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Tensile strength of sand, palygorskite and calcium carbonate mixtures and interpretation with the effective stress theory

M.R. Mosaddeghi [a,*], M.A. Hajabbasi [b], H. Khademi [b]

[a] Department of Soil Science, College of Agriculture, Bu-Ali Sina University, Hamadan 65174, Iran
[b] Department of Soil Science, College of Agriculture, Isfahan University of Technology, Isfahan 84156, Iran

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Abstract

Many soils in arid regions of the world including those of central Iran contain palygorskite and carbonates in their mineral fraction. There is, however, little information on the effects of these minerals on soil physical and mechanical behaviour. A laboratory experiment was carried out to evaluate tensile strength of artificial mixtures of sand–palygorskite–calcium carbonate ($CaCO_3$). Palygorskite and calcium carbonate were mixed with sand (1–0.05 mm) in proportions of 0, 5%, 10%, and 20% w/w for palygorskite and 0 and 30% w/w for $CaCO_3$. Tensile strength (ITS) of the mixtures was determined using the indirect (Brazilian) method. The ITS was measured at the matric suctions ($-\psi_m$) of 30, 100, 300, 500 and 1000 kPa. Tensile strength of the similar mixtures was also determined at air-dry condition. Effective stress (σ') generated by matric suction was calculated as $-\chi\psi_m$ where χ was assumed to be equal to the degree of saturation. The maximum value of ITS obtained at a matric suction depending on the amount of palygorskite and/or carbonate (fine particles) in the samples. The higher amount of the palygorskite or $CaCO_3$ in the mixtures pushed this point toward the higher matric suctions. For the all mixtures, ITS had a second order polynomial relationship with the matric suction meaning that ITS was maximum at an intermediate matric suction, and ITS declined at the lower or higher values. As matric suction increased, the fine particles could be pulled by water menisci to the points of contact between the larger (sand) particles. Subsequent shrinkage of the mixtures brought about mineral particles to be bonded together by capillary forces through the effective stress, which resulted in the higher strength. In addition, dissolution of carbonates upon saturation and subsequent precipitation during drying might be expected. The effect of 5% palygorskite on ITS was approximately similar to that of 30% $CaCO_3$. This might be due to the fibrous structure and the higher surface area of palygorskite as compared to $CaCO_3$. The fibrous units could act as binding bridges around and between the sand particles. The significant linear relation between ITS and σ' ($-\chi\psi_m$) showed that internal stresses through the effective stress acting on particles are important forces affecting the strength or compaction of palygorskite and/or carbonates-containing soils.

Keywords: Indirect tensile strength; Palygorskite; Calcium carbonate; Effective stress; Compaction; Central Iran

1. Introduction

In central parts of Iran (aridic regions), we are dealing with structurally unstable soils that are intensively and conventionally tilled. These soils are very low in organic matter and have unique behaviour concerning soil compaction and tillage systems (Hem-

* Corresponding author. Tel.: +98 811 4223367; fax: +98 811 4227012.
E-mail address: mosaddeghi@basu.ac.ir (M.R. Mosaddeghi).

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mat, 1998; Hajabbasi and Hemmat, 2000; Mosaddeghi et al., 2000; Shirani et al., 2002). They are top-crusted (Eghbal et al., 1996) and behave similarly to slaking, crusting and hardsetting soils (Mosaddeghi et al., 2003), and contain large amounts of palygorskite in their mineral fraction. Other major clay minerals in the region are mica/illite, smectites, and kaolinite. Carbonates and sulfates also include a considerable amount of the mineral fraction in the soils of the region (Khademi and Mermut, 1998, 1999).

Palygorskite is a so-called "special clay," characterized by microfibrous morphology and a relatively low surface charge (Singer, 1989). Neaman and Singer (2000) investigated the rheology and thixotrophy behaviours of suspensions of different palygorskites as a function of chemical properties such as adsorbed ions, pH and electrolyte concentration. They concluded that the models developed to explain the rheological behaviour of "platy" clay minerals do not always account for the behaviour of palygorskite, because of differences in particle morphology and surface structure.

Although heavy and intensive traffic, improper tool and wetting conditions, and low soil structural stability are reported to be responsible for the soil compaction and hardening in the dry regions (Mosaddeghi et al., 2000; Mullins, 1997, 2000), natural hardening of soil (hardsetting) is an important process occurring in the arid soils. Hardsetting of a cultivated soil usually involves slumping, a compacting process that occurs without applying an external stress (Northcote et al., 1975). This phenomenon is sometimes confused with compaction, which is caused by the external stresses, whereas the forces causing hardsetting are generated within the soil (Mullins et al., 1987, 1990; Ghezzehei and Or, 2000). This process is called self-compactive behaviour by Indian scientists (cited in Mullins, 2000). Young et al. (1988) showed that bulk density as high as 1.7 Mg m^{-3} is attained a few months after plowing in the plowed layer of a hardsetting soil. This provides a clear demonstration that external loading is not always the cause of high bulk density in the topsoil. Bresson and Moran (2003) reported that slumping of hardsetting seedbeds upon wetting is likely to determine the shrinkage, increase in packing state and development of strength upon drying. Reducing the wheeling area on such soils, without changing management systems may have little influence on the compaction problem.

Hardsetting behaviour often occurs in soils with low organic matter and dominant non-swelling clay minerals (e.g. kaolinite, mica and illite) and in the range of loamy sand to clay loam textural classes (Mullins et al., 1987, 1990). The role of clay minerals is not well known because of their diverse effects on the strength of different soils. Mullins and Panayiotopoulos (1984) indicated that kaolinite has an important effect on the strength of sand–kaolin mixtures and hardsetting soils. They were able to explain strength changes upon drying by the effective stress theory. Singer et al. (1992) attributed variation of soil aggregate stability in response to wetting and drying cycles to different clay–clay and clay–sand interactions caused by inherent structural differences among the clays. They concluded that depending on the type of the clay, stability of the aggregates might decrease or increase with the number of drying and wetting cycles. Chartres et al. (1990) showed that poorly ordered silica and aluminosilicates could act as temporary cementing agents in the hardsetting soils. Clay minerals are important not only to the hardsetting behaviour of soils but also to soil erosion. Bradford and Blanchar (1999) reported that erodibility of Ca–montmorillonite–sand mixtures was 4 to 40 times lower than that of Ca–illite–sand and Ca–kaolinite–sand mixtures.

The hardsetting behaviour is closely related to the irrigation techniques because the hydric stresses due to matric suction are important in this regard (Keller, 1970; Ghavami et al., 1974; Kemper et al., 1975). Tension wetting as an irrigation technique is recommended on the hardsetting soils (Mullins et al., 1990). For proper irrigation practices, the physical behaviour of the wetted soils is of paramount importance. Nearly all palygorskite-containing soils are found in the dry areas, where irrigation is indispensable for profitable agriculture. There is however, almost no information on the effect of fibrous clay minerals (appologites) on the hardsetting behaviour of the soils. These effects might vary with water content or matric potential and may be modified by soil amendments, such as calcium carbonates. Calcium carbonate is usually recommended as a soil amendment to increase aggregation and physical quality of soils. In central regions of Iran, the amount of calcium carbonates of the soils is very high (often 30–50% w/w or more). It is however, questionable if this high amount of carbonate promotes aggregation and provides better soil physical condition or takes part in the hardsetting behaviour.

The effect of common clay minerals, such as smectite, kaolinite and illite, on the properties of soil has been studied extensively (e.g. Dixon and Weed, 1989). However, with regard to the palygorskite, little information of this nature is available. This constitutes a serious impediment for the proper management of palygorskite-containing soils. The hypothesis in this research is that internal stresses are the main causes of soil hardening in the region and the dominant minerals might have decisive effects in this regard. The objectives of the study were: (1) to measure the tensile strength of artificial mixtures of sand, palygorskite and calcium carbonate at different matric suctions, and (2) to interpret this phenomenon using the concept of effective stress theory.

2. Materials and methods

2.1. Preparation of samples

Sand used in the experiment was collected from sand dunes and gravel excavation site at Segzi area located in east of Isfahan, central Iran. The sand (that was dominantly quartz) was dry sieved to separate the large particles and gravel, and then repeatedly washed with distilled water before air-drying. Particle size ranging from 1 to 0.05 mm was then separated by dry sieving. The percentages of the particles of the sand were 2.8%, 52.7%, 18.1% and 26.4% w/w for 0.05–0.1, 0.1–0.25, 0.25–0.5 and 0.5–1 mm size ranges, respectively.

Reference palygorskite from Gadsden County, Florida, provided and coded by the Clay Mineral Society (CMS) as PF1-1, was used. Its chemical formula is $(Mg,Al)_2(OH)(Si_4O_{10})\cdot 4H_2O$ in fibrous looking masses and light brown to pure white color with particle density of 2.2 Mg m^{-3}. Calcium carbonate as pure $CaCO_3$ from Merck was also used in the experiment.

Sand, palygorskite and $CaCO_3$ were mixed in different proportions. The percentages of the palygorskite in the mixtures were set at 0%, 5%, 10% and 20% w/w. Calcium carbonate was added of 0 and 30% w/w. Selected proportions (especially the highest values) of the minerals were more or less close to their actual fractions in the soils of central Iran. Seven treatments in three replicates consisted of palygorskite and $CaCO_3$ (as percentage) were prepared as: (0,30), (5,0), (5,30), (10,0), (10,30), (20,0) and (20,30). The mixtures were thoroughly mixed and carefully poured into steel cylinders with the diameter and height of 5 and 2 cm, respectively. We did our best to achieve a uniform bulk density (BD) of 1.2 Mg m^{-3} among the treatments. However, as the minerals, especially palygorskite, had a low BD due to its fluffy structure, a lower BD was achieved for the treatments containing high amounts of this mineral. Fine pieces of cloth were tightened under the cylinders by rubber before filling them with the mixtures. The cylinders had smooth internal walls and were lubricated by oil before filling to minimize the friction between the mixtures and the cylinder wall. Their walls had been cut vertically to facilitate separating the "undisturbed" cores before the strength's measurements. Prepared cores were saturated by distilled water from bottom (to prevent air entrapment) for 2 days and weighed. The saturated cores were then placed in a pressure plate extractor for adjusting the matric potential (ψ_m) to the values of −30, −100, −300, −500 and −1000 kPa. The equilibration time varied between 2 and 7 days depending on the matric potential. Equilibrium was assumed to be achieved when no further water exited from the outlet.

With another set of the samples, the moulds were removed when the samples were sufficiently stiff to hold their own shape and were allowed to air dry before the strength testing. Air-dry samples were also prepared after saturation and air drying in the lab. Total number of the prepared samples were 126 ($7\times6\times3$). After equilibrium, the cylinders were weighed; the cores were carefully separated from the cylinders and immediately loaded for strength measurements. After strength measurements, the cylinders were oven-dried for 48 h at 105 °C to calculate gravimetric and volumetric water contents and BD.

2.2. Strength measurements

Tensile strength is probably the most useful measurement of seedbed strength and a sensitive indicator of soil condition (Dexter and Kroesbergen, 1985). It has been used in soil friability and tillability studies (Snyder and Miller, 1985; Dexter and Watts, 2000) and to characterise the hardsetting behaviour (Young and Mullins, 1991; Young et al., 1988; Mullins et al., 1992a,b; Mullins, 1997, 2000). Tensile strength was measured on the prepared samples.

A compression test machine (ELE) was used for measurements at 1.5 mm min^{-1} deformation rate and 0.2 mm increments. The accuracy of the displacement gauge was 0.01 mm. The tensile strength was determined by applying load along the cores between two flat parallel plates according to the indirect Brazilian test described by Dexter and Kroesbergen (1985) and Dexter and Watts (2000). Failure occurred when fracture was observed at both ends of the soil core. The failure was easily determined by placing a mirror behind the sample as suggested by Young and Mullins (1991) while loading was applied. The indirect tensile strength (ITS) was calculated from an equation proposed by Frydman (1964):

$$\mathrm{ITS} = \frac{2Fg(x)}{\pi dl} \tag{1}$$

where F is the polar force required to fracture the core and d and l are the sample diameter and length, respectively measured by a calliper. The flattening coefficient, $g(x)$, was defined as suggested by Frydman (1964):

$$g(x) = \left(\frac{-d}{2a}\right)\left\{2x - \sin 2x - \left(\frac{2y}{d}\right)\ln\tan\left\{\frac{\pi}{4} + \frac{x}{2}\right\}\right\} \quad (2)$$

where x is flattening ratio such that $x = a/y$, and a is the width of the flattened portion and y is the distance between the flattened portions at failure measured by a calliper. Frydman (1964) suggested that Eq. (2) may be used as long as $g(x)$ is greater than 0.9.

2.3. Calculation of effective stress generated by matric suction

Terzaghi (1943) effective stress theory was first developed for saturated soils. In unsaturated soil and artificial mixtures and in cases where the externally applied stresses are absent as in the present study, the water bridges between particles pull them toward each other as a result of two phenomena: the negative pore-water (hydrostatic) pressure in the bridges and surface tension of the water forming the bridges (Fredlund and Rahardjo, 1993).

A relatively simple but still useful theory is that of Towner and Childs (1972). When the degree of saturation (S) is higher than 0.3, the hydrostatic pressure term dominates and the surface tension term can be ignored. When the soil is drier (i.e. $S<0.3$), then the surface tension term dominates and the hydrostatic pressure term may be ignored. Since S was >0.3 for almost all the samples in this study, only the matric potential component ($-\chi\psi_m$) was used as the effective stress (σ') where χ was assumed to be equal to the degree of saturation (S) and ψ_m represents the matric potential. Degree of saturation (S) was calculated by dividing the volumetric water content by the porosity of the mixtures. It was assumed that the non-effective residual water content is negligible for the mixtures. Validity of the assumptions has been justified for granular material (Towner and Childs, 1972), sand–kaolin mixtures (Mullins and Panayiotopoulos, 1984) and structurally unstable soils (Mullins, 2000). Mullins and Panayiotopoulos (1984) proposed that the tensile strength could be given as:

$$\mathrm{ITS} = c - \chi\psi_m \quad (3)$$

where c is the cohesion due to chemical bonds between the particles. Snyder and Miller (1985) proposed a pore shape factor, $f(S)$, to be added to the equation to account for stress concentration around the soil pores, giving:

$$\mathrm{ITS} = c - \frac{\chi\psi_m}{f(S)} \quad (4)$$

$f(S)$ depends on the pores' shape having a value of 2 for spherical pores which means the contribution of effective stress is effectively halved. Its value becomes progressively greater for more elongated pores. The regression analysis was performed on the data to fit Eq. (4) by SPSS. The data were examined for the approximate values of $f(S)$ which would be required for the different mixtures and matric suctions. It was assumed that the contribution of c to ITS is negligible in this case.

3. Results and discussion

3.1. Water characteristic curve of the mixtures

The water characteristic curve (WCC) is a fundamental property used in the soil physics studies. The shape of the WCC was used to interpret the effect of matric suction on the soil strength development upon drying (Aluko and Koolen, 2000). Water characteristic curves of the sand–minerals mixtures are shown in Fig. 1. With an increasing fraction of the fine particles, the WCC was shifted toward the higher water contents. This might be due to adsorption of water by the palygorskite and $CaCO_3$ and/or due to the creation of micropores in the mixtures.

The slope of the WCC was increased (became steeper) with an increase in the fraction of the fine particles. The high slope and water content at a constant matric suction implies the higher effective stress generated by matric suction ($-\chi\psi_m$) because of increasing chi-factor (χ). So the increase in the effective stress would develop a high strength upon drying. The effect of the palygorskite on the shape and slope of the WCC of the mixtures was greater than that of $CaCO_3$. The higher influence of the palygorskite on the WCC might be due to its greater surface area and activity.

3.2. Tensile strength variation upon drying

Due to high flattening of the wet samples during loading in the indirect Brazilian test, in some cases, $g(x)$ was smaller than 0.9. However, having no alternative, Eq. (1) was used for calculating ITS. Tensile strength characteristic curves (ITS vs. water content) of the mixtures are shown in Fig. 2. Strength generally

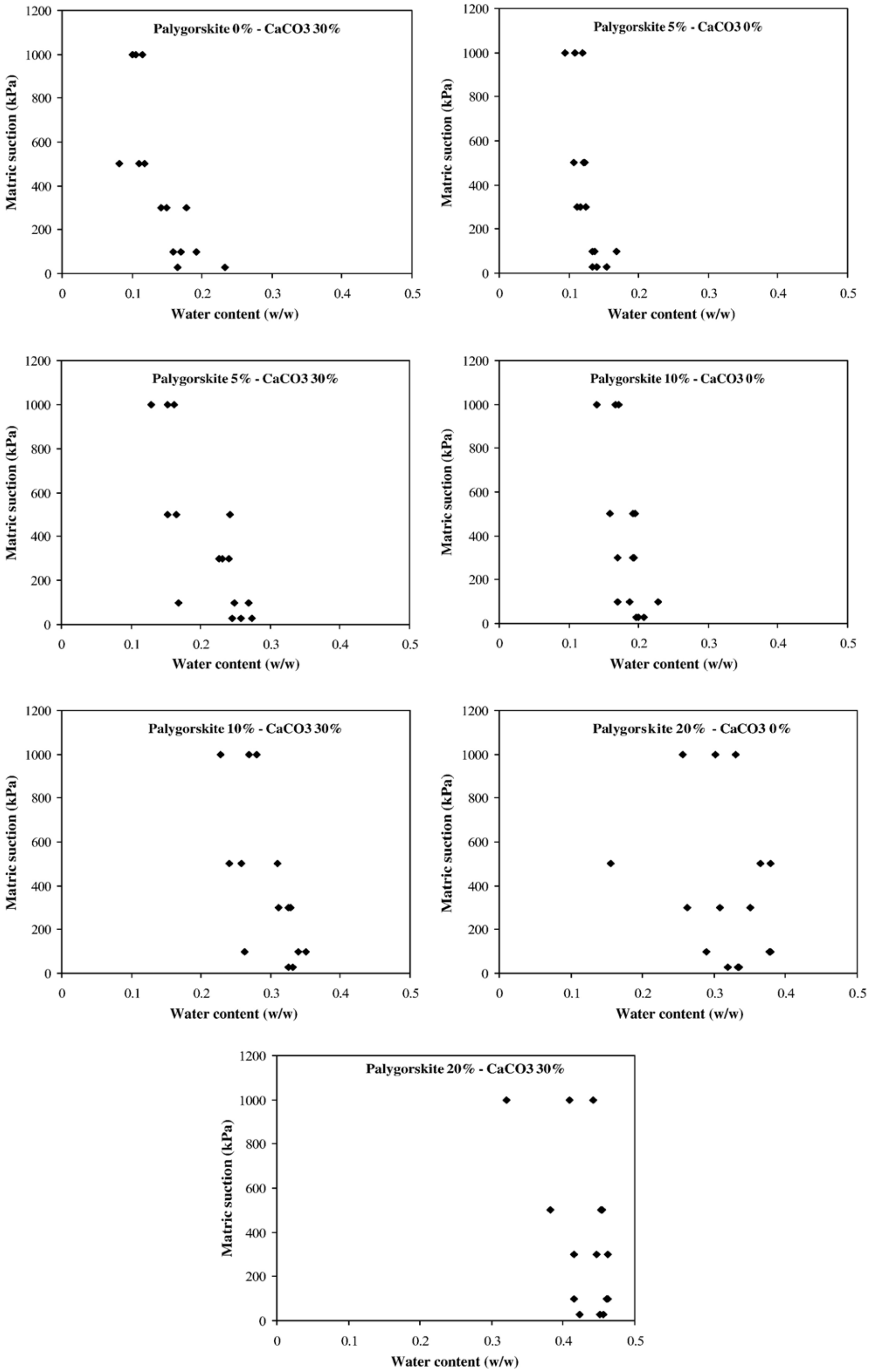

Fig. 1. Water characteristic curves (WCC) of the palygorskite–$CaCO_3$–sand mixtures.

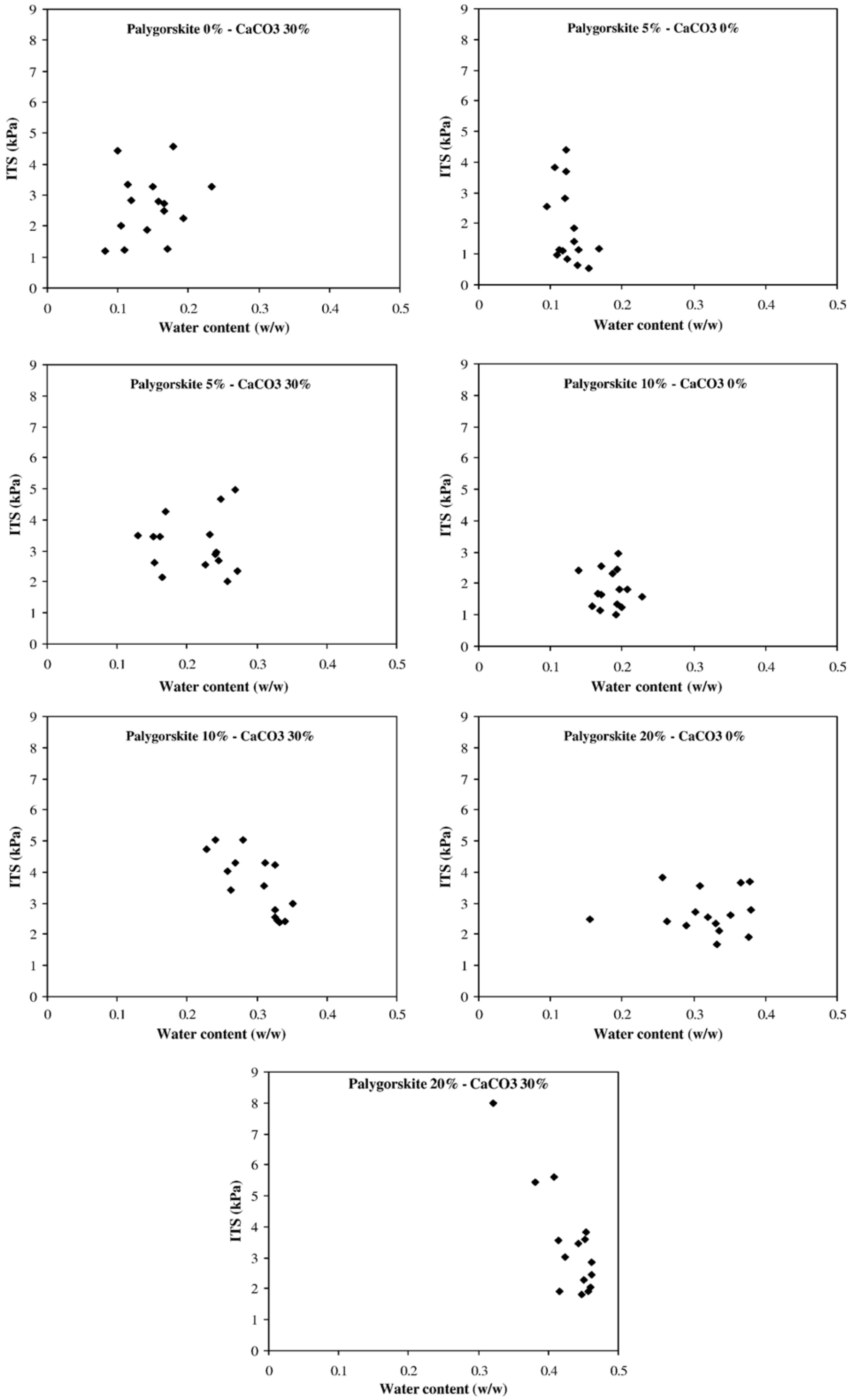

Fig. 2. Tensile strength characteristic curves (ITS vs. water content) for the palygorskite–$CaCO_3$–sand mixtures.

increased with a decrease of water content especially when the amount of the fine particles in the mixtures increased. This is due to the inter-particle forces generated by the internal stresses (i.e. matric suction).

Further decrease of the water content caused decreasing the strength of the mixtures (Fig. 2). This is probably due to the progressive rupture of the water menisci between the particles, as the water content decreases. Effective stress generated by the matric suction increased soil strength where continuity of water films around the particles was preserved (i.e. at high water contents). Fracture mechanics might explain the changes of the strength at low water contents (Hallett et al., 1995). The higher amount of the palygorskite or $CaCO_3$ in the mixtures caused the increment of this point toward the higher water contents. It means that maximum value of the ITS occurs at a specific water content which depends on the amount of the palygorskite and carbonate (fine particles) in the mixtures. However, water content itself is not a good indicator of the strength variations upon drying. The simple effective stress formula ($-\chi\psi_{\mathrm{m}}$) implies that the combined effects of the degree of saturation (i.e. the cross section area of the porous media which is affected by internal stresses) and the internal stresses (i.e. matric suction) determine the change of the strength upon drying (Aluko and Koolen, 2000).

As the proportion of the palygorskite and $CaCO_3$ increased, the strength of the mixtures tends to be unchanged or decreased (Fig. 2). It implies that the high amount of the fine particles would create a loose mass which might have a lower strength because of the flexibility of the fine particles. Perhaps, they behave as a matrix of fine particles containing microcracks which limit the strength development upon drying. Sand particles may be assumed to act as the skeleton domains which have a great role in increasing the strength. It has been reported that in addition to the cementing agents, the presence of the coarse particles is necessary for the hardsetting behaviour (Mullins and Panayiotopoulos, 1984; Mullins et al., 1990; Mullins, 1997, 2000; Fabiola et al., 2003). In other words, coarse particles act as fixed surfaces for the water annuli to pull the fine particles to the contact points and increase the strength. In contrast to Mullins and Panayiotopoulos (1984), four treatments in this study contained fine materials equal or more than 30% w/w. So these samples were observed to behave in a qualitatively different fashion to those with insufficient fine material to fill all of the voids between the sand particles. In addition, increasing the fine particles (palygorskite and $CaCO_3$) in the mixtures would promote formation of the microcracks (weak spots) upon drying. Consequently, the tensile strength of the mixtures will decrease because it completely depends on the existence of the weak spots (Dexter and Kroesbergen, 1985; Dexter and Watts, 2000).

3.3. Tensile strength vs. matric suction

For the all treatments, ITS had a second order polynomial relationship with the matric suction such that ITS was maximum at an intermediate matric suction, and declined at lower and higher suctions. Higher amount of the palygorskite or $CaCO_3$ in the mixtures pushed this point toward the higher matric suctions. It might be the case that the equilibration time was too short for some samples to reach the target matric suctions. According to Fig. 1, the very little decrease of the water content at the high matric suctions might be due to the non-equilibration condition of the finer mixtures. The hydraulic contact of the samples with the ceramic plate might also be failed for the high pneumatic pressures. So the second order polynomial relationship between ITS and the matric suction may be due to the lower actual matric suctions of the drier samples in comparison with the expected nominal values.

As matric suction increased, the fine particles (i.e. palygorskite and calcium carbonate) would be pulled by water menisci to points of contact between larger (sand) particles. Subsequent shrinkage of the mixtures will result in an increase in the number of contact points and will cause the particles to be bonded together by capillary forces through the effective stress. Both effects will increase the strength. In addition, dissolution of the carbonate on saturation and subsequent precipitation during drying may have occurred. When water menisci retreat to annular regions surrounding the points of contact, carbonate will precipitate in these regions and act as a cement, increasing mixtures' strength. However, the approximate solubility of $CaCO_3$ in cold water is 0.014 g L^{-1}. If the volumetric water content at saturation was approximated to an average value of 0.5, this leads to solubility of 0.007 g $CaCO_3$ per kilogram dry mixtures. In the extreme conditions (air-dry), it might be expected that all of the dissolved carbonates precipitate. However, such low value of solubility supposes that many wetting and drying cycles (which is certainly possible in natural soils) would be required to accumulate sufficient cementation to have a detectable effect. These processes will occur as long as the continuity of water films around the particles is maintained (up to a specific matric suction). Thereafter, strength will decrease as matric suction increases further.

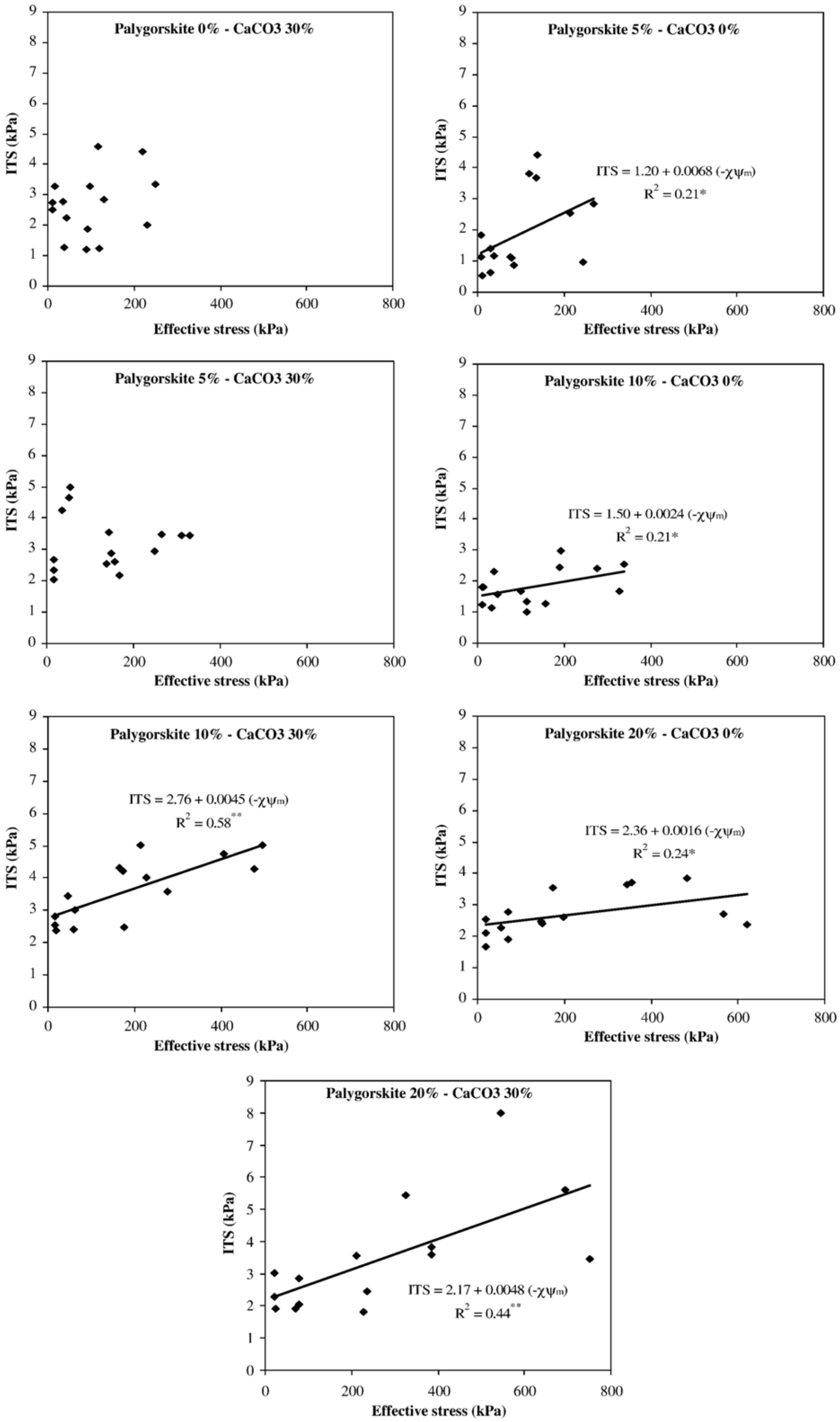

Fig. 3. Tensile strength (ITS) vs. effective stress generated by the matric suction ($-\chi\psi_m$) for the palygorskite–$CaCO_3$–sand mixtures. * and ** mean significant relations at 0.1 and 0.01 levels of probability, respectively.

3.4. Effective stress generated by matric suction and tensile strength

The best way to explain changes in the soil strength on drying is to use the effective stress theory, because it combines the effect of matric suction ($-\psi_m$) and the wetted area (χ) on the strength (Mullins and Panayiotopoulos, 1984; Mullins et al., 1992b; Mullins, 1997, 2000). The ITS had a positive and significant linear relationship with the effective stress ($-\chi\psi_{\mathrm{m}}$) generated by the matric suction for some mixtures (Fig. 3). This implies that the internal stresses are among the important forces affecting the strength of palygorskite- and/or carbonates-containing soils. Variability of the results of the sensitive indirect (Brazilian) test might be the reason for non-significant relation for some cases. However, validity of the assumptions of the effective stress theory is questionable when the microcracks are formed in the mixtures (Towner and Childs, 1972; Mullins and Panayiotopoulos, 1984; Mullins, 2000).

The approximate calculated $f(S)$ varied from 4 to values higher than 200. It means that all of the pores generated upon drying in the mixtures were elongated. Palygorskite is a fibrous mineral expected to create elongated or irregular shaped pores and consequently could reduce the influence of the effective stress on ITS.

The slope of the linear relationship between ITS and σ' was increased in the mixtures containing palygorskite and $CaCO_3$ (Fig. 3). However, the effect of palygorskite on ITS of the mixtures was greater than $CaCO_3$. Nevertheless, the slope was slightly changed for the high amount of palygorskite and $CaCO_3$. Accordingly, we concluded that, the amount of sand particles had an important role in the hardening of the mixtures and unstable soils upon wetting and drying cycles. The effect of 5% palygorskite on the strength of the mixtures was approximately equal to the effect of 30% $CaCO_3$ (Fig. 3). The greater effect of the palygorskite on the strength of the mixtures may be due to its fibrous structure and high surface area. Its fibrous units may act as binding bridges around and between the sand particles. High surface area would enhance high physical and chemical activity and strong clay–clay or clay–sand bonds.

The values of ITS measured in this study were slightly lower than the findings of Mullins and Panayiotopoulos (1984) on sand–kaolin mixtures. This might be due to the different clay mineral (kaolinite) which they used. It is also likely that "dry packed" samples will more easily develop crack failure. It was observed when the samples became drier and/or finer, some cracks were generated within the mixtures before the strength's measurements. However, Mullins and Panayiotopoulos (1984) completely remoulded the wet pastes of the mixtures before matric potential adjustment and strength measurements. This might have caused the better contacts between the particles and lower crack development, and resulted in the higher strength. It is believed that the "dry packed" condition used in this study might only govern the effect of fine particles but not smearing and puddling (compaction by external stresses) due to remoulding on the strength.

3.5. Tensile strength at air-dry condition

Values for air-dried samples have not been included in Figs. 2 and 3 because air entry would have occurred within the fine particles causing uncertainty regarding the effective stress. But, air-dry condition was also included in this study because tensile strength at the air-dry condition has been used as a quantity for the hardsetting behaviour of soils. Variation of ITS among the palygorskite–$CaCO_3$ mixtures at the air-dry condition is shown in Fig. 4. Generally, tensile strength increased with an increase in the amount of binding agents. As seen in Fig. 4, adding both the palygorskite and $CaCO_3$ caused a greater increase in the strength as compared with their individual treatments. The effect of 5% palygorskite on the air-dry strength of the mixtures was approximately equal to the effect of 30% $CaCO_3$. With an increase in the amount of palygorskite to 20%, ITS decreased due to the flexibility of its fibers and more possibility of crack formation upon drying (Fig. 4).

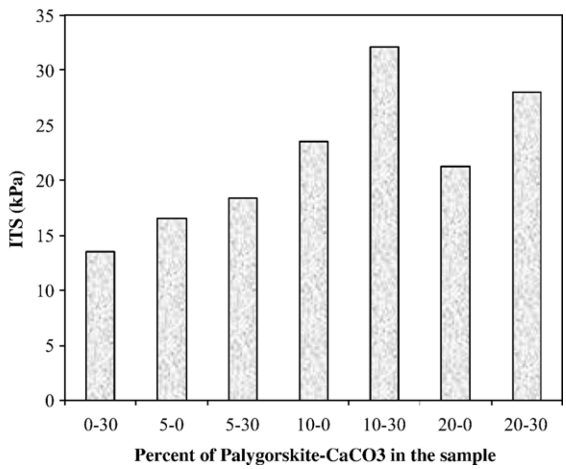

Fig. 4. Tensile strength (ITS) changes with the percent of palygorskite and $CaCO_3$ in the mixtures at the air-dry condition.

4. Conclusions

The results of this study showed that palygorskite and calcium carbonate, the two important minerals in the arid soils, significantly affected the strength of the artificial mixtures with sand. Although there was disagreement between theoretical and measured values, the general trend of the variation of strength with water content and with matric suction was well explained and, in particular, the sharp increase in the strength happened between the matric suctions of 30 and 1000 kPa. Because of the steepness of the water characteristic curve in this region, the increase in strength occurred for a comparatively small reduction in the water content. This sharp increase of strength over a narrow range of water content is characteristic of the hardsetting soils that are widespread in Africa (e.g. Kowal and Kassam, 1978), Australia (Northcote et al., 1975) and Asia (Mosaddeghi et al., 2003). It is concluded that, the internal stresses are among the important forces affecting the strength or compaction of palygorskite- and/or carbonates-containing soils in the region. Matric suction (internal stresses), through the effective stress, had a crucial and significant effect in this regard. Therefore, the effect of internal stresses should not be overlooked in the arid soils and the best wetting manner and irrigation technique need to be investigated and chosen for sustainable management of the soil hardening and self-compactive behaviour.

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