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Review Article

Tensile Testing of Soils: History, Equipment and Methodologies

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Abstract

Tensile strength of soil is indeed one of the important parameters to many civil engineering applications. It is related to wide range of cracks especially in places such as slops, embankment dams, retaining walls or landfills. Despite of the fact that tensile strength is usually presumed to be zero or negligible, its effect on the erosion and cracks development in soil is significant. Thus, to study the tensile strength and behavior of soil several techniques and devices were introduced. These testing methods are classified into direct and indirect ways depending on the loading conditions. The direct techniques including c-shaped mold and 8-shaped mold are in general complicated tests and require high accuracy as they are based on applying a uniaxial tension load directly to the specimen. On the other hand, the indirect tensile tests such as the Brazilian, flexure beam, double punch and hollow cylinder tests provide easy ways to assess the tensile strength of soil under controlled conditions. Although there are many studies in this topic the current state of the art lack of a detailed article that reviews these methodologies. Therefore, this paper is intended to summarize and compare available tests for investigating the tensile behavior of soils.

Keywords: Tensile Strength of Soils; Direct/ Indirect Tensile Test; Brittle Materials; Brazilian Tensile Test; Double Punch Test.

1. Introduction

Soil tensile behavior plays a significant role in various engineering applications [1]. Furthermore, understanding the formation and development of soil cracks is indeed a key factor affecting its performance in fields such as geological, geotechnical and environmental engineering [2-4]. In general, tensile cracks of soil are related to its mechanical and hydraulic properties [5]. These cracks occur when the induced tensile stress or strain exceed the soil capacity [6]. In fact, soil is weak in tension [7], therefore, engineers often assume the tensile strength of soil to be zero because it is relatively small in comparison to the its compressive strength [1, 8-11]. As a result, many strength improvement methods have been discussed in the literature. These efforts encouraged scholars in this filed to introduce and develop several testing techniques to study soil's tensile behavior [8]. However, due to some factors such as the brittleness of the material, finding the tensile strength of soil is considered to be very difficult and needs proper and careful setup in order to reach the best stress state [12]. Regardless of that, available testing methodologies are defined into either direct or indirect technique based on the way of applying the load and computing the tensile strength of soil. In the direct tests, the sample is placed in a cube, cylinder or prism mold then a uniaxial tensile force is imposed to the two ends of the sample [13]. On the other hand, the indirect tests involve the correlativity of different parameters and soil characteristics to measure the tensile strength of soils in simple and easy way compared to the direct one since it

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prevents some problems such as sample misalignment, sample fixing or attaching and stress concentration [13]. Despite that fact that many studies were done to assess the tensile behavior of soil only limited information is presented in soil mechanics' textbooks [14]. Furthermore, the current state of the art lack of a detailed study that discusses and compares these developed testing methodologies. Therefore, these points are rising the need for a comprehensive review that highlight, discuss and compare available techniques to assess the tensile behavior of soil.

2. Previous Works

This section represents a short state of the art review highlighting some of the remarkable studies on testing tensile behavior soils. In general, each table is arranged in succession with respect to the time line.

Table 1. Previous works on direct tensile testing apparatus

Author/s	Test Apparatus	Type of soil tested	Remarks
Tschebotarioff et al. 1953 [15]	Strain rate controlled uniaxial direct tension tests	Wyoming Bentonite clay	In fact, the tensile strength and strain at failure are highly affected by the nature of clay, moisture content, rate of tensile strain and time between mixing and testing. Mixing sand with pure clay improved the tensile strength up to 50% more than pure clay only. This increase of tensile strength for pure clay and sand mixture can be seen clearly with sufficient addition of granular particles. Furthermore, montmorillonite exhibited the highest values in terms of tensile strength and strain at failure while the kaolinite showed the least values.
Hasegawa and Ikeuti 1964 [16]	Load-controlled unconfined direct tension tests	Obaradai clay	The tensile strength showed a primary dependency on the water content. In this study, it was concluded that using a water content ranged between 80 to 100% caused a reduction in maximum tensile strength of almost 0.2 of the total tensile value while the maximum strain increased about 10 times and the secant modulus of elasticity reduced about 0.066 of the total value.
Ajaz and Parry 1975 [17]	Direct tension tests in both load-controlled and strain rate controlled	Compacted Gault clay and Balderhead clay	Despite the type of tensile strength test, the tensile strain at failure increased proportionally as the water content increased for above and below proctor optimum of the tested clay specimens. Moreover, the increase was larger in balderhead clay compared to gault clay. However, load-controlled direct tensile test exhibited higher tensile strains and stresses at failure in comparison to strain rate controlled direct tensile tests.
Leavell and Peters 1987 [18]	Two gripping jaws, rigid base, slide table, linear variable displacement transformer (LVDT), load cell, and a loading mechanism	Compacted Vicksburg silty clay	At lower failure tensile strains, results from direct tensile strength test showed higher values in comparison to indirect values. Furthermore, for used compaction stress, the tensile strength was dependent mainly on the water content in relation to the optimum value in which the tensile strength progressively reduced with the increase in the water content reaching to the optimum value.
Perkins 1991 [19]	Described in section 3.3	Terrestrial-Based Lunar soil simulant	The lunar regolith simulant exhibited extraordinary behavior due to the low cohesion content, noticeably small tensile strength values and very large internal angle of friction values with the nonexistence of water which presents a dilatant behavior even for loose materials. In addition to that, full attention must be paid to the tensile strength and cohesion while developing a constitutive model for quite low stress values where they influence the behavior significantly.
Mikulitsch and Gudehus 1995 [20]	Described in section 3.4	Undisturbed and disturbed soil samples	The tensile strength is related to the capillarity and cementation at wide range of moisture contents.
Ziegler 1998 [21]	Modified version of direct shear apparatus for direct tensile test	Synthetic clays with discrete Polypropylene fibers	The clays incorporated with fibers exhibited higher values in terms of tensile strength and showed ductility behavior in comparison to control samples. In addition to that, screen fibers of 0.3% resulted in tensile strength value of 31.5 kPa while 0.3% of fibrillated fibers yielded in tensile strength value of 16.4 kPa. Thus, screen fibers appear to present better performance as the dosage increases beyond 0.3%.
Tang and Grahm 2000 [22]	Tensile mold and load frame	Sand-bentonite mixture known as buffer	Both square box and semi-circular forms showed relatively similar results in terms of tensile strength with higher values from square box form. Furthermore, the tensile strength showed nonlinear increment relationship with suction which proves the reliability of this method to yield accurate and clear tensile failure results for normal cylindrical samples.

Munkholm et al. 2002 [23]	Adjustable steel bar, pressure transducer, plastic cap, two-piece cylinder, rigid frame	Plough-layer compacted soil	Plough-layer compacted soil exhibited higher direct tensile strength value in comparison to the control sample. For instance, plough-layer compacted soil showed a value of 3.2 kPa compared to 2 kPa for control sample. This result aligns well with the aggregate tensile strength findings and with site soil fragmentation findings. The soils cores showed similar results in terms of tensile strengths to the expected values measured using aggregate tensile strength findings.
Kim and Hwang 2003 [24]	Modified from the original version developed by Perkins (1991)	Quartz granular soil with different sizes	The tensile strength of soils exhibited higher values depending the relative destiny and fiber concrete but mainly on the water content. Both granular soils with and without fines showed higher with the increase of water content up to 4%. However, granular soil with fines resulted in higher tensile strength values compared to soils without fines. For example, for water content of 1%, soils with fines yielded between 610 to 825 Pa depending on the compactibility of the soil whereas for soils without fines, the tensile strength ranges from 580 to 730 Pa. This can be observed for both types of soil up to the tested water content of 4%.
Nahlawi et al. 2004 [25]	Modified version of direct shear test rig apparatus for direct tensile test	Werribee clayey soil with cement stabilized basaltic crushed rocks	The water content is the primary factor affecting the tensile strength so as the water content increases the tensile strength reduces while the tensile strain at failure increases. For example, when 21.5% water content used, the tensile strength was 122.8 kPa while for 58% and 122% water contents, the tensile strength was 6.9 kPa and 2.16 kPa respectively.
Lu et al. 2005 [26]	Digital angle prob, ball-bearing, adjustable plate, mounting plate, sample tubing and hinge.	White fine and medium silica mineral sands	Two porosity percentages were tested mainly 37% and 45%. For soil with fine sand and porosity of 37%, the tensile strength was 1500 Pa while for the same soil with 45% porosity, it was 1200 Pa. On the other hand, soil without sand exhibited tensile strength varying between 800 and 900 Pa for the mentioned porosity percentages.
Tamrakar et al. 2005 [27]	C-shaped mold test	Mixture of clay, sand and silt	The inclusion of fibers and the increase of dry density have positive effect on the value of tensile strength of soils.
Rodríguez et al. 2007 [28]	Modified version of Mikulitstch and Gudehus 1995	Hematite	The tensile strength of soils increased as the degree of saturation increased from 0.3 till the optimum value of 0.8 and starts to reduce beyond that.
Wang et al. 2007 [29]	Two clamps, loading pole, load and displacement sensors	Clay mixed with small amount of gravel	As the dry density and/or water content increase, the tensile strength increases considerably. In addition to that, tensile strength was recorded to vary between 19 and 90kPa for dry densities of 1.6 to $1.76\frac{g}{cm^3}$ and water content of 16.3 to 19.3%. However, the highest tensile strength was recorded at 18.4% water content and $1.76\frac{g}{cm^3}$.
Arslan et al. 2008 [30]	The direct tension device that used was built by Kim in 2003	Granular soils	The tensile strength of soils mainly depends on height and density of samples. Furthermore, the tensile strength varied linearly with the height of specimen where the tensile strength dropped from 780 to 600 Pa with the reduced from 16.7 to 6cm. However, the tensile strength increased from 780 to 960 and reached 1380 Pa with the dry density varies from 1.6 to 1.7 and finally $1.8\frac{g}{cm^3}$ respectively.
Divya et al. 2013 [31]	Adopted this method after Arslan et al. (2008) and Kim and Sture (2008)	Powai silt with bentonite	The tensile strength of soils incorporated fibers showed higher values in comparison to the control ones. This can be attributed to the length and content of fibers. In general, the tensile strength increased 1.7 times when the fiber content changed from 0.25% to 0.75% at the same fiber length. Moreover, when the length of fiber increased from 30 to 90 mm at constant fiber content of 0.25% and 0.5%, the tensile strength increased by 1.15 and 1.29 times respectively, while for fiber length of 90mm and content of 0.75%, the tensile strength showed the maximum value with increment of 2.5 times.
Tang et al. 2014 [5]	8-shaped mold	Clayey soil	The influence of dry density on the tensile strength can be seen clearly at low water content compared to higher ones.

Table 2. Previous works on indirect tensile testing apparatus

Author/s	Testing Approach	Type of soil tested	Remarks
Suklje and Drnovsek 1965 [33]	Hollow cylinder	Undisturbed tertiary clay	The hollow cylinder test is highly recommended for deformation tests at stress states with one principal stress in tension. However, this test requires full attention in order to avoid any errors or inaccurate results by terminating any potential development of air bubbles inside the liquid cell that is responsible to provide pressures and measurement of volume change on the inner and outer faces of the cell. Thus, to avoid such possible errors, it is advised to apply the test for large specimens, use accurate voltmeters, and standardize the temperature and deformation effects and use organic liquid in the cell.
Fang and Chen 1971 [10]	Double punch	Silty clay	Similar to other findings this study has shown that when the water content increases, the effect of higher dry density on tensile strength reduces noticeably compared to the case of low water content.
Fang and Hirst 1973 [34]	Double punch	Soil	The tensile strength proportionally increases with the plasticity index increasing at optimum water content.
Al-Hussaini and Townsend 1974 [13]	Double punch and Hollow cylinder	Clay	Hollow cylinder test provides a better way for finding the tensile parameters of soil compared to other conventional methods used for brittle materials. In addition, hollow cylinder method produced the highest observed tensile strengths in comparison to the double punch tests.
Gopala Krishnayya et al. 1974 [35]	Brazilian	Compacted Mica till and mica till mixed with bentonite	For typical low to medium plasticity core soil, the tensile strength can be ignored for designing and analysing objectives. However, if the design needs to meet the condition of reducing the potential of cracking for earth dam the stress-strain properties are required.
Ramanathan and Raman 1974 [36]	Brazilian	Cohesive soils	All tested cohesive soils with water content lower than the optimum for compaction effort showed satisfying results for indirect tensile test. The tensile strength was reported as 86.3 kPa at 24.5% of optimum water content while the least tensile strength was 16 kPa at 16.3 and 25.6% of optimum water content for sandy clay and Illite Sriperum respectively.
Ajaz and Parry 1975 [17]	Flexure	Compacted Gault clay and Balderhead boulder clay	Flexural tensile strength provided higher values compared to the direct tensile strength with ratio of flexural tensile strength to direct tensile strength of 1.3 to 1.6 for gault clay at water content ranging between 20 to 31% resulting in maximum flexural tensile strength of 100 kPa. On the other hand, Balderhead clay exhibited ratio of flexural tensile strength to direct tensile strength between 1.7 to 1.8 with water content varying from 10 to 18% leading to a maximum flexural tensile strength of 155 kPa. Generally, the flexural tensile strength increment in Balderhead clay is higher than that in gault clay.
Al-Hussainil 1981 [37]	Hollow cylinder	Clay	This test can help in obtaining realistic and accurate tensile parameters for compacted soils including modulus of elasticity and Poisson's ratio via measuring the radial deformation developed alongside the inner and outer surfaces of the samples.
Fang and Fernandez 1981 [38]	Unconfined penetration	Clay	The results of the study have shown that the unconfined penetration test results are in agreement to the split-tensile ones. Furthermore, unconfined penetration test always causes failure on the weakest plane, resulting in a measured true tensile strength.
Maher and Ho 1994 [39]	Flexure	Kaolinite-clay	Similar to previous findings, the tensile strength is related to the content and length of fibers used. Furthermore, the effect of incorporating fiber can be seen more clearly as water content decreases. In this study, the maximum tensile strength was 430 kPa with 5% polypropylene fiber and while it was 400 kPa when 3% glass fiber was used.
Das et.al. 1995 [40]	Brazilian	Fine grained rounded silica sand	The tensile strength increases as the cement content increased. The highest tensile strength was almost 300 kPa with 8% cement content while the lowest value was almost 95 kPa for 4% cement content.

Thusyanthan et al. 2007 [41]	Flexure	Kaolin clay	The stress states of the extreme fiber in tension of used beam specimens at the initiation of a crack showed that cracks are initiated when the effective stress state either reaches the tension cut off line for low mean effective stresses or it reaches the 'apparent failure line' for higher mean effective stresses corresponding to Hvorslev's normalization of the Mohr-Coulomb failure envelope.
Viswanadham et al. 2009 [42]	Flexure	Kaolin-sand mixture	The flexural tensile strength is affected by the type of soil, its water content and the applied compaction energy.
Consoli et al. 2011 [43]	Brazilian	Silty sand, clayey sand and fine sand	As the cement content increased and porosity decreased, the tensile strength of all soil types increased even with different water content at constant dry density.
Olgun 2013 [44]	Brazilian	Polypropylene fiber with clayey soil	The tensile strength showed higher values with the addition of fibers and stabilizing material in which the tensile strength increased 11 times from 25 to reach 285 kPa after 28 days of curing.
Liang et al. 2014 [45]	Unconfined penetration	Q3 loess	In similar to other studies it was concluded that as the moisture content increases for all dry density values, the tensile strength starts to decrease considerably.
Taha et al. 2018 [46]	Brazilian	Clayey sand mixed with bentonite	The inclusion of carbons fibers at Nano-level achieved the needed soil characteristics since the diameter and high aspect ratio of nanocarbons allow the distribution of the fiber on smaller scale compared to higher levels and connects the inter-particles voids.

3. Direct Test

The direct method of testing the tensile capacity of soil can be performed by applying uniaxial tension force on the longitudinal axis of the soil sample through both ends of the specimen, and then it becomes possible to use this force to measure the specimen's tensile strength [5, 47, 48]. Nevertheless, it can be difficult to control this type of test because of the complexity, but some improvements can be introduced on the techniques and approaches that are used in the preparation and control of the sample during the experiment.

3.1. C-shaped Mold Test

This test is deemed to be one of the most commonly used amongst other direct tensile strength tests of soil and it consists of a horizontal application of uniaxial force on the soil specimen. Tamrakar et al. [27] introduced the C-shaped mold as an easy and accurate tool to measure the tensile strength of various soil types [49]. This devicehas a horizontal base, two boxes of the same size in a C-shaped from the outside and half-circled from the inside, motor shaft, load cell and rollers. During testing, one of the boxes is pinned to the horizontal base while the other is left to move freely in order to reduce the friction on the surface between the moving box and the platform using rollers. Thereafter, the load is observed through a load cell that is placed between the motor shaft and the moving box [50]. Finally, the tensile strength is obtained by dividing the tensile load over the area of the tensile crack perpendicular to horizontal pulling [51].

3.2. 8-shaped Mold Test

The 8-shaped mold test is similar to the C-shaped mold, which requires the application of uniaxial tensile force in a vertical direction on the soil specimen [52]. The device utilized for testing was developed by Tang et al. [5] to be used in measuring the tensile capacity of soil. The equipment is made of various parts including a crossbeam, scale, weight, loading disk, control panel, data logger, computer and a mold that is divided into two parts, as the upper one is suspended to the crossbeam while the lower one is placed on the scale. Thereafter, the tension force is imposed through the weight by moving the scale downwards with the loading disk slowly in a uniform speed where higher load is applied by increasing the displacement of the disk until the failure occurs [1].

3.3. Perkins (1991)

Perkins [19] devised a machine for investigating the tensile strength of soil directly [51]. This device was invented to measure the tensile strength of granular soils [9]. The device apparatus consists of motor, load cell, base plate and two parts. The first part is installed on the guide rail with the help of roller bearing blocks positioned at the lower of the first box whereas the second box placed on two rigid blocks to stratify it on the same level as of the first box while the motor and the load cell are placed on the base plate [51].

3.4. Mikulitsch and Gudehus (1995)

Mikulitsch and Gudehus [20] designed a device that is similar to Perkins's [19] one for determining the direct tensile strength of soil with one difference that the sample must be placed in-between two inclined walls. This change is bound to improve the tension strength over the center plane via reducing the friction between the box and sample by fastening the first box and attaching the other to a system of bearing ball. In addition, a hanging bucket filled with water is used to apply an increased tension force on the specimen [51].

3.5. Tang & Graham (2000)

Tang and Graham [22] devised a machine for identifying the tensile strength of soil directly, which consists of a dial gauge, motor mounted on a mechanical load frame. The tensile or compressive force can be applied at constant rate of displacement. The welded two parts at the mold middle are connected to the platen and crosshead of the load frame [22].

3.6. Lu et al. (2005)

The main parts of Lu et al. [26] apparatus that was developed to measure directly the tensile strength of cohesionless soil. In general, it includes two segments of sample tubing, mounting plate, digital probe and a table. The first piece of the tube is fixed to the table while the other one is freely moving on the roller bearing. The table is inclined progressively to increase the gravitational force along the longitudinal axis of the specimen to apply a tension force. Finally, the slope angle is recorded by the digital probe when the sample breaks into two halves. The obtained angle and the specimen weight are used to calculate the sample tensile strength [26].

3.7. Kim and Hwang (2003)

In fact, Kim and Hwang [24] apparatus to observe directly tensile strength relies on the proposed one by Perkins [19]. It involves rigid blocks, rollers, loading-bucket and box divided into two parts. The first segment is placed on the roller bearing system to move freely, while the other one is mounted on two rigid and stiff blocks. Both parts are connected together and located at the same level using four pegs installed in the box to reduce the friction with sample. This procedure allows obtaining the maximum tensile strength through the plane of surface and the designed pegs angles, bigger than the material angle of dilatancy by 20°, preventing any possible soil movement. Thereafter, the plane of failure with uniform distribution of stress and the loading-bucket are used as the imposed tensile force in the system [53].

4. Indirect Test

Indirect test is based on achieving empirical correlations of different soil parameters to compute the soil tensile strength [1, 5, 6, 47]. It involves the application of point or linear non-tensile force for producing tensile stress that is assumed to be uniform on the plane of failure. Therefore, indirect test is more convenient for elastic and brittle materials [54]. Due to the difficulties and wide limitations of direct tests, the indirect method was introduced as an alternative technique to measure the tensile strength of soils [48].

4.1. Brazilian Test

It is an easy and indirect testing method that can be used for measuring the tensile strength of brittle materials including rocks and concrete [55]. The required presumptions of tensile strength calculation by Brazilian approach are: (1) the material exhibits biaxial linear elasticity behavior, (2) shows homogeneity and isotropy in terms of its strength and elastic properties [54]. Furthermore, the Brazilian test was modified from the ASTM D3967-08 by placing the sample in a disc-shaped mold that is loaded diametrically on its circumference using the platens [54]. The test consists of the application of compressive load on the horizontal cylindrical disk sample through two rigid and opposed platens. The increasing compressive load generates a perpendicular tensile stress between the two platens over the surface until the failure of the sample occurs [47]. The stress of soil is assumed to be constant along the diameter in accordance to the elastic theory, and then the tensile strength can be determined using the following formula [47]:

$$\sigma_t = \frac{2P}{\pi D L} \tag{1}$$

Where σ_t is maximum tensile stress; P is applied load at failure; D is diameter of the sample; L is thickness of the sample.

4.2. Flexural (Bending) Beam Test

Similar to the Brazilian test, flexural beam is an indirect procedure to examine the tensile behavior of soil, concrete and rocks [47]. It includes the application of compressive concentrated force at the center of the supported soil beam that is known as third-point bending test or by two equal loads placed at one third of the specimen beam also called as fourth-point bending test until the specimen failure is occurred [48]. During the test, the soil beam gets deformed under the action of load as a result of compressive and tensile stress at the top and bottom of the beam respectively [47]. Therefore, this test is more useful for brittle a material rather than the ductile one, since the distribution of stresses over the plane of failure is uniform and the mid span of the beam experiences zero shear force and maximum bending moment. In fact, this test does not determine the tensile strength directly but instead it measures the specimen's modulus of rupture, in which the beam bends in circular arc through the supports [47]. This issue is based on the bending theory that assumes the material to be linear elastic with equal Young's modulus in tension and compression and ignores the self-weight of the beam [14, 42, 48]. In general, the flexure beam test apparatus developed by Leonards and Narain [56] to determine the tensile strength of cohesive soil using a simple flexure test involving a clay-beam to predict the cracking behavior of earth dams [9, 57]. The apparatus consists of loading system applied to the middle of section with ball-bearing balls along with pulley to prevent any eccentricity to occur. On the other hand, the one proposed by Ajaz and Parry [17] had a concentrated load system applied at equal distances from the middle of the beam through two circular Perspex rods with constant bending moment between these two rods in addition to another two Perspex rods as supports to the beam with dial gauges to detect the deflection of the beam at each load increment until failure. The tensile strength of the specimen in this test can be determined using the following equation [48]:

$$\sigma_t = \frac{M\bar{y}}{I} \quad (2)$$

In which σ_t is maximum tensile stress; M is bending moment; $\bar{y}$ distance of the tensile surface of the beam from the neutral axis; I is moment of inertia.

4.3. Double Punch Test

Double punch test is an indirect method developed by Fang and Chen [10] for measuring tensile strength of soils. It consists of cylindrical shape sample placed vertically between a platen of loading with two circular discs centered on the top and bottom of the soil surface [13]. Thereafter, the specimen is subjected to compressive force along its two opposite faces [58]. Usually, this test gives lower tensile stress results compared to the Brazilian due to the fact that the plane of failure in the Brazilian test is predetermined and the cracks are always formed vertically whether it is the strongest or weakest plane whereas the failure in this test can occur on any one of the infinitely many radial planes which means that the plane of failure is not predetermined and thus and so will fail in the weakest plane only [58].

In fact, the perfect plasticity theory for soils was developed by Chen and Drucker [59] with two essential presumptions: (1) enough local soil deformability exists in both tension and compression in order to the limit analysis theorems to be applicable and viable for perfect plastic material behavior, (2) assuming the surface of failure of the adjusted Mohr-coulomb as a yield surface for soils [60, 47]. Therefore, using perfect plasticity theory and depending on the maximum load, the tensile strength of the sample can be determined [47]. In addition, double punch test has a huge advantage since it doesn't require any heavy machines to be applied which means that California bearing ratio or compaction soil tests can be linked to it while performing the test in laboratory or field easily [10]. The tensile strength for double punch test can be determined as follows [60]:

$$\frac{P}{\pi a^2} = \frac{1-\sin\varphi}{\sin\alpha\cos(\alpha+\varphi)}\frac{q_u}{2} + \tan(\alpha+\varphi)\left(\frac{bh}{a^2} - \cos\alpha\right)\sigma_t \quad (3)$$

Where σ_t is maximum tensile stress; P is applied load; a is radius of disk; φ is inclined cone angle to the surface; α is angle of cone; q_u is unconfined compressive strength; b is radius of specimen; h is height of specimen.

In the case of calculating the maximum pressure that is responsible for failure, the equation can be reduced to the following equation and tensile strength can be computed as:

$$\delta_t = \frac{P}{\pi(kbh - a^2)} \quad (4)$$

Where δ_t is tensile strength; P is applied load; $k = \tan(2\alpha + \varphi)$ this value depends on the angle of friction, compressive-tensile strength ratio and sample-punch dimension ratio; b is radius of specimen; h is height of specimen.

4.4. Unconfined Penetration Test

Unconfined penetration test is an indirect test adjusted from double punch test by Fang and Fernandez [38] to measure the tensile strength of soil [9]. Same as double punch test, this test requires the following assumptions to be made: (1) enough local soil deformability exists in both tension and compression in order to the limit analysis theorems to be applicable and viable for perfect plastic material behavior, (2) assuming the surface of failure of the adjusted Mohr-coulomb as a yield surface for soils [38]. One major advantage of unconfined penetration test is can be connected with any normal compaction test to calculate the CBR for different samples sizes and shapes easily. The plane of failure of this test is not predetermined and thus it will fail in the weakest plane only which results in measurement of true tensile strength [45]. The test involves the application of a vertical load to the two disks after placing them to the top and bottom of cylindrical sample until failure is met [38]. The same equations for calculating the tensile strength of soil of double punch test are used for unconfined penetration test.

4.5. Hollow Cylinder (Ring) Test

Hollow cylinder test is an indirect technique used to define tensile parameters of brittle materials [61]. In 1973, Al-Hussaini and Townsend [13] developed a tensile strength testing device for identifying the tensile characteristics of soils [48]. The test involves studying the behavior of soil under the alteration of the three principal stresses in triaxial conditions. This can be done by applying uniform and distributed pressures internally and externally to the soil sample to find the radial compressive and tangential tensile stresses. To achieve that, internal hydrostatic pressure must be introduced to the sample until tensile failure is met, then tangential tensile stress will be obtained [48]. When some radial cracks emerge suddenly parallel to sample axis, failure of hollow cylinder test occurs [13]. The hollow cylinder test consists of two ring-shaped platens where the specimen is placed, two thick membranes that surround the platens on inner and outer faces, pressure chamber that is filled with fluid and capable of tolerating very high confining pressure, base support that acts as basis for centralizing the device, two lateral deformation sensors for tracking and determining the change in both the inner and outer diameter laterally through the testing, two molds in which one is placed in the inner part and the other on the outer one of the compacted sample, and loading system to maintain a controlled confining pressure around the whole sample [13].

5. Advantages and Disadvantages

This section will describe the advantages and disadvantages of the most common soil tensile testing techniques.

Table 3. Previous works on direct tensile testing apparatus

Type of Test	Applicability	Advantages	Disadvantages
Direct methods	Applicable for most of the soil types as far as the load is applied uniaxial on the specimen	• Homogeneity of stresses and strains. • Can measure true stress-strain relationship under tension. • No need to correct the results to find the tensile strength. • Satisfies the condition of true uniaxial tension.	• Difficulty of applying a uniform stress distribution to the entire specimen. • The influence of stress concentration and eccentric loading cannot be avoided. • Complete elimination of misalignment is relatively impossible. • Difficulty for clamping or holding the end of the specimen.
Brazilian Tensile Test	Applicable for rocks, concrete and soil under the assumption of elastic theory.	• Most commonly used tensile strength testing due to its simplicity and efficiency.	• Requires a number of assumptions such as the material behaves with biaxial linear elasticity in two-dimensions and is homogeneous and isotropic in terms of its strength and elastic properties. • Used for soils in brittle conditions only.
Flexural (Bending) Beam Test	Applicable for soils under the assumptions of elastic bending theory.	• Its simplicity in performing. • Its loading conditions can simulate typical site conditions more closely.	• Requires assuming a linear elasticity behavior in the soil. • Neglecting the effects of beam's self-weight during the calculation.
Double Punch Test	Applicable for soils under the assumptions of theory of plasticity instead of elasticity.	• There is no stress concentration or misalignment from grips. • The simplicity of sample preparation. • Testing of specimens at various orientations. • Test doesn't require any heavy machines to be applied and CBR or compaction soil tests can be connected and linked with this test and perform the test in laboratory or field easily.	• The necessity of assuming linear elasticity. • The stress value in the field cannot be obtained exactly based on the loading and boundary. • More suitable for brittle materials such as rock, concrete and pavement materials.

Hollow cylindrical (Ring) Test	Applicable for brittle material.	• No clamping is required to set up a specimen so that misalignment stresses are introduced in the test. • The uniform tensile stress is acting on the entire volume of cylindrical specimen. • The magnitude of the radial compressive stress is considerably smaller than the tangential tensile stress. • The possibility of applying axial stress in addition to the internal and external pressure in many devices.	• The necessity of assuming linear elasticity or rigid plasticity to calculate the stress distribution. • The uniaxial direct tensile stress is not purely applied.

6. Conclusions

This paper has focused on reviewing available studies regarding the possible techniques and tests for measuring and assessing the tensile strength of soils. On the bases of the above statement the following points are concluded:

- Studying the tensile strength of soils is very significant and impactful on evaluating and understanding the development of tensile cracks.
- Direct tests can be used to give the best, accurate and precise results but it is harder to apply and needs suitable arrangement.
- Indirect tests can be used as an alternative to the direct ones that are easier to be performed but less accuracy.
- The most common tensile test technique is the Brazilian method that can be used for most of the brittle materials such as rocks, concrete and soils.
- Tensile strength of soil is progressively influenced by its water content.
- Using fibers in soil is an effective way to increase its tensile strength capacity.

7. Conflicts of Interest

The authors declare no conflict of interest.

8. References

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