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The combination of splitting tensile strength and unconfined compression tests on unsaturated soils to measure the evolution of unsaturated shear strength

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Abstract. The paper presents experimental results from unconfined compression and splitting tensile tests used in combination in order to estimate the cohesion intercept of unsaturated soils. Samples of different soils in the form of slurry were subjected to various suction values using the axis translation technique in a pressure plate extractor and then these samples were removed and subjected to unconfined compression and splitting tensile tests. Mohr' circles for the two loading conditions were drawn and the tangents plotted in order to obtain the cohesion intercept for each soil and each suction. Cohesion intercept was then plotted against suction for each soil and the angle of shear strength increase due to suction increase was estimated and compared to the value of the angle of shearing resistance of the fully saturated soil. The method allowed insight into the evolution of unsaturated soil shear strength of slurried fine-grained soils, and seems to be an interesting low-cost alternative compared to established controlled suction methods to estimate unsaturated shear strength, yet it is based on two assumptions: first that the failure envelope is linear in the range between zero vertical stress and the stress corresponding to unconfined compression loading, and second that the suction applied to the samples does not change significantly from the moment a sample is removed from the pressure plate extractor until it is subjected to loading. The former assumption seems a fair one given the range of stress involved; the latter was investigated by conducting an unconfined compression test with suction measurement during loading. This test indicated that the latter assumption is a fair one too. Furthermore, results of the angle of strength increase relative to suction φ_b were normalised by the angle of shearing resistance of each soil indicating that a reasonable relation for the evolution of φ_b seems valid.

1 Introduction

Unsaturated soils exhibit several differences in comparison to fully saturated soils. Their shear strength is usually higher, although for certain coarse-grained materials it can increase with increasing suction initially and then, as suction increases further, it can stabilise or even decrease. Their volume changes are similarly different and depend strongly on the combination of activity, density, stress level and suction level, resulting either in swelling or collapse strains upon changes of the degree of saturation. Finally, permeability exhibits strong differences manifesting themselves in different ways at different scales. Micropermeability, i.e. permeability controlled by voids' size at the interparticle level, decreases with increasing suction, but macropermeability, i.e. permeability controlled by voids formed at a scale considerably larger than the particle size scale, increases with increasing suction in high, and on occasion medium, plasticity clays, due to cracking.

The one different characteristic of unsaturated soils that has attracted more attention is shear strength. Volume changes of unsaturated soils can be very important but this importance is often topical, as topical is the occurrence of soils exhibiting significant volume changes due to changes in degree of saturation. Similarly, differences in the permeability of unsaturated soils also do not attract as much attention, probably following the smaller attention attracted by seepage in soils, and the even larger difficulty of contemplating the effect of partial saturation on permeability, even larger than the effect on shear strength and volume changes. The effect of partial saturation on the shear strength of unsaturated soils however benefits from commonly encountered occurrences and associated failures, like catastrophic landslides and landslips occasionally with fatalities, leading to awareness on the loss of shear strength on unsaturated soils upon inundation. Fig. 1 shows a commonly encountered sight, practically in all worksites and mines with dumps of materials. Dumps of coarse-grained materials of various grain-size distributions expected to stand at angles of repose coincident with their angle of shearing resistance at constant volume (given their low relative density and lack of compaction), often stand with local angles of repose extending this value by far, and on occasion stand even vertically for several meters of height and for considerable time. This manifestation of partial saturation reaches spectacular examples on occasion. Fig. 2 shows a World War II bunker standing on the dump of coarse-grained excavations from the original construction of the Corinth Canal in the 1880s. The

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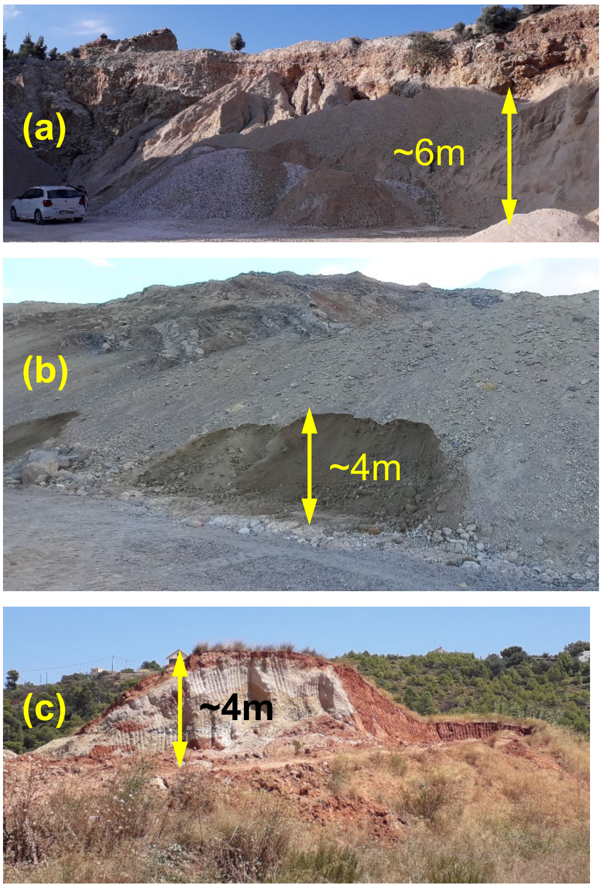

Fig. 1. Examples of very high angles of repose in dumps of soils: a) a dump of coarse-grained sand in a quarry in Rhodes, b) a cut at the foot of a dump of excavated sandy silt to silty sand in the site of the Corinth Canal remediation measures near Corinth, and c) a dump of coarse-grained materials from various excavations in east Attica. Slopes denoted with arrows showing their height are extremely steep to even vertical.

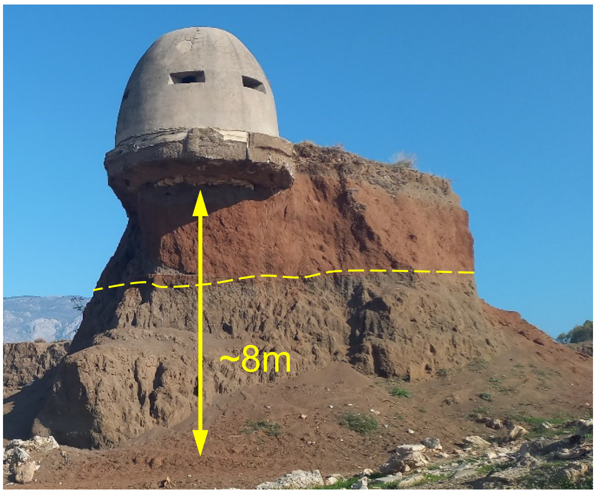

Fig. 2. World War II bunker standing on the dump of coarse-grained excavations from the original construction of the Corinth Canal in the 1880s.

Fig. 3. Bassales landslide in Skiros island, North Aegean Sea, Greece. A landslide activated by heavy, prolonged rainfall, leading to large deformation causing the characteristic translation and rotation of the house in the ellipse.

bunker was constructed before the erosion/landslip shown underneath its forefront side now standing in the air. Still, photographs indicate that it has been standing without failure in the condition shown in Fig. 2 for at least 20 years at the time of this publication. A similar bunker was lifted by crane in the same area and it weighed 146tons. The height of the sand dump is approximately 8m and the lower part (gray sand) is a fine- to medium-sand with only fractions of silt, and the upper (brown sand) is a silty fine- to medium-sand, on occasion exhibiting slight plasticity (but in most samples found non-plastic). This upper sandy formation stands below the bunker at even negative angles. Suction from the surface of both sandy formations in Fig. 2 was measured using a chilled-mirror hygrometer in the order of 50 MPa. Examples in Fig. 1 and 2 show the positive effect of suction on shear strength, which can be considerably long-lasting as in the case of the bunker in Fig. 2. Unfortunately, this increased shear strength often decreases, occasionally very rapidly, leading to catastrophic failures, often landslides, associated with heavy, prolonged failure. Fig. 3 shows an example from Greece, on the island of Skiros in North Aegean. An east-facing slope consisting of various clayey and silty formations, failed initially in 2004 after very heavy rainfall, with spectacularly large deformations as shown by the house that moved and even rotated without failure. The landslide remained at its place practically with minimum interventions after 2004, simply remediating a local road crossing the landslide, but was reactivated in 2019, again after heavy, prolonged rainfall which led to the design of heavy stabilisation measures currently being constructed. As part of the geotechnical investigation following the 2019 reactivation, a field station measuring suction and volumetric water content was installed. Measurements were made at three different depths, down to 1.70m, and showed for a period of measurements extending over more than three years values of suction as high as 200 kPa decreasing during wet periods to as low as 20 kPa, but not to zero over the particular monitoring period [1]. All three examples indicate the importance of partial saturation on the shear strength of unsaturated soils, making the need for its measurement and, if possible estimation, a stark need in geotechnical engineering practised especially in countries with the climatic conditions establishing suction values in the ground like those presented.

Given the importance of unsaturated soils' shear strength, test methods allowing its measurement that have been established for saturated soils, have also been extended for unsaturated soils. Yet this usually ends in methods that are quite expensive, time-consuming and presently quite limited in very few research centres and even fewer industry partners. On top of that, something often overlooked, is the need for very experienced and specialised personnel not necessarily available as easily and frequently as one may think. Attempts to use low-cost alternatives to estimate unsaturated soil shear strength parameters have already been presented [2]. The method already proposed combines the Mohr's circles obtained from unconfined compression and splitting tensile (brazilian) tests on samples of soils subjected to a suction value in a pressure extractor (or a controlled relative humidity chamber if one wishes to extend the range of applied suction values). The method makes two assumptions: first that suction does not change significantly during the loading tests, and second that the generalised Mohr-Coulomb failure criterion for unsaturated soils [3] is fairly linear for stress changes in the range of stress involved in unconfined compression and splitting tensile tests. The latter assumption is used to extrapolate the tangent to the two Mohr's circles backwards to the zero vertical stress axis in order to obtain an estimate of the cohesion intercept corresponding to the suction value applied to the samples prior to loading. This paper follows on discussion of both assumptions in previous work [2] and presents additional experimental data and their summary and normalisation leading to a possible method of estimation for the angle of shear strength increase relative to suction φ_b of the generalised Mohr-Coulomb failure criterion for unsaturated soils.

2 The soils tested

The soils tested included soil materials ranging from non-plastic sandy silts to high plasticity clays. Their soil properties are presented in Table 1. Index properties, soil-water characteristic curves and results from unconfined and indirect tensile strength tests for the first five soils mentioned have already been reported [2]. In this paper, similar data for three more materials are presented. As in [2], the combination of unconfined compression and indirect tensile strength test results is presented and the results are compared to the fully saturated shear strength parameters of the soils.

The index properties of the soils are summarised in Table 1. The Corinth Marls are a very well-studied formation [4] through which the Corinth Canal was excavated in late 19th century and extensive remediation measures for instabilities that closed the canal are currently constructed. Various experimental investigation programmes have been undertaken in order to investigate the properties of this material including the SWCC of the undisturbed marl and its recomposed counterpart [5], where recomposed is the material consolidated from a slurry condition to a desired value of void ratio (preferably that of the undisturbed soil) and then unloaded to zero stress. The Chalkoutsi Marl is a formation found 35km north of Athens. High, steep slopes are formed in the formation by sea erosion of their toe with occasional landslides occurring along the 5km coast that the formation outcrops in the highest slopes. The SWCC of the undisturbed material and its recomposed counterpart have already been reported [5]. Parnitha weathered siltstone is found in mount Parnitha 30km to the north of Athens close to the ground surface. Samples of Maroussi Clay came from boreholes drilled as part of a site investigation in the suburb of Maroussi in Athens close to the 2004 Olympic Games complex. Samples of Skiros weathered phyllite came from a low road-cut in the north part of the island of Skiros, Greece. The new soils tested, include Mazaraki clayey silt, Piraeus Marl and Armou bentonitic clay. Mazaraki clayey silt came from the area of a proposed dam at Mazaraki in the district of Ioannina. Piraeus Marl from the eroded material of stone blocks made out of this formation in Piraeus and used in the construction of the Ancient Walls of Acropolis, Athens. Armou bentonitic clay came from the Armou landslide in Paphos province of Cyprus. This is a high plasticity clay outcropping in many parts of the Paphos province in west Cyprus, with particularly low shear strength, often leading to many instabilities and major landslides in the area. The soils tested in the past [2] and the new soils tested make a wide range of fine-grained soils covering the whole range from non-plastic silts to high plasticity clays. Conclusions on their behaviour and experience from their testing should be limited to soil materials within the same range.

Table 1. Index properties of the soils tested.

Soil	Clay (%)	Silt (%)	w_L (%)	I_P	φ'	US CS
Corinth Marl (CM)	6.5	84.7	30.5	5.5	27.5	ML
Chalkoutsi Marl (ChM)	20.5	64.2	51	30	25.0	CH
Parnitha weathered siltstone (PWS)	27.5	47.1	33	17	24.7	CL
Maroussi clay (MC)	40.1	41.9	47	28	19.2	CL
Skiros weathered phyllite (SWP)	1.3	71.6	N.P.		35.3	ML
Mazaraki clayey silt (CL)	26	63	34	18	22.1	CL
Piraeus Marl (PM)	4.5	58.2	28.5	7.5	31.1	CL
Armou bentonitic clay (ABC)	54	42	143	108	20.3	CH

3 Experimental method

The axis translation technique as applied in a Soilmoisture Equipment Corp. pressure extractor with 1500 kPa air-entry value porous ceramic disks was used for matric suction control. Tests were performed on samples prepared in the form of slurry. All slurries were prepared at an initial water content of 1.5 × w_L using deaired, deionised water, left for hydration for two days in a humidity chamber with occasional stirring in order to avoid sedimentation of coarser particles in the slurry and then placed for at least half an hour under vacuum for removal of air. Samples were placed in lubricated plastic tubes taped on the porous stone of the pressure extractor. Given that samples were slurries in their initial condition, volume decrease during their drying was large. Careful lubrication of the inner surfaces of the tubes was critical so as to avoid cracking of the samples during shrinkage as any inhibition of the diameter decrease by adhesion to the inner surface of the tubes would result in cracking.

Regarding shear strength, direct shear tests were performed on all soils tested, with the samples in the form of slurries with an initial water content of 1.5 × w_L. Angles of shearing resistance measured are summarised in Table 1. The larger the plasticity of the soils (the smaller therefore the angle of shearing resistance), the larger was the scatter of experimental points as slurries were becoming progressively more and more difficult to handle, despite the w_o/w_L ratio being the same for all soils. This often resulted in quantity of the material flowing out of the gap between the top cap and the cell, creating problems summing up to the larger scatter observed for higher plasticity soils. The measurement of the angle of shearing resistance of the fully saturated soils was considered essential in order to interpret the unconfined compression and splitting tensile tests on the samples subjected to various values of suction. As shown in Fig. 1, Mohr's circles from these two types of tests were plotted for each suction and the tangent to the circles was drawn in order to obtain the cohesion intercept corresponding to the applied suction on the assumption that the shear strength envelope is linear. Mohr's circles for splitting tensile strength tests were plotted using established calculations for minimum and maximum stress during this type of loading condition [6]. The same tangent may be used to obtain the angle of shearing resistance; still as the two loading conditions (unconfined compression and splitting tensile loading) correspond to very low stress, these values were expected to be practically the same or higher and were not used (it was only checked for each soil that they are practically the same or higher than those in Table 1).

In previous research the assumption that suction changes insignificantly from the end of drying until the unconfined compression test is performed, has been proven a valid one, as in the coarsest of the soils tested, the difference in suction was only 3-4% [2]. For the other soils that were more fine-grained and plastic (let alone splitting tensile tests which are quicker) this difference is anticipated to be even smaller.

4 Unconfined compression and splitting tensile tests and their combination

For all samples tested at each value of suction, Mohr's circles were plotted as shown in Fig. 4 (for samples of Mazaraki clayey silt under 300 and 600 kPa of suction) and the cohesion intercept was determined. This was then plotted vs suction for each soil along with the line corresponding to the angle of shearing resistance of the same soil reconstituted and fully saturated (φ'_{rec}). These plots are presented in Figures 5a through 5c for Mazaraki clayey silt, Piraeus Marl and Armou bentonitic clay. These plots were used in accordance with the Mohr-Coulomb failure criterion for unsaturated soils [3] presented in Eq. 1, where (σ-u_a) is the total stress minus the pressure in the air phase, s is suction, c is the cohesion intercept of the fully saturated soil, φ is the angle of shearing resistance and φ_b is an angle, the tangent of which expresses the increase of shear strength τ with suction s for constant vertical stress.

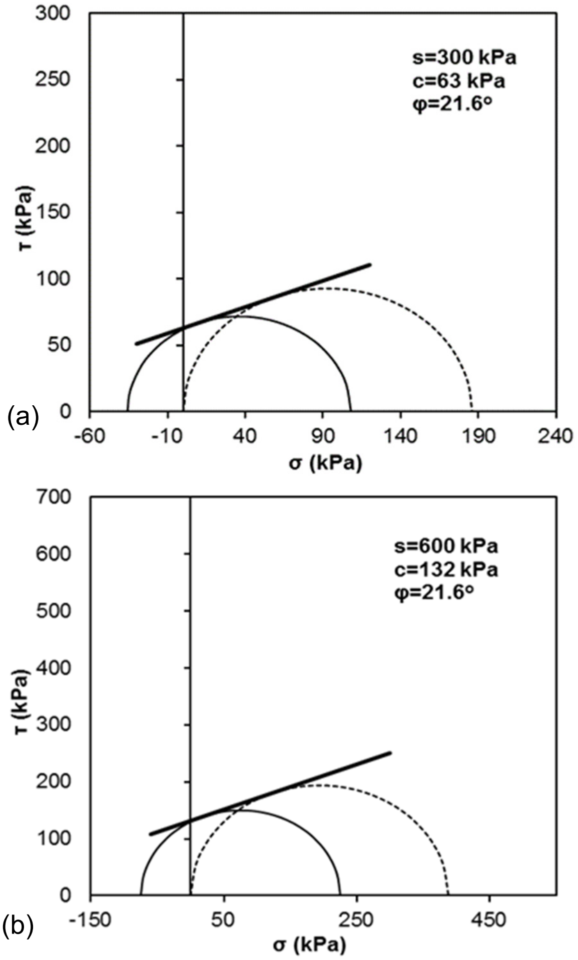

Fig. 4. Mohr's circles from unconfined compression and splitting tensile strength tests on samples of Mazaraki clayey silt under 300 kPa (a) and 600 kPa (b) values of suction.

$$\tau = c + (\sigma - u_a)\cdot \tan\varphi + s\cdot \tan\varphi_b \qquad (1)$$

Eq. 1 as originally proposed [3] concerns the full range of suction from 0 to maximum. An approach better related to the soil-water characteristic curve and the validity of the principle of effective stress for suction values up to the air-entry pressure is the addition that φ_b equals φ for s smaller than the air-entry pressure, and φ_b as measured from tests like the ones described in this paper (and other suction controlled shear strength tests) for s larger than or equal to the air-entry pressure. Given this clarification, measured angles are presented in

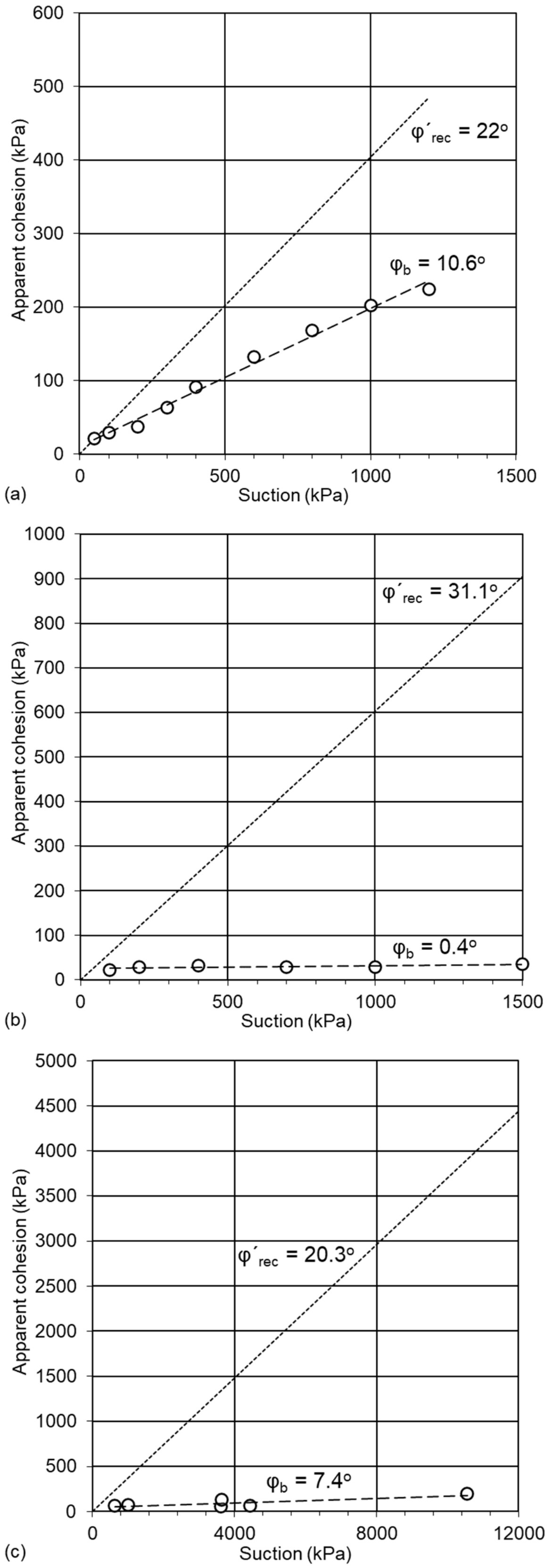

Fig. 5. Apparent cohesion vs suction values for a) Mazaraki clayey silt, b) Piraeus Marl, and c) Armou bentonitic clay.

Table 2. Values of angle of shear strength increase with suction φ_b for suction values larger than the air entry pressure vs angle of shearing resistance measured on the same soil when reconstituted in a slurry form.

Soil	USCS	φ'	φ_b
Corinth Marl (CM)	ML	27.5	2.9
Chalkoutsi Marl (ChM)	CH	25.0	5.0
Parnitha weath. siltstone (PWS)	CL	24.7	4.8
Maroussi clay (MC)	CL	19.2	11.2
Skiros weath. phyllite (SWP)	ML	35.3	0.0
Mazaraki clayey silt (CL)	CL	22.1	10.6
Piraeus Marl (PM)	CL	31.1	0.4
Armou bentonitic clay (ABC)	CH	20.3	7.4

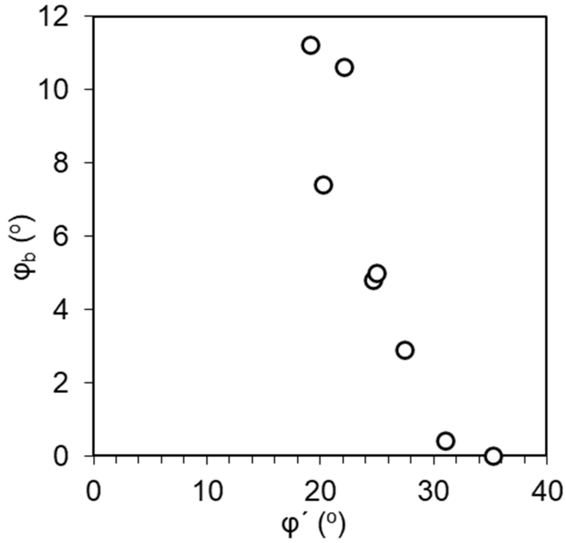

Fig. 6. Angle of shear strength increase with suction φ_b for suction values larger than the air entry pressure vs angle of shearing resistance measured on the same soil when reconstituted in a slurry form.

Table 2 and φ_b is plotted against φ'_{rec} in Fig. 6. A tendency for φ_b decrease with increasing φ'_{rec} is identified in Fig. 5. In search for a better correlation, tan φ_b was normalized by dividing with tan φ'_{rec} and their ratio is plotted against tan φ'_{rec} in Fig. 7. A best-fit linear relation was identified and described by Eq. 2. By multiplying both sides of Eq. 2 with tan φ', Eq. 3 is obtained which provides a means to estimate the angle of shear strength increase with suction φ_b of a reconstituted fine-grained soil with plasticity from the angle of shearing resistance of the same soil fully saturated and in the form of a slurry. This estimation is based on data from very few soils, tested only in the form of a slurry and should not be extended to other types of soils and soil conditions before further validation and additional experimental data become available. For this reason, factors used in Eq. 2 & 3 have only one decimal as higher accuracy is not considered relevant at this point of this research. Still, in its original form (Eq. 2), the relation has a strong degree of correlation (R^2=0.9) and satisfies basic trends expected:

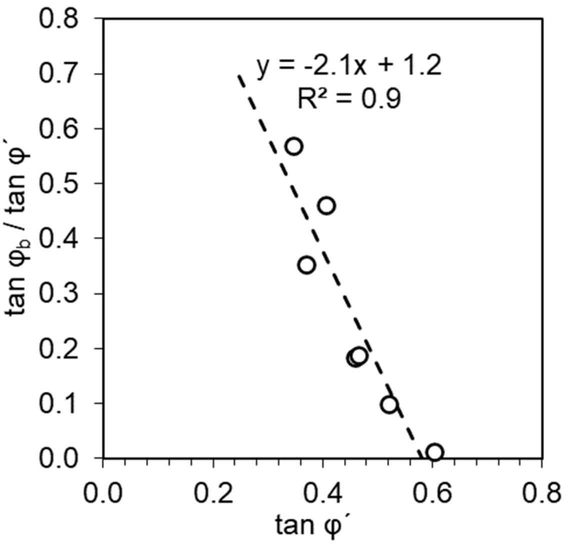

Fig. 7. Tangent of the angle of shear strength increase with suction φ_b for suction values larger than the air entry pressure divided by the tangent of the angle of shearing resistance vs the tangent of the angle of shearing resistance measured on the same soil when reconstituted in a slurry form.

$$\tan \varphi_b / \tan \varphi' = 1.2 - 2.1 \times \tan \varphi' \qquad (2)$$

$$\tan \varphi_b = 1.2 \times \tan \varphi' - 2.1 \times \tan^2 \varphi' \qquad (3)$$

decrease of the angle of shear strength increase with suction with increasing angle of shearing resistance of the fully saturated soil, i.e. decrease with decreasing plasticity, and fair limits; φ_b 0 corresponding to approximately φ' of 30° and $\varphi_b = \varphi'$ at approximately $\varphi' = 6°$. If such a value of φ' exists, it would correspond to a clayey soil, of so high plasticity, that no air-entry pressure would be measurable and φ_b would have to be equal to φ'. Apparently this equation needs further validation and reevaluation with additional experimental data. A general note, is that φ' is considered generally in equations herein the angle of shearing resistance of the fully saturated soil, in the particular case of the tests performed being the φ'_{rec} of the reconstituted soil in a slurry form.

5 Conclusions

Unconfined compression and splitting tensile strength tests on samples of fine-grained soils in the form of slurry subjected to various values of suction were combined in order to obtain the cohesion intercept of these soils for various values of suction. This method yielded values of the angle of shear strength increase with suction φ_b which were related with the angle of shearing resistance of the same soils, fully saturated, in the form of slurry. The tests performed show that depending on the plasticity of each of the fine-grained soils tested, the development of suction may not affect the development of shear strength. Tangent of φ_b was normalized by dividing with the tangent of φ'_{rec} and this ratio showed a strong linear relation with the tangent of φ'_{rec} allowing for Eq. 2 to be obtained. When rearranged by multiplying both sides with the tangent of φ'_{rec}, an equation allowing the estimation of the angle of shear strength increase with suction φ_b of a reconstituted fine-grained soil with plasticity from the angle of shearing resistance of the same soil fully saturated and in the form of a slurry. This estimation is based on data from very few soils, tested only in the form of a slurry and should not be extended to other types of soils and soil conditions before further validation and additional experimental data become available. Still, it provides a fair estimation of the angle φ_b satisfying basic expectations for its evolution with plasticity of fine-grained soils and their corresponding angle of shearing resistance.

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7 References

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