Effect of partial saturation of soil pastes between masonry stones on the tensile strength of the masonry walls

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ABSTRACT

Dry-stone masonry walls are often analysed and modelled on the assumption that there is practically no cementing agent of any kind between stones. The whole wall therefore is considered a purely frictional assembly of high strength units, the stones, interlocked because of the building/stone stacking arrangement. Field observations of existing walls however indicate that there is often a thin film of soil between individual stones. This film may be the result of soil deposition following water transport from soil masses retained by the wall, the product of erosion from stone units due to micromovement between them at their contacts or weathering of less sound stones in the wall and on occasion actual use of soil-based mortar by ancient builders, as well documented for many monuments from prehistoric times all the way to modern times. In addition, quite often the soil in this film is found in an unsaturated condition. The paper presents the experimental work carried out to investigate the effect of the existence of this film of soil between stones of various types of rock under various values of the degree of saturation of the soil paste and the soil suction inside it. In all cases, unsaturated soil pastes induced very high tensile strength as the soil pastes dried especially close to their residual water content. These test results indicate that under weather conditions imposing partial saturation to existing soil pastes between masonry wall stones (either masonry walls with soil-based mortars or dry-stone masonry walls where soil has been deposited between individual stones), masonry walls should be considered having a considerable tensile strength and modelled accordingly.
Keywords: masonry walls, dry-stone walls, soil-based mortars, partial saturation, unsaturated soils, soil suction

INTRODUCTION

Dry-stone masonry walls (i.e. without mortar of any kind between individual stones *at the beginning* of their construction) are often analysed and modelled on the assumption that there is practically no cementing agent of any kind between individual stones. The whole wall therefore is considered a purely frictional assembly of high strength units, the stones, interlocked because of the stone stacking arrangement. Field observations of existing walls however indicate that there is often a thin (or even thicker) film of soil between individual stones (for instance Bardanis, 2016b, 2017a). This film may be the result of soil deposition following water transport from soil masses retained by the wall downstream of the wall, the product of erosion from stone units due to micromovement between them at their contacts or actual weathering of stones from less sound rock that does take place over the time that monuments have survived until now (on occasion thousands of years). The practice of using stones of more sound rock close to the external boundary of a wall and stones of less sound rock close to its internal boundary has been documented (for instance Bardanis, 2016b, 2017b; Bardanis & Dounias, 2026) and can contribute to the transport of weathered soil material from the inner-side, less sound units practically to the whole of the width of the wall, creating a film of fine-grained soil even between stones of more sound rock. These mechanisms are summarised in Fig. 1.

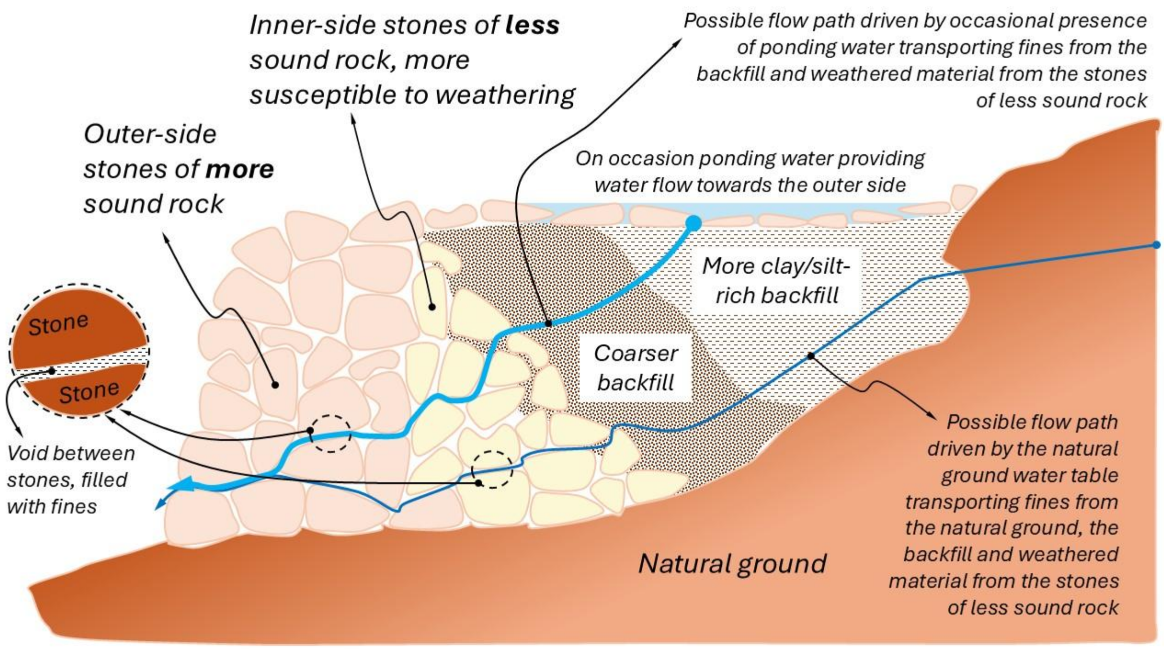


Figure 1. *Possible mechanisms of origin, transport and accumulation of fines between the stones of a backfilled retaining dry-stone masonry wall. The section is purely fictional and does not correspond to any actual monument.*

On many occasions, soil-based mortars have actually been used by ancient builders, as well documented for many monuments from prehistoric times all the way to the 19th century. Stone walls using mainly clay/silt-rich soil as mortar represent one of the oldest and most widespread masonry techniques, predating lime- or cement-based mortar use in the construction of stone walls. These mortars will be termed soil-based mortars throughout this paper (the term earth-based is equally valid); soil meaning predominantly clay/silt-rich soil, *without* any chemically reacting with water binders like pozzolan, lime, cement or other. Their main function is that they add binding and filling for stability, weatherproofing, and insulation while remaining flexible and breathable. Soil for these mortars was typically local (often from foundation excavations), cheap, and sustainable, but less durable against prolonged water exposure without protection (e.g., renders or roofs). They allowed walls to "breathe" and flex, aiding longevity in many climates. In terms of mechanical behaviour, once these soil-based mortars dry, they add extra shear strength to the whole wall dictated by their partial saturation as summarized in the next section and the experimental results presented in this paper. This method appears globally in various cultures due to the availability of soil and stone, making it a foundational technology in human building history before industrialized binders. Modern interest in conservation and low-carbon building has revived attention to these techniques.

Examples of use include early stone walls of Jericho (around 8,000 BC) and other early sites. Dry-stone techniques existed alongside or evolved with soil-based mortars for filling gaps and binding. In Scotland, this tradition dates back over 5,000–5,500 years to the first masonry buildings (Walker et al., 1996). Early Egyptian pyramids (Old Kingdom, ~2600–2500 BC) used mud/clay or clay-sand mortars for limestone blocks before shifting to gypsum or lime. Indus Valley Civilization and other ancient sites in the Indian subcontinent used gypsum and related binders, with simpler earth mixes earlier. Celtic, Anatolian, Quechua (Inca-related), and other cultures commonly used mud mortar for stone houses. Iron Age and earlier fortifications in Europe sometimes incorporated soil-based mortars. While Greeks and Romans advanced lime mortars (often with pozzolanic additives), soil-based mortars continued in vernacular or simpler construction as a low-cost, local option. In medieval times (roughly 5th–15th/16th centuries), the use of soil-based mortars was very common across Europe. Many medieval churches and buildings in the UK used soil-based mortars as the core binder, often with lime pointing or rendering on the exterior for protection. In Scotland, soil-based mortar was standard for many masonry buildings; some structures initially mistaken for dry-stone were actually constructed with soil-based mortars (with mortar washed out over time). In post-medieval times up to the 19th century, the use of soil-based mortars continued in vernacular building, especially in rural or clay-rich areas. The use declined with industrialization, better transport, and the rise of lime/cement, but persisted in some traditional construction. Modern interest in conservation and low-carbon building associated with earth-based construction reviving attention to these techniques.

BASICS OF UNSATURATED SOIL MECHANICS – THE EFFECT OF SOIL SUCTION

Soil-based mortars are practically clay/silt-rich soil with sand, so essentially soil used as a construction material. Soils are particulate materials with three phases: solid, liquid and gas; the most frequent being minerals originating from parent rock as solids, water as the liquid and air as the gas. When the voids between the solid particles are full of water, the soil is termed fully saturated; when they contain no water at all, the soil is termed completely dry; finally when they contain both water and air they are termed unsaturated. Degree of saturation, S_r, is defined as the ratio of the volume of voids containing water, V_w, over the total volume of voids, V_v (often expressed as a percentage and ranging between 0% - completely dry soil- and 100% -fully saturated soil) and describes quantitavely the unsaturated state of a soil ($S_r = V_w / V_v$).

The drained shear strength of fully saturated soil is very well documented in modern soil mechanics; *drained* indicating the shear strength developing without the effect of excess pore water pressure due to rapid changes in total stress. Drained shear strength increases with increasing applied vertical effective stress, σ´ (i.e. the excess of total stress, σ, over positive pore water pressure, u_w, $\sigma' = \sigma - u_w$) with the failure “envelope” corresponding to a straight line described by the Mohr-Coulomb failure criterion (Eq. 1) attributing shear strength τ to effective stress σ´ vertically acting on the plane considered, and two parameters dictated by soil nature and (generally) “geological” history, the angle of shearing resistance φ´ and the cohesion intercept, c´ (the tone in all cases used, denoting effective stress or parameters related to effective stress). More elaborate explanations of soil shear strength and more complicated shear strength models (focusing on non-linearity with effective stress and more parameters) may be found, but the Mohr-Coulomb failure criterion will suffice for the needs of this paper and the majority of cases in practice that the shear strength of soils may be of interest.

$$\tau = c' + \sigma' \times \tan \varphi' \quad (1)$$

Although full saturation of soils is a valid assumption when one needs to introduce the drained shear strength of soil to students and non-geotechnical engineers (or even non-engineers) especially in order to introduce the effect of pore water pressure, on many occasions soils are not fully saturated but unsaturated (Fredlund & Rahardjo, 1993; Jaquin & Augarde, 2012; Bardanis, 2016a; Bardanis, 2019). In the case of unsaturated soils, one of the simplest ways to express their shear strength is by using two state variables; the net total stress, σ, and the soil suction, s (Fredlund & Morgenstern, 1977). In that case, the shear strength increases with increasing applied net total stress *and* with increasing soil suction, s, with the failure “envelope” corresponding to a surface described by the Mohr-Coulomb failure criterion generalised for unsaturated soils (Fredlund et al., 1978) attributing shear strength τ to net total stress σ vertically acting on the plane considered, and three parameters dictated by soil nature and (generally) “geological” history, the angle of shearing resistance φ, the cohesion intercept, c, and the angle corresponding to the increase of shear strength with increasing soil suction under constant total suction, φ^b (the absence of a tone in all cases used, denoting net total stress or parameters related to net total stress). Again, more elaborate explanations of the shear strength of unsaturated soils and more complicated shear strength models (focusing on non-linearity with effective stress and more parameters) may be found, but the generalized Mohr-Coulomb failure criterion will suffice for the needs of this paper and the majority of cases in practice that the shear strength of unsaturated soils may be of interest.

A notable exception is indeed the effect of soil suction. Although the generalized Mohr-Coulomb failure criterion, describes qualitatively the general effect of net total stress and soil suction, depending on the type of soil, the effect of soil suction on shear strength can be non-linear, and even negative for soil suction values beyond the air-entry pressure (soil suction at which a soil becomes unsaturated) in the case of coarse-grained soils (Fig. 2c). Mathematically this can be solved by negative values of φ^b and the use of more complex variables and mathematical models (Bardanis, 2016a; Bardanis & Kavvadas, 2008b). Fig. 2a presents the linear generalized Mohr-Coulomb failure criterion (Eq. 2), Fig. 2b a conceptual representation of the non-linear for suction generalized Mohr-Coulomb failure criterion, and

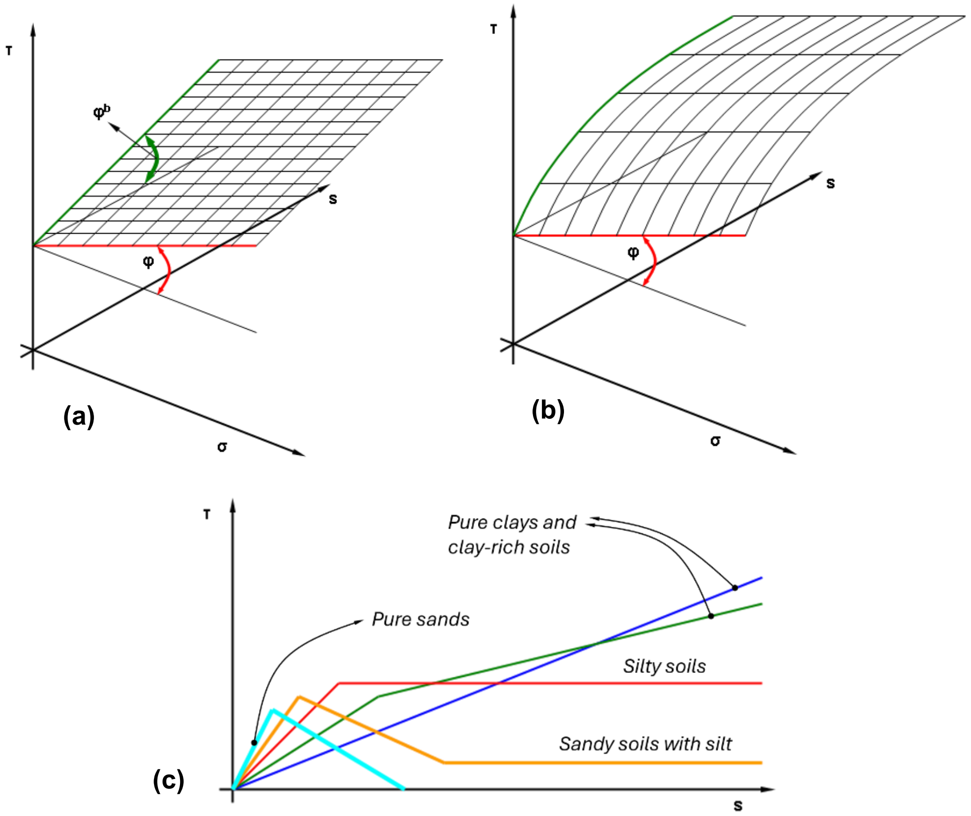


Figure 2. *a) Linear generalised Mohr-Coulomb failure criterion, b) non-linear for suction generalised Mohr-Coulomb failure criterion, and c) evolution of shear strength with soil suction for zero net total stress for various types of soils under conditions where they have zero cohesion intercept.*

Fig. 2c the evolution of shear strength with soil suction for zero total stress for various types of soils under conditions where they have zero cohesion intercept.

$$\tau = c + \sigma \times \tan \varphi + s \times \tan \varphi^b \quad (2)$$

Soil suction is the positive quantity conventionally defined as the opposite (negative) of the gauge pore-water pressure u_w when that pressure is negative (with atmospheric pressure taken as the zero reference). It governs both the hydraulic (water retention and flow) and mechanical (strength and stiffness) behaviour of unsaturated soils. In saturated soils, pore-water pressure, u_w, is measured with a piezometer and controls effective stress ($\sigma' = \sigma - u_w$). The same definition and measurement principle apply for soil above the water table, or in any occurring unsaturated soil: the only difference is that u_w is negative. The water level in a (hypothetical) piezometer would stand below the measurement point. As negative pressures are inconvenient to handle and historically difficult to measure directly (Ridley, 1993; Fredlund & Rahardjo, 1993; Bardanis, 2016a), it is usual to work with the positive quantity soil suction $s=-u_w$. Total suction ψ (free energy of soil water expressed via relative humidity and temperature, practically coinciding with the soil suction present in soil when the osmotic component is ignored -i.e. the component related to the presence of solutes in the pore-water) is related to relative humidity and temperature via Kelvin's law (Thomson, 1871) as per Eq. 3 (where R is the universal gas constant, T is temperature, v_w is the partial molecular volume of water vapour and RH is the relative humidity).

$$\psi = -\frac{RT}{v_w} \ln (RH) \quad (3)$$

All fully saturated soils dry when left in atmospheric conditions. Drying is driven by evaporation caused by the relative humidity and temperature of the atmosphere as dictated by Kelvin's law (Thomson, 1871). Drying causes the pressure of the water inside the soil to become initially negative for as long as the porosity, grain-size distribution and mineralogy of the soil maintains the degree of saturation equal to

100%, and then it will become suction once the soil is desaturated (i.e. its degree of saturation becomes smaller than 100% and soil suction becomes larger than the air-entry pressure of the soil). Drying will continue to a value of water content, called the residual water content (Bardanis & Kavvadas, 2006 & 2008a). If smaller relative humidity is applied or the material is heated, drying will continue to practically zero degree of saturation corresponding to approximately 10^6 kPa (Fredlund & Rahardjo, 1993). Degree of saturation, S_r, vs negative pore water pressure/ suction, s, has the general form shown in Fig. 3a. Drying generally causes shrinkage leading to a decrease to residual void ratio (Bardanis & Kavvadas, 2006 & 2008a) as shown in Fig. 3b corresponding to a maximum dry unit weight as shown in Fig. 3c. Residual water content, residual void ratio and the corresponding maximum dry unit weight are strongly dependent on initial void ratio and water content (Bardanis & Kavvadas, 2006) as well as structure caused by various factors in natural soils or compaction energy per volume in compacted soils (Bardanis & Kavvadas, 2008a).

Partial saturation induced by drying is the driving factor making soil used in adobe and mudbrick constructions (Bardanis et al., 2023a, 2023b) and soil-based mortars gain strength and, in the case of soil-based mortars act as binders between stones. Soil pastes between stones are deposited or constructed with the state properties of the soil (void ratio, water content, and dry unit weight) corresponding to a point either on the full saturation portion of the curves shown in Fig. 3 or slightly into the portion between desaturation and residual drying conditions (between points A & B in Fig. 3b & 3c). Drying to the relative humidity and temperature of the atmosphere in most climates corresponds simply to the completion of drying of the mortar soil material to its residual drying characteristics: residual water content, residual void ratio and the corresponding maximum dry unit weight consistent with the initial state characteristics. It should be noted that in wetter climates and for soil pastes considerably away from the external boundary of masonry constructions, soil will not necessarily reach the condition of residual water content. Nevertheless, drying is expected to cause major increase of the shear strength (including tensile strength) and the experimental programme described and presented in the next sections presents relative data for the case of drying soil pastes between masonry stones.

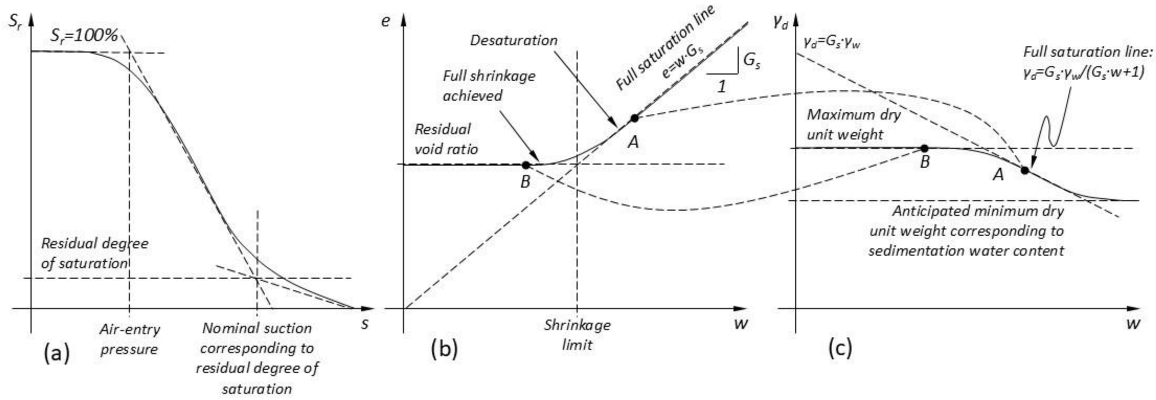


Figure 3. *a) General shape of the relation between degree of saturation, S_r, and negative pore water pressure/suction, s, during drying (soil-water characteristic or water retention curve), b) general shape of the relation between void ratio, e, and water content, w, during drying (shrinkage curve) and c) the way it corresponds to dry unit weight, γ_d, evolution during drying.*

EQUIPMENT AND EXPERIMENTAL SET-UP

In order to measure the direct (unconfined) tensile strength created between stones due to the presence of a dry soil paste, rock samples from various walls were saw-cut and trimmed to create mirror-surfaced samples. Hooks were steadily attached on the back-side of these rock samples (ensuring co-axiality of hooks so that the load application would remain uniaxial; a critical experimental detail the effect of which should be further investigated in the future) and then soil pastes were applied on the saw-cut surface of the samples. The composite rock-soil paste-rock samples were then carefully laid on specially built wooden cradles that could accommodate the hook of the bottom rock specimen so that the soil paste between the rock samples could dry under laboratory atmospheric conditions. Once the required drying in the atmosphere had taken place, the composite samples were carefully transported to the loading frame, placed between the hooks attached to the base plate and the s-shaped load cell at the reaction beam of the loading frame and then tension was applied by means of displacement rate control of the base plate. A low rate of only 0.1 mm/min was selected so that sufficient measurements of load and displacement could be recorded before failure. Once the tension tests were finished, the dry soil paste attached to the rock specimens was visually examined and removed from the surface of the rock part of the composite specimen with part of it used to measure the gravimetric water content, w ($w = m_w / m_s$, where m_w is the mass of water in the sample and m_s the mass of the solids in the sample), of the soil pastes and part of it used to measure soil suction in a METER chilled-mirror hygrometer (Bardanis, 2016a). A summary of the set-up and the stages of preparation is presented in Fig. 4.

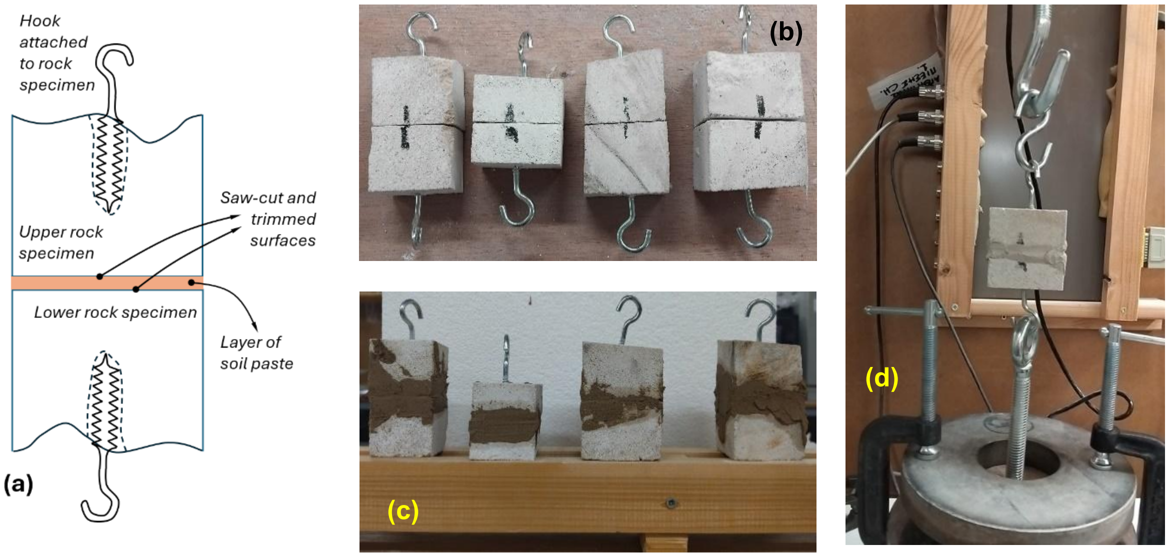


Figure 4. *a) Schematic of the composite samples with upper and lower rock specimen with attached hooks and layer of soil paste between rock specimens, b) examples of rock specimen twins before the application of the soil layer, and c) immediately after the application of the wet layer of the soil paste, and d) composite specimen after drying to residual water content of the soil paste on the loading frame to apply tension.*

VARIOUS CASES

The procedure for measuring the direct (unconfined) tensile strength created between stones due to the presence of a dry soil paste was applied in the case of four actual cases of real monuments. The first case was about part of the northern walls of the Acropolis of Athens (Bardanis, 2016b), the second about the walls of the St Dimitrios cavaliere of the Venetian walls of Chania, Crete (Bardanis & Dounias, 2026), the third about the prehistoric walls of Poliochni, Lemnos (Bardanis, 2017b), and the fourth and final case about the walls of the Old Palace of Phaistos, Crete (Bardanis, 2024a). In the first three cases, the walls examined are retaining walls, while in the fourth case they are load bearing walls of a palatial building. The walls examined span from prehistoric times to the 16th century AD. Table 1 summarises the types and properties of rocks and soils used in the composite rock-soil paste samples prepared for each case. The results of the measurement of direct (unconfined) tensile strength developed between stones due to the presence of a dry soil paste for each case are presented and discussed in the following sections.

The northern walls of the Acropolis of Athens

The first case examined is from the northern part of the circuit walls of the Acropolis of Athens. A geotechnical investigation was carried out in 2016 for the structural materials of the walls (both fallen fragments of the stones of the walls and soil material from the voids between stones) and its results are reported by Bardanis, 2016b. The inner side of the circuit walls remains for a very small length (approx. 5m) visible since the large excavation of the Acropolis between 1885 and 1890 (Kavvadias & Kawerau, 1907). Fig. 5 shows the inner side of the north wall of the Acropolis of Athens where stones of very low

Table 1. *Summary of the types of rocks and soils used in the composite rock-soil paste samples prepared for each case of walls examined.*

Walls	Type of Rock	Soil paste characteristics
Northern Walls of the Acropolis of Athens	Micritic limestone to clay-rich dolomitic limestone of medium strength (Type I-II in Table 2), with 40-50 MPa σ_c, dry unit weight 20 to 23.5 kN/m^3, 40-80% calcite, 15-55% dolomite, 4-5% quartzite, 1% chlorite and 1% illite	Sandy silt with gravel and traces of clay, classified as SC to CL according to USCS with w_L 26 to 30% and I_p 8 to 9%, dry unit weight 11 to 13 kN/m^3 and Gs 2.78 to 2.80, 90-95% calcite, 4-5% quartzite, 1% chlorite and 1% illite
St Dimitrios cavaliere of the Venetian walls of Chania, Crete	Marly limestone with 14-16 MPa σ_c, dry unit weight 20 to 22 kN/m^3, predominantly calcitic	Clayey silt with sand, classified as CL according to USCS with w_L 29 to 31% and I_p 12 to 13%, Gs 2.75 to 2.78, predominantly calcitic
Poliochni, Lemnos	Fine-grained sandstone, with 30-60 MPa σ_c, dry unit weight 21 to 26 kN/m^3, predominantly quartzitic	Sandy silt, with traces of clay, classified as CL according to USCS with w_L 25 to 27% and I_p 8 to 9%, Gs 2.70, predominantly quartzitic
Old Palace of Phaistos, Crete	Fossiliferous limestone with secondary micritic matrix of calcitic nature, with 10-25 MPa σ_c, dry unit weight 17.5 to 20.5 kN/m^3, 95% calcite, 5% quartzite	Sandy silt with traces of clay, classified as CL according to USCS with w_L 34% and I_p 12% and Gs 2.72, 40-45% calcite, 40% quartzite, 7% alvite and 7% bassanite

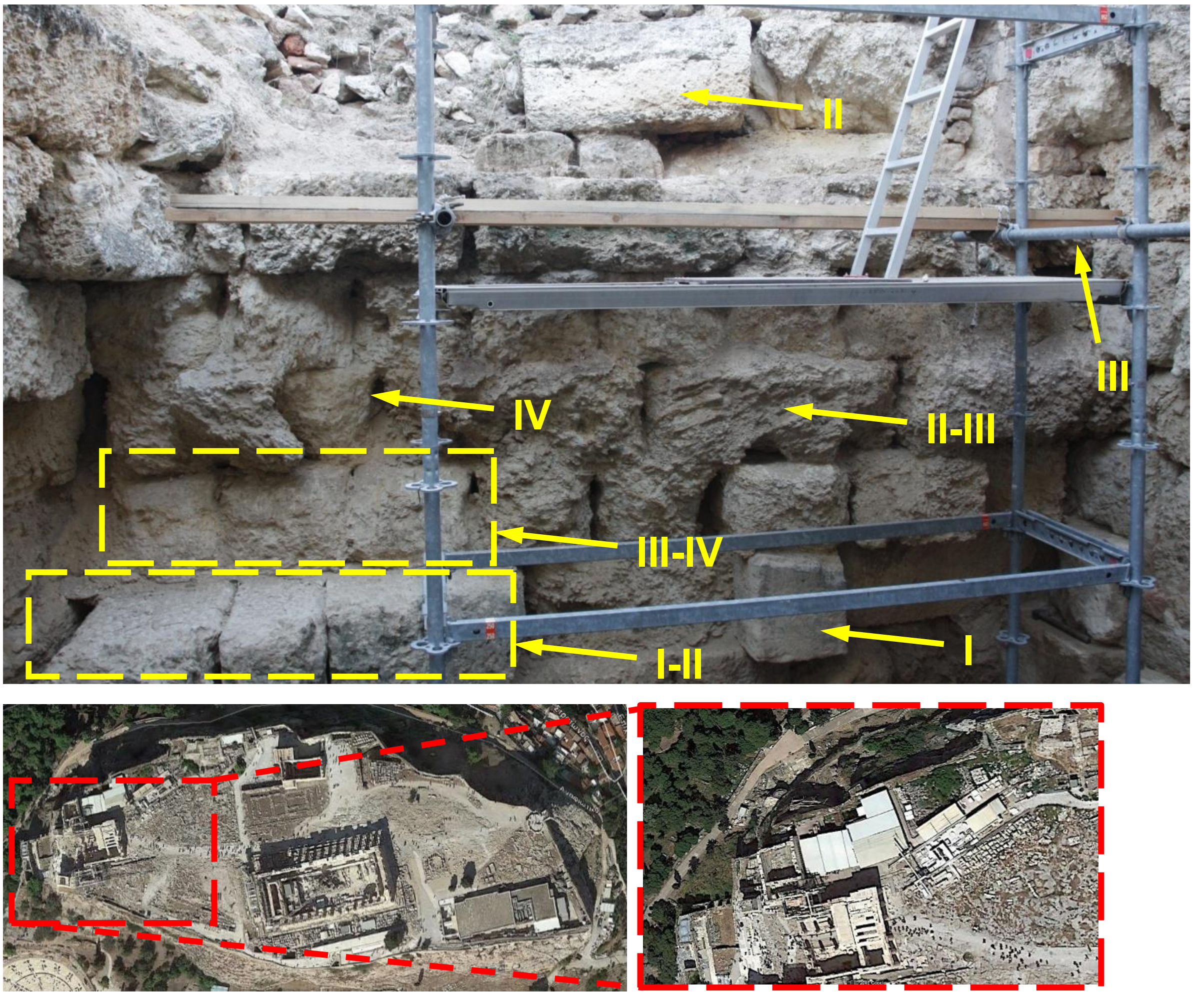


Figure 5. *a) Inner side of the north wall of the Acropolis of Athens where stones of very low soundness (practically hard soils, rather than rocks) may be seen (classified as Type IV in Table 2), b) satellite image of the Acropolis of Athens (GoogleEarth), and c) detail of satellite image showing the location of the inner side of the wall still without backfill covering it.*

Table 2. *Lithological identification of the Acropolis Walls stones from the location shown in Fig. 5, rock and discontinuities weathering characteristics.*

Lithological phase	**Higher strength – Rock material of medium strength (I)**	**Lower strength – Rock material of low strength (II)**	**Lithological phase corresponding to weak rock – Locally weathered to soil-like material (III)**	**Lithological phase of minimum strength – Fully weathered material (classified as hard soil) (IV)**
Visual impression	Medium strength rock	Low strength rock	Weak rock, locally weathered to soil	Material fully weathered to soil maintaining strength due to cementation caused by contained minerals and partial saturation
Weathering	None to slight	Slight to medium	Overall slight, high at the locally weathered to soil part of the stone	High to completely decomposed
Block removal or scarification	Impossible without tools	Impossible to very difficult without tools	Generally needs tools – By hand from the locally weathered to soil part of the stone	Scarred easily by hand.
Weathered/ eroded material present	Non-existent or transported	Non-existent or transported	From the locally weathered to soil part of the stone or transported	Weathered or transported material present. Locally may have undergone secondary cementation.
Visual impression of discontinuities	No cementing. Maybe at contacts between the stones.	No to minor cementing at contacts, crushed due to stress concentration.	Minor to locally like Phase IV due to the presence of the weathered to soil part of the stone	Infilled and cemented. Presence of weathered material (mostly of calcite composition) with cohesion either due to secondary cementation or partial saturation.

[a] For discontinuities with material of worse lithological phase, the properties of the worse category apply.

soundness (practically hard soils, rather than rocks) may be seen (Bardanis, 2016b). The stones visible were identified and classified as in Table 2, ranging from medium strength, unweathered rock of calcitic and dolomitic origin (Type I) to fully weathered Peiraeus Marl, a material classified as hard soil in geotechnical context (Type IV) and a distinctive mechanical behaviour of hard soils/weak rocks (Bardanis, 2024a). It is notable in Fig. 5 that there is a number of stones of Types III to IV on the bottom part of the inner side of the walls, the types that would be more easily weathered under atmospheric conditions or the presence of water movement from the backfill towards the external boundary.

Fragments of stones classified as Type I to II were saw cut and trimmed in order to form the part of the composite rock-soil paste samples described in the previous section. The slurry produced during wet saw cutting of all the samples was collected and after drying in atmospheric conditions was used as a representative material to form the soil paste that would be applied between the rock specimens. It is noted that in terms of soil mechanics classification, this material was practically coinciding both in terms of grain-size distribution and Atterberg limits with the soil materials collected on site. Two tests were performed and their results are shown in Fig. 6 with tensile strength related both to the soil suction measured on the soil paste after the test and to the gravimetric water content of the soil pastes. Different values of soil suction were achieved by letting the composite specimens dry for different time in the atmospheric conditions of the laboratory. The average value of the tensile strength is 25-30 kPa.

The walls of the St Dimitrios cavaliere of the Venetian walls of Chania, Crete

The second case examined is from St Dimitrios Cavaliere in the old city of Chania in Crete, Greece (Bardanis & Dounias, 2026). Cavalieri were elevated banks of earth in the form of circular hills constructed uphill of bastions originally in Venetian forts. Their circular crest offered an elevated fortified location to position artillery and offer it larger range because of the increased elevation, towards many directions from where the enemy could attack. On occasion like for instance the St Dimitrios Cavaliere the toe of the circular hills was contained within walls retaining the whole soil mass. The St Dimitrios Cavaliere has suffered by many failures of its toe walls and higher slope, which were thoroughly investigated in recent years (Bardanis & Dounias, 2026).

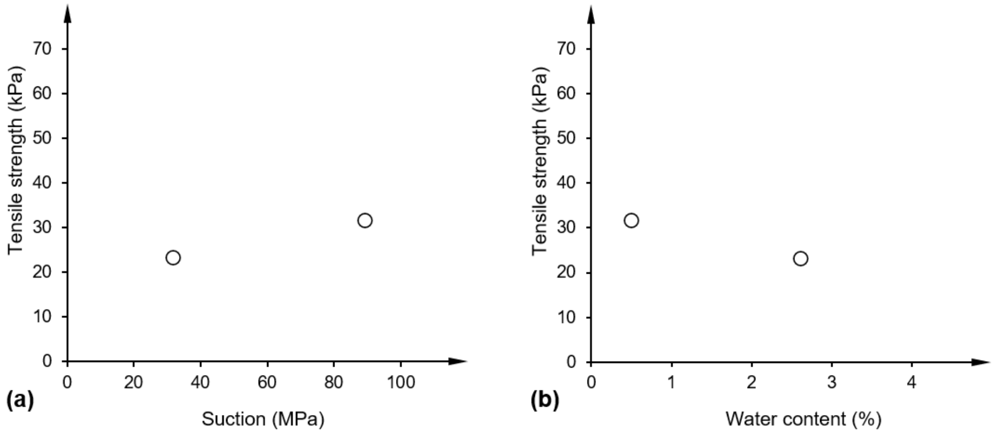


Figure 6. *Tensile strength tests results for composite samples from the Northern Walls of the Acropolis of Athens a) tensile strength vs suction, and b) tensile strength vs water content.*

A fragment of a stone from the walls of the Cavaliere at the location of one of the failures was saw cut and trimmed in order to form the part of a single composite rock-soil paste sample described in the previous section. Soil material found between the stones was used as a representative material to form the soil paste that would be applied between the rock specimens. Due to limited quantities of samples, only one test was performed and the result is shown in Fig. 7 with tensile strength related both to the soil suction measured on the soil paste after the test and to the gravimetric water content of the soil pastes. The value of the tensile strength is again in the range 25-30 kPa.

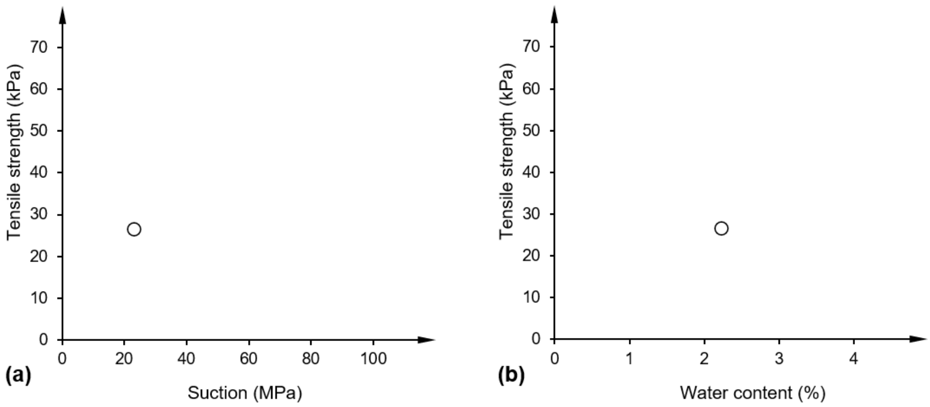


Figure 7. *Tensile strength tests results for composite samples from the walls of the St Dimitrios cavaliere in Chania, Crete a) tensile strength vs suction, and b) tensile strength vs water content.*

The walls of Poliochni, Lemnos

The third case examined is from the walls of Poliochni on the island of Lemnos, Greece. Poliochni lies on the eastern coast of Lemnos. It is a major Early Bronze Age Settlement widely regarded as one of the earliest urban centres in Europe. Its enclosure wall is one of the most significant public works of the city and a defining marker of the city’s transition from an open village to a closed, organised proto-urban settlement which appeared first around 3200 BC. Its preserved height is 4.5-5.0m with a width of 0.7 to 2.8m. Investigation of the properties of the stones of the wall and the backfill behind it were performed in 2017 (Bardanis, 2017b).

The stones of the wall examined were mostly sandstones, trachytes and chert. Fragments of stones from sandstone were saw cut and trimmed in order to form the part of the composite rock-soil paste samples described in the previous section. Soil material from the backfill was used as a representative material to form the soil paste that would be applied between the rock specimens. Six tests were performed and their results are shown in Fig. 8 with tensile strength related both to the soil suction measured on the soil paste after the test and to the gravimetric water content of the soil pastes. Different

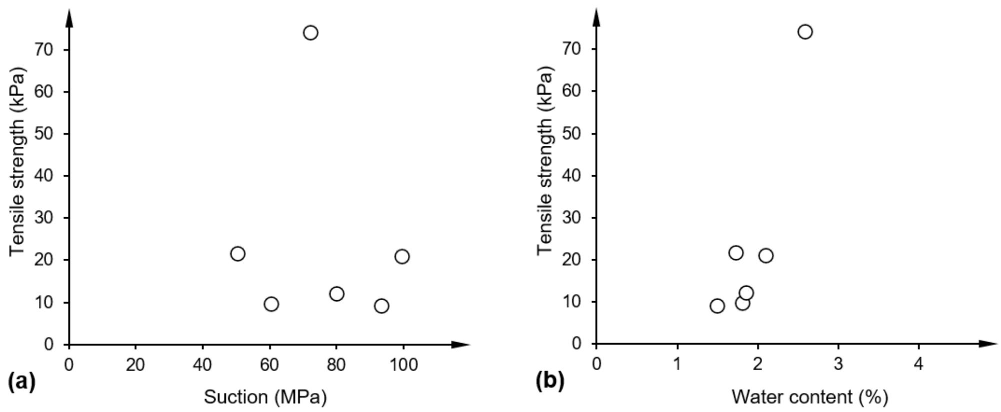


Figure 8. *Tensile strength tests results for composite samples from the walls of Poliochni, Lemnos a) tensile strength vs suction, and b) tensile strength vs water content.*

values of soil suction were achieved by letting the composite specimens dry for more time in the atmospheric conditions of the laboratory. The average value of the tensile strength is 15 kPa (exempting a single much larger value of 75 kPa).

The walls of the Old Palace of Phaistos, Crete

The Old Palace of Phaistos constitutes a unique prehistoric monument with masonry with soil-based mortars. An extensive geotechnical investigation was carried out between 2024 and 2026 investigating both the properties of the materials used in the construction of the Old Palace of Phaistos (Bardanis, 2024b) and the surroundings of the Phaistos Hill due to slope instabilities in the northern and southeastern slopes of the hill (Bardanis, 2024c).

The stones of the wall examined were limestones of various strengths and porosities. Fragments of a stone from fossiliferous, medium strength limestone were saw cut and trimmed in order to form the part of the composite rock-soil paste samples described in the previous section. Two soil materials were used as representative material to form the soil paste that would be applied between the rock specimens. As part of the investigations carried out, soil materials practically identical to those used in the soil-based mortars of the masonry walls were identified in the low ground of the southeastern slopes of the Phaistos hill. Both the soil used in the mortar and the soil in the southeastern slopes of the hill had practically the same range of Atterberg limit values and the same grain-size distribution range after removing from the natural materials the fraction above the maximum grain size identified in the soil of the mortars. Given these results, composite samples were prepared like those prepared in the previous cases with soil pastes prepared from two large soil batches: a soil sample in the form of dry material collected from the floor of the monument (called herein “authentic”, denoted “Auth”) and a mixture of soil from the top 1-4m of boreholes drilled in the low ground of the southeastern slopes of the hill (called herein “mimicking”, denoted “Mim”).

Several tests were performed and their results are shown in Fig. 9 with tensile strength related both to the soil suction measured on the soil paste after the test and to the gravimetric water content of the soil pastes. Different values of soil suction were achieved by letting the composite specimens dry for different times in the atmospheric conditions of the laboratory. The average value of the tensile strength is 70-80 kPa for both soils used for the soil pastes, with the “authentic” soil leading to a larger range of results from 15 to 165 kPa, despite the same average with the results from the tests with the “mimicking” soil used for the soil paste. Given the larger quantities of materials available, more tests were performed and emphasis was placed to achieve some values of relatively low soil suction, i.e. in the order of 1 MPa and even below that. A number of tests with soil suction values in this order were performed and a tensile strength in the order of 50-60 kPa was achieved.

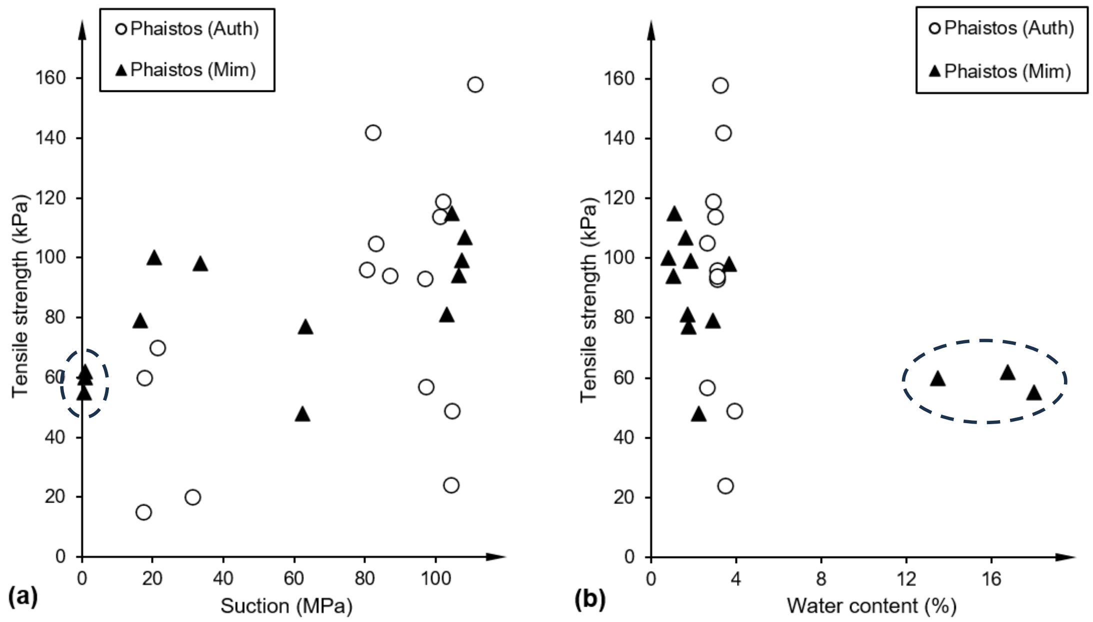


Figure 9. *Tensile strength tests results for composite samples from the walls of the Old Palace of Phaistos, Crete a) tensile strength vs suction, and b) tensile strength vs water content. Dashed line ellipses denoting tests with values of relatively low soil suction.*

DISCUSSION OF RESULTS AND CONCLUDING REMARKS

In the previous sections the results for each case of walls were presented separately. In this section all of the test results have been collected in the same figure and are shown in Fig. 10 with tensile strength related both to the soil suction measured on the soil paste after the test (Fig. 10a) and to the gravimetric water content of the soil pastes (Fig 10b).

Emphasis is placed more on the relation of the tensile strength measured on the composite samples with soil suction rather than with water content. A rigorous evaluation of the effect of water content for different soils used in the soil pastes would demand the knowledge of the water retention curve of each of these soils which is not available currently. Therefore similar values of water content in Fig. 10b for different soils can correspond to different points on the water retention curve (and therefore different values of the degree of saturation of the soil). As a result, Fig. 10b is not discussed further and readers are alerted to the need for water retention curve knowledge of a soil (let alone different soils) in order to evaluate tensile strength-water content relations.

Soil suction on the other hand is a variable contributing to unsaturated soil shear strength in a straightforward manner (as for instance shown by the generalised Mohr-Coulomb failure criterion). Its effect on the tensile strength measured on the composite rock-soil paste samples seems to create a very large range of values. This range seems to have a minimum of 10 kPa and a maximum described by an envelope leading to values of tensile strength in the order of 50 kPa for minimum values of suction and a maximum even above 150 kPa for values of suction in the order of 100 MPa. Two important notes should be made here:

- Suction values of 100-120 MPa are approximately the largest values of suction that could be achieved if a soil is left to dry to residual water content conditions under the effect of relative humidity and temperature values found in temperate climates. Data of *actual suction values measured on soil mortars inside walls* are enormously limited but it should be generally anticipated the so high values of soil suction are highly unlikely to develop within the interior of walls at a large distance from their external boundary.
- The author has limited measurements of soil suction values measured on soil pastes found between stones in the Walls of Acropolis (Bardanis, 2016b) and the Walls of the Old Palace of Phaistos (Bardanis, 2024b). The range of these values is enormous, from values indeed close to 100 MPa for samples very close to the external boundary but closer to 1-10 MPa just a few cm from the external

boundary. To the knowledge of the author, no data of this kind have been published in the literature. Given this, it is prudent to consider only the range of tensile strength values for the low range of soil suction values. Still, even at this range of soil suction, the tensile strength measured on composite samples ranges between 10 and 60 kPa.

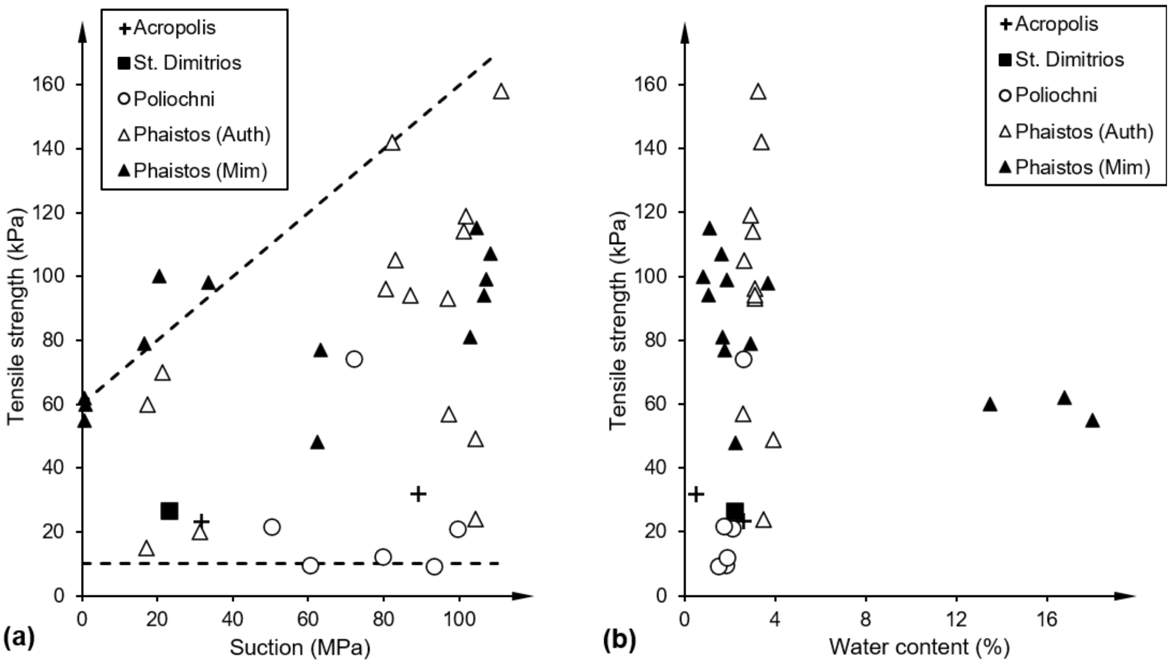
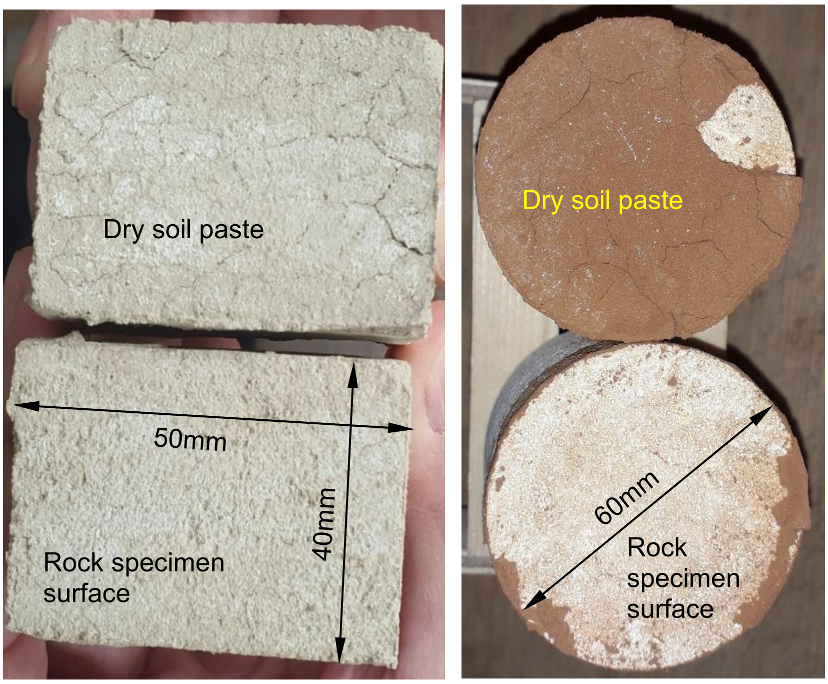


Figure 10. *Tensile strength tests results for composite samples from all the walls investigated a) tensile strength vs suction with dashed lines defining the range of tensile strength values, and b) tensile strength vs water content.*

Another point that should be noted in Fig 10a is the large difference in results from the composite samples of Phaistos and the other walls. Samples in the case of Phaistos were larger and allowed for more tests which itself makes a difference when comparing the results with the other cases. On top of this, the general observation from failed composite specimens (in all cases) is that the actual crack occurs at the interface of the soil paste with one of the faces of the two rock specimens (examples shown in Fig. 11). Given this observation, it is anticipated that a more porous rock, allowing fresh soil paste of high water content to enter its pores more easily, would probably create a better contact between the soil paste and the stone. The fossiliferous limestone from the walls of Phaistos had much lower dry unit weight (therefore much higher porosity) than the rocks in all other cases. This could offer an explanation to the systematically larger values of tensile strength obtained from the composite samples of Phaistos in comparison to the samples from the other walls. On the other hand, and on a more general comment, all tensile strength values measured should be considered underestimated when compared to reality, as stones used in actual walls (especially ancient walls) are highly unlikely to have so flat and polished surfaces as those produced from saw-cutting of rock samples. Rough surfaces of stones are anticipated to be able to create a better "grip" of the stones from the dried soil paste between them (even in pure tension conditions; far more in shear conditions).

To summarise, tensile strength values measured on composite rock-soil paste samples were presented and related to the soil suction of the soil pastes between the rock specimens of the composite samples. These values were found to be of considerable magnitude. This magnitude is probably underestimated as stones used in actual walls (especially ancient walls) are highly unlikely to have so flat and polished surfaces as those produced from saw-cutting of rock samples in the laboratory. There seems to be an increase of the values of this tensile strength that describe the maximum of the envelope with increasing soil suction of the dried soil pastes. This relation makes even more important the need for actual measurements of soil suction values measured on soil pastes found between stones of actual walls. Very limited data available from the author's work indicate that values above 10 MPa should not be considered and more probable values for temperate climates and further from the external boundaries



(a) (b)

Figure 11. *Examples of composite samples after failure showing full or practically full coverage of one surface of the rock specimens with dry soil paste and the other without it a) an example from Phaistos with the "mimicking" soil as soil paste, and b) the test from St Dimitrios Cavaliere (small part of the paste -top right- fell after the test).*

of the walls are in the range 1-2 MPa. There seems to be an increase of the tensile strength of the composite samples with the porosity of the stones of the walls.

Further research into the subject should focus on
- the relation between stone porosity and the tensile strength of the composite samples,
- the investigation of the properties of more rock-soil combinations,
- the effect of rock specimen surface roughness,
- the effect of sample size (quite often, especially for real monuments, it cannot be specified as rock samples and their fragments can be very small and limited in umber and quantities), and
- the actual values of soil suction developing in soil pastes of real walls by long-term field measurements of suction in soil pastes.

ACKNOWLEDGEMENTS

The work presented is the result of many projects carried out under contract for various branches of the Ministry of Culture of the Hellenic Republic, namely:
- Acropolis Restoration Service for the results on the materials of the Northern Part of the Ancient Walls of the Acropolis of Athens;
- Ephorate of Chania and Directorate of Byzantine and Post-Byzantine Monuments (ΔΑΒΜΜ) for the results on the materials of the St Dimitrios Cavaliere of the Venetian walls of Chania, Crete;
- Ephorate of Lesvos for the results on the materials of the Poliochni Wall; and
- Directorate for the Restoration of Ancient Monuments (ΔΑΑΜ) for the results on the materials of the walls of the Old Palace of Phaistos, Crete.

Both the Author and EDAFOS Engineering Consultants S.A. acknowledges gratefully the help received from the personnel of these Services and various collaborators from cooperating private companies during these projects.

All tests presented in the paper were performed in the Soil Mechanics Laboratory of EDAFOS Engineering Consultants S.A. with assistance from current (G. Vettos, D. Kokoviadis) and former laboratory personnel (S. Grifiza, D. Tzarela, O. Daferera, J. Patapis, N. Kalantzis and M. Tsoukaladakis).

REFERENCES

Bardanis, M. (2016a). Experimental and Analytical Investigation of the Mechanical Behaviour of Unsaturated Soils. PhD Thesis, National Technical University of Athens, 1300 pp. In Greek.

Bardanis, M. (2016b). *Geotechnical Evaluation of Field and Laboratory Investigation of Structural Materials from the Northern Walls of the Acropolis of Athens*. EDAFOS Engineering Consultants S.A., under contract for the Acropolis Restoration Service (ΥΣΜΑ) of the Ministry of Culture of the Hellenic Republic. In Greek.

Bardanis, M. (2017a). *Geotechnical Evaluation and Design for the Restoration of the Walls of the St Dimitrios Cavaliere of the Venetian Fortifications of the Old City of Chania*. EDAFOS Engineering Consultants S.A., under contract for the Ephorate of Chania of the Ministry of Culture of the Hellenic Republic. In Greek.

Bardanis, M. (2017b). *Presentation of Laboratory Test Results on Stones and Backfill from the Poliochni Wall*. EDAFOS Engineering Consultants S.A., under contract for the Ephorate of Lesvos of the Ministry of Culture of the Hellenic Republic. In Greek.

Bardanis, M. (2019). Nature, Mechanical Behaviour and Occurence of Unsaturated Soils. Proc. of the Hellenic Soc SMGE on Unsaturated Soils, 1st July 2019, pp. 1-42. In Greek.

Bardanis, M. (2024a). Direct Shear Testing of Various Hard Soils and Weak Rocks from Greece. Geotech Geol Eng 42, 3231–3250 (2024). https://doi.org/10.1007/s10706-023-02726-9

Bardanis, M. (2024b). *Investigation of Construction Materials*. Study for the stabilisation and restoration of ancient remains, construction of canopies and slope stabilisation of the Minoan Palace of Phaistos. “ZIDIANAKIS & PARTNERS - EDAFOS S.A. - IT&KV CONSULTING ENGINEERS” consortium, under contract for the Directorate for the Restoration of Ancient Monuments (ΔΑΑΜ) of the Ministry of Culture of the Hellenic Republic. In Greek.

Bardanis, M. (2024c). *Geotechnical Evaluation of Field and Laboratory Investigation*. Study for the stabilisation and restoration of ancient remains, construction of canopies and slope stabilisation of the Minoan Palace of Phaistos. “ZIDIANAKIS & PARTNERS - EDAFOS S.A. - IT&KV CONSULTING ENGINEERS” consortium, under contract for the Directorate for the Restoration of Ancient Monuments (ΔΑΑΜ) of the Ministry of Culture of the Hellenic Republic. In Greek.

Bardanis, M., Dounias, G. (2026). Investigation, analysis and rehabilitation of the failures of St Dimitrios Bastion in the old city of Chania, Crete. 4th Intnl Symposium on Geotechnical Engineering for the Preservation of Monuments and Historic Sites, Athens, Greece, 16-18 September, 2026.

Bardanis, M., Kavvadas, M. (2006). Prediction of the limiting void ratio of clayey soils after drying. Geotechnical Special Publication No. 147, proc. 4th Int. Conf. on Unsaturated Soils, Carefree, Arizona, USA, April 2-5 2006, Vol. 1, pp. 1085-1096. https://doi.org/10.1061/40802(189)88.

Bardanis, M., Kavvadas, M. (2008a). Prediction of the residual void ratio of clayey soils after drying, from their initial state, physical properties and structure. Unsaturated Soils: Advances in Geo-Engineering, Toll et al. (eds), Proc. 1st Eur. Conf. on Unsaturated Soils, Durham, UK, 2-4 July, 2008, pp. 381-387.

Bardanis, M., Kavvadas, M. (2008b). Modifying the Barcelona Basic Model to account for residual void ratio and subsequent decrease of shear strength relative to suction. Unsaturated Soils: Advances in Geo-Engineering, Toll et al. (eds), Proc. 1st Eur. Conf. on Unsaturated Soils, Durham, UK, 2-4 July, 2008, pp. 589-595.

Bardanis, M., Marinis, Th., Toumbakari, E.-E., Dounias, G. (2023a). Investigation of the properties and behaviour of ancient and newly constructed mudbricks from the ancient walls of Eleusis. E3S Web of Conf., 382, https://doi.org/10.1051/e3sconf/202338217001.

Bardanis, M., Marinis, Th., Toumbakari, E.-E., Dounias, G. (2023b). Reproduction and long-term monitoring of drying of mudbricks and small mudbrick walls for the preservation of the ancient mudbrick wall of Eleusis. E3S Web of Conf., 382, https://doi.org/10.1051/e3sconf/202338217002.

Fredlund, D. G., Morgenstern, N. R. (1977). Stress state variables for unsaturated soils. J. Geot. Eng. Div. ASCE, 103, 447-466.

Fredlund, D. G., Rahardjo, H. (1993). Soil mechanics for unsaturated soils. John Wiley & Sons, New York, N.Y., 517 pp.

Fredlund, D. G., Morgenstern, N. R., Widger, R. A. (1978). The shear strength of unsaturated soils. Can. Geot. J., 15, 313-321.

Jaquin, P., Augarde, C. (2012). Earth Building – History, science and conservation. HIS BRE Press, Bracknell.

Kavvadias, P., Kawerau, G. (1907). The Excavation of the Acropolis between 1885 and 1890. Library of the Archaeological Society in Athens. Estia Publications. Bilingual edition in Greek and German.

Ridley, A. M. (1993). The measurement of soil moisture suction. PhD Thesis, Imperial College of Science, Technology and Medicine, University of London, 281 pp.

Thomson, W. (1871). Philosophical Magazine. 42, pp. 448.

Walker, B., McGregor, C. & Little, R. (1996). Earth Structures and Construction in Scotland. A Guide to the Recognition and Conservation of Earth Technology in Scottish Buildings. Edinburgh: Historic Scotland.