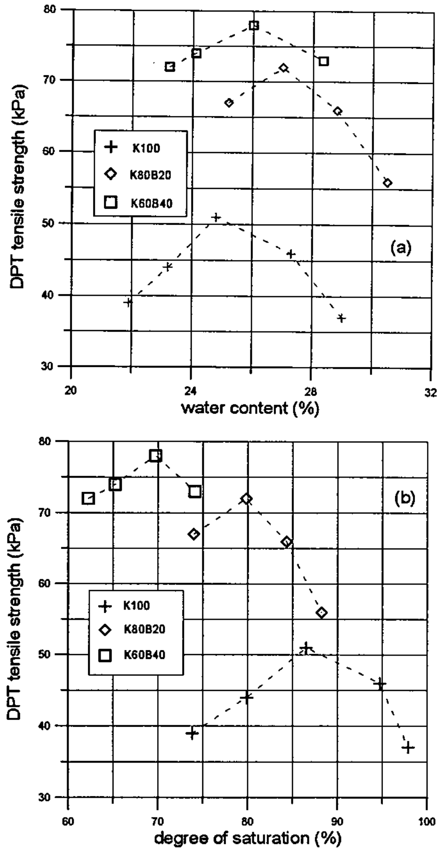

Figure 6: Double-Punch tests: (a) tensile strength vs. water content; (b) tensile strength vs. degree of saturation.

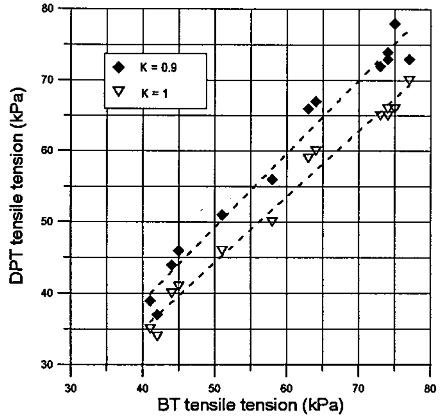

Figure 7: Correlation between tensile strength obtained from BT and DPT, varying empirical coefficient K.

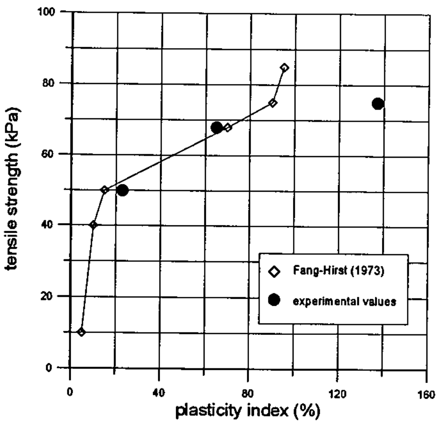

Figure 8: Tensile strength vs. plasticity index for samples compacted at OWC.

between two groups of data is obtained assuming k equal to 0.9 rather than to 1 (Fig.7). Tensile strength of the mixtures, compacted at corresponding OWC, is plotted vs. plasticity index in Fig. 8 and compared to the curve proposed by Fang and Hirst (1973). Tensile strength strongly increases for I_p ranging between 5 and 15%; beyond 20% tensile strength ranges from 50 to 75 kPa. Though the available experimental data are not so many, the trend seems to be similar to that proposed by Fang and Hirst, at least for I_p lower than 80%.

Unconfined compression strength σ_u is plotted vs. water content and degree of saturation in Fig. 9. σ_u increases for water content lower than OWC and then decreases. Maximum compression strengths σ_u of the mixtures are not so different, ranging from 410 to 430 kPa. Furthermore when the plasticity index is low, small variations of water content cause relevant effects on the compression strength σ_u.

Lastly ratio between unconfined compression strength σ_u and tensile strength σ_t are plotted vs. plasticity index. The ratio ranges between 5 and 12 and decreases as plasticity index increases, particularly for I_p lower than 20%. Experimental data are compared (Fig.10) to a curve proposed by Fang and Chen (1972) and a good fitting was observed.

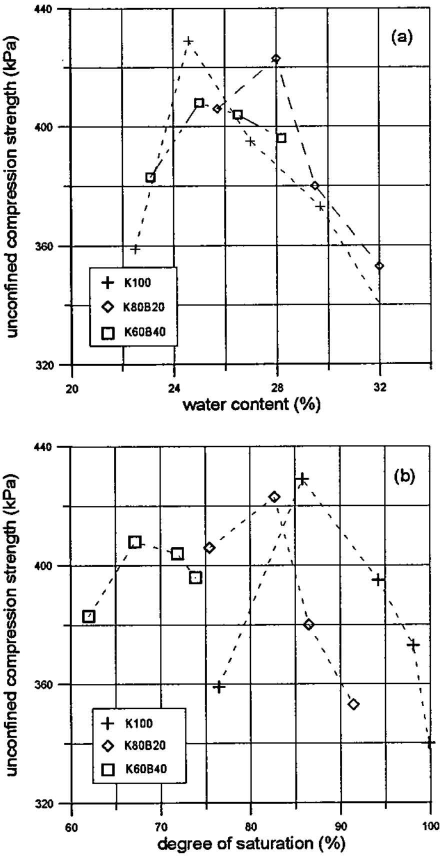

Figure 9: Unconfined compression tests: (a) compression strength vs. water content; (b) compression vs. degree of saturation.

5. CONCLUSION

Maximum tensile strength of cohesive compacted soils increases as their plasticity increases; furthermore tensile strength increases up to a critical water content (and a critical degree of saturation) always lower than OWC, and then decreases.

Tensile strengths determined with Brazilian and Double-Punch equipments are very similar if constant k of expression (2) is assumed equal to 0.9.

Compaction laboratory procedure allows to make test samples composing of three successive horizontal layers: this orientation, parallel to the load direction in Brazilian test and perpendicular in Double-Punch test, influences the failure mechanism and the deformation value at failure.

Lastly σ_u/σ_t (unconfined compression strength/tensile strength) ratio strongly depends on both clay fraction and water content. However water content becomes more relevant than clay fraction as soil plasticity increases.

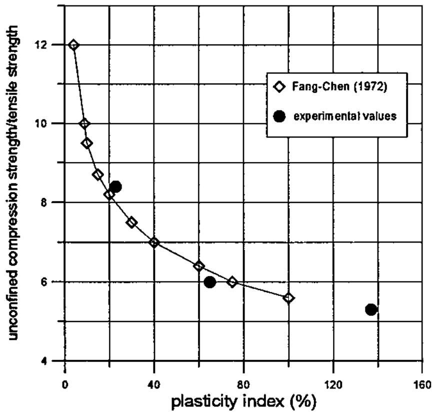

Figure 10: Unconfined compression strength/ tensile strength ratio vs. plasticity index for sample compacted at OWC.

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