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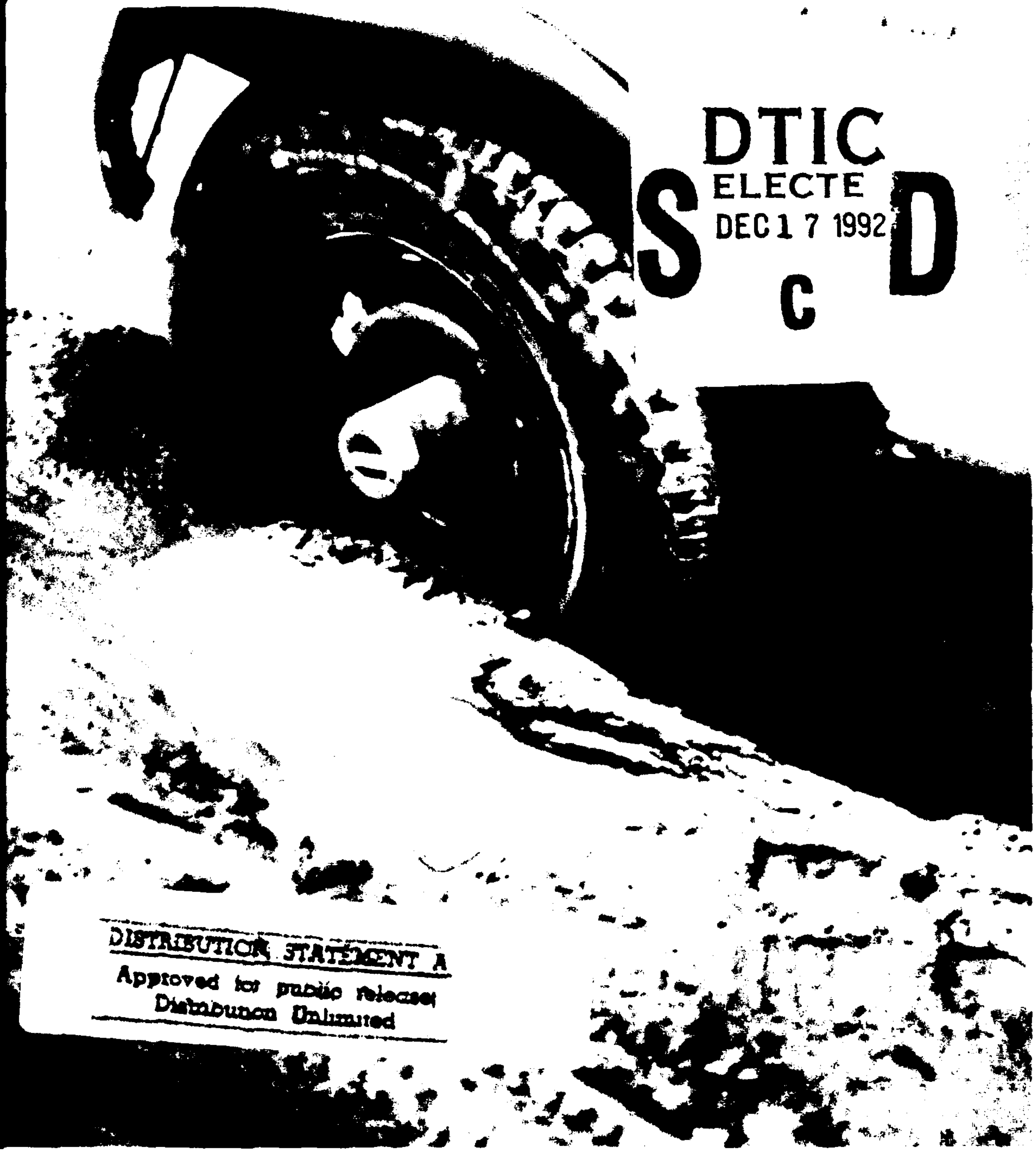
CRREL

Comparison of Thawing Soil Strength Measurements for Predicting Vehicle Performance

Sally A. Shoop

September 1992



Abstract

The CRREL Instrumented Vehicle (CIV), shear annulus, direct shear, and triaxial compression devices were used to characterize the strength of thawed and thawing soil. These strength values can be used in simple traction models to predict the tractive performance of vehicles. Strength was evaluated in terms of the parameters c' and ϕ' based on the Mohr–Coulomb failure criterion. It is proposed here that an instrumented vehicle is best suited for terrain characterization for mobility studies because the conditions created by a tire slipping on a soil surface are exactly duplicated. The c' and ϕ' values from the shear annulus were found to overpredict traction because of the low normal stress applied by the annulus and the curved nature of the failure envelope. Of all the tests, the direct shear test yielded the highest ϕ' value, most likely because the test was run at a slow deformation rate under drained conditions. The triaxial test results were the most similar to those from the vehicle. All test methods show ϕ' increasing with soil moisture up to the liquid limit of the soil and then decreasing. As measured with the vehicle, ϕ' was also found to be strongly influenced by the thaw depth.

Cover: The instrumented wheels of the CRREL Instrumented Vehicle can be used to measure the soil–tire shear strength required for vehicle traction.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, *Metric Practice Guide*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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illy A. Shoop

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PREFACE

This report was prepared by Sally A. Shoop, Research Civil Engineer, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The project was funded by DA Project 4A762784AT42, *Design, Construction, and Operations Technology for Cold Regions*; Task CS, Work Unit 007, *Off-Road Mobility in Thawing Soils*.

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The author thanks the following people who contributed to this work: Glenn Durell performed all the triaxial testing; Richard Roberts performed the direct shear tests; Stephen Decato, Rosanne Stoops, and Gunars Abele assisted with the shear annulus and the vehicle tests; and George Blaisdell, Gunars Abele, and Maria Bergstad provided many helpful comments regarding this paper.

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Comparison of Thawing Soil Strength Measurements for Predicting Vehicle Performance

SALLY A. SHOOP

INTRODUCTION

Objective

The objective of this work is to compare terrain strength measurements made using an instrumented vehicle with the more traditional soil strength measurements. In addition, the validity of using strength characterizations based on measurements with an instrumented vehicle to predict the tractive performance of other vehicles is assessed.

Because of technological advancements in tire rubber and tread design, the weak link in the soil–vehicle system is nearly always the soil strength. To predict off-road vehicle performance, the soil must be characterized. Here, a very simplistic model, based on the well known Mohr-Coulomb yield criterion, was used to predict vehicle performance. The soil strength parameters, cohesion (c') and internal angle of friction (ϕ'), and the vehicle weight and tire contact area were used as input to the model. Several different test methods for measuring soil strength were used to determine the most appropriate method. All tests were performed on a thawing silty sand as part of a larger study of vehicle mobility on thawing soils.

Background

In the past, a large number of vehicle mobility prediction schemes have been based on Cone Index values and empirical correlations generated from large data sets. Generally, a hand-held cone penetrometer is used to obtain a Cone Index of the soil. The penetrometer has the advantage of being portable, lightweight, and easy to use. However, the application of the Cone Index to research on vehicle mobility on thawing soils is problematic. The cone penetrometer was intended for gross estimates in "go" or "no-go" situations; it was not in-tended to differentiate between more subtle differences in terrain conditions. This makes it difficult to apply the method to research studies. In addition, as reported in Shoop (1989), cone penetrometer readings for a thawing silty sand do not correlate with the observed vehicle traction (Fig. 1). This lack of correlation has also been observed for other soil conditions by Wulfsohn et al. (1988).

Other methods of measuring soil strength have been applied to vehicle mobility. Chamberlain et al. (1988) and Blaisdell et al. (1987) tested cored soil samples in triaxial compression to characterize the soil conditions for mobility. Kogure et al. (1988) compared different soil strength tests (unconfined compression, vane shear, and direct shear) and determined that each test can give considerably different results. They note that the direct shear test resembles most closely the failure mechanism of soil beneath a tire. In the 1950s a field instrument called the Bevameter was developed (Bekker 1969). This apparatus was designed to load and fail the soil in a manner similar to that caused by a vehicle. The soil properties measured would then be more applicable for use in predicting vehicle performance.

The constitutive equations describing unsaturated soil behavior are very complicated. Soil strength is dependent on many things, such as soil density and degree of saturation, not to mention the natural inhomogeneity

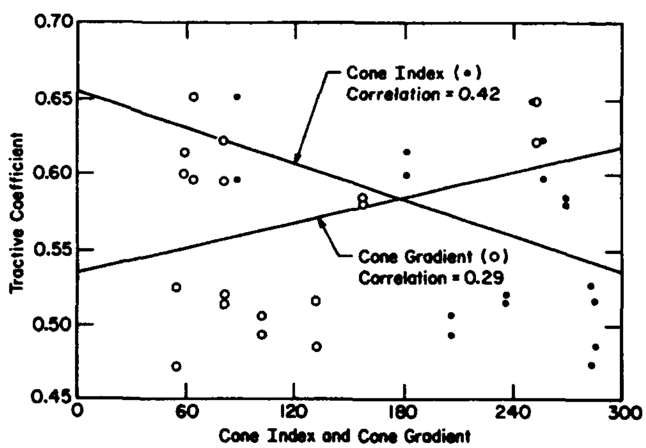


Figure 1. Poor correlation between cone index or cone gradient and tractive coefficient (after Shoop 1989).

and anisotropy of the material. Even for a uniform soil sample, the failure mode and strength depend on the stress distribution. Based on the complicated behavior of soils and the need for a reasonably simple description of soil behavior for practical mobility prediction schemes, it makes sense to duplicate the soil loading conditions created by a vehicle in order to simplify the soil behavior equations. The Bevameter attempted this, although imperfectly.

It seems only logical to measure the soil strength properties using a vehicle, thereby duplicating the loading conditions exactly. The mobility strength parameters can then be used to predict the performance of other vehicles. A method for doing this using an instrumented vehicle was developed for this purpose. In addition, a comparison between traditional soil strength measurements and those obtained using a vehicle is helpful in determining which technique best represents soil strength for mobility studies if a test vehicle is unavailable or impractical.

This report presents a comparison of soil strength measurements obtained using an instrumented vehicle with traditional soil strength measurements. The instrumented vehicle, the direct shear and triaxial compression devices, and a shear annulus device (part of the Bevameter) are used to characterize the shear strength of a silty sand under several conditions of moisture and thawing. The strength values are compared with measured values of vehicle traction. To indicate the potential of such measurements, an example is presented where the strength determined using the instrumented vehicle is used to predict the traction of another, much larger vehicle.

STRENGTH MEASUREMENT TECHNIQUES

The standard laboratory tests—triaxial compression and direct shear—were performed along with in situ tests using a shear annulus device and the CRREL Instrumented Vehicle (CIV). Both of the in situ methods aim to duplicate the type of failure initiated by a tire slipping on a soil surface and are therefore more closely related to vehicle mobility but less similar to the strength of the soil as measured by laboratory tests.

All in situ testing occurred in the vehicle mobility test basin in the Frost Effects Research Facility at CRREL. The test area is 36.6 × 13.1 m and can be frozen using freezing panels and thawed with elevated constant air temperature. The test soil used for this study was a frost-susceptible silty sand. The grain-size distribution curve is shown in Figure 2.

All the test data were analyzed in terms of cohesion, c', and internal angle of friction, ϕ', as determined by using the Mohr-Coulomb yield criterion:

$$\tau = c' + \sigma_n \tan \phi' \quad (1)$$

The parameters c' and ϕ', rather than any of the other soil mechanics or mobility parameters, were chosen to characterize soil strength for two reasons. First, they can be determined using simple and well-known testing and analysis techniques, assuming linearity or partial linearity of the Mohr failure envelope. Second, the parameters c' and ϕ' have some physical significance, ϕ' being related to friction and dependent on applied normal stress and c' being related to material cohesion. All of the parameters in eq 1 can be measured in both soil mechan-

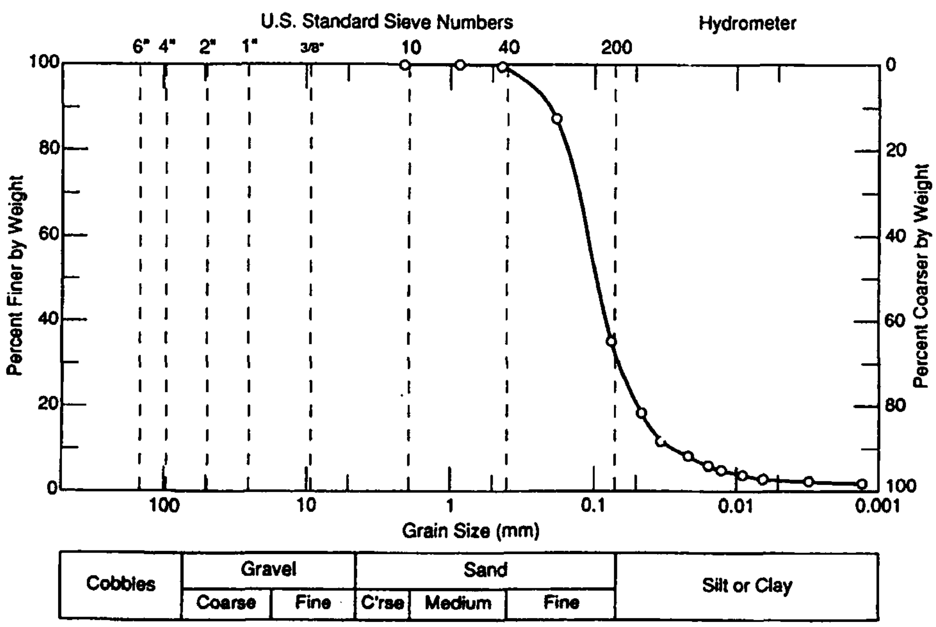
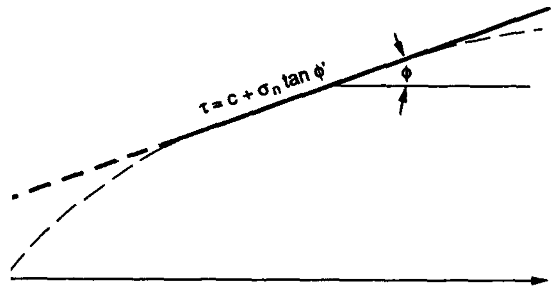


Figure 2. Grain-size distribution for Lebanon sand.



ure 3. The Mohr-Coulomb failure (or yield) criteri- :s a straight-line approximation of the curved failure 'elope (shown in dashed line).

and terramechanics. Although more complicated ns of yield criteria exist, the simplest form was ısen here as an initial approach. In addition, simpler thods are more likely to be adopted for practical ılication.

Since much of the work described here is based on Mohr-Coulomb model, I will begin with a brief cussion of the model. The Mohr failure envelope is ıerated by drawing a tangent to a series of Mohr's :les plotted in shear stress–normal stress space. The ulting tangent is not necessarily linear; in fact, it ıally takes on a concave downward shape (Fig. 3). ulomb, in studying the shear resistance of soils, ob- ved a stress-dependent component of shear strength l a stress-independent component. He noted that the :ss-dependent component is similar to sliding fric- n; he named that component "the angle of internal :tion" and gave it the symbol ϕ'. The other component :med to be related to the intrinsic cohesion of the terial, and he called it c'. Thus the Mohr failure en- ope could be approximated by a straight line with a pe of $\tan\phi'$ and an intercept of c'. The combination of ulomb's observations and Mohr's failure theory re- ted in the Mohr-Coulomb failure criterion, as ex- :ssed in eq 1. Using this model, the effect of the soil ıtrix suction is included in the cohesion term as ap- ·ent cohesion.

iaxial compression

In the triaxial compression test, a cylindrical sample ılaced in a loading frame and loaded vertically while onfining pressure is applied in the horizontal direc- n. By testing the soil at various confining pressures l plotting the corresponding Mohr's circles, the fail- : envelope of the material is determined, as indicated Figure 4.

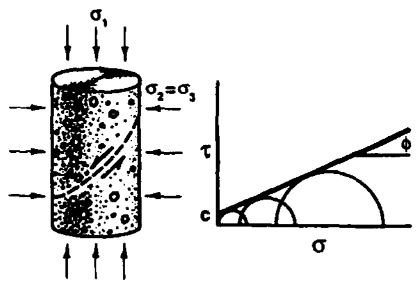


Figure 4. Schematic of the triaxial compression test and analysis of results.

Triaxial test specimens were machined from frozen cores taken from the vehicle mobility test basin. Cores were taken during different freeze cycles and soil conditions so that the water content and density of each specimen varied. All specimens were 5.1 cm in diameter and approximately 13 cm in height. The frozen samples were prepared for testing and then allowed to thaw at room temperature overnight. Tests were performed at room temperature. Four confining pressures were used: 0, 34.5, 68.9, and 137.8 kPa. The sample was loaded at a constant axial strain rate of 10% true strain per second. For a sample length of 12.7 cm, this corresponds to a maximum deformation rate of 1.27 cm/s. Previous work by Blaisdell et al. (1987) showed that the effect of higher strain rates on strength was small compared with the effects of other sample variations. The results of the triaxial confining test are summarized in Table 1.

Direct shear

The direct shear test is performed by mounting a cylindrical sample in a pair of rings and applying a shear force across the rings to shear the sample. This is done for a range of normal loads, and the peak (or residual) shearing force for each test is plotted against the applied normal load to determine c' and ϕ' values, as shown in Figure 5.

Table 1. Triaxial test data.

Sample no.	*Confining pressure (kPa)*	*Failure stress (kPa)*	*Water content (%)*	*Dry density (g/cm^3)*	*Total density (g/cm^3)*
s-9	0	70.97	16.0	1.592	1.846
s-6	0	163.98	16.5	1.672	1.948
s-1	0	175.01	18.7	1.654	1.963
s-3	0	207.39	18.8	1.659	1.971
s-4	34.4	55.81	11.6	1.539	1.718
s-3	34.4	122.64	7.4	1.704	1.830
s-2	34.4	115.75	9.7	1.701	1.866
s-5	68.9	228.75	21.7	1.558	1.897
s-12	68.9	229.38	18.4	1.630	1.931
s-7	137.8	319.70	15.1	1.574	1.811
s-11	137.8	266.64	12.5	1.629	1.833
s-4	137.8	320.39	18.6	1.650	1.957

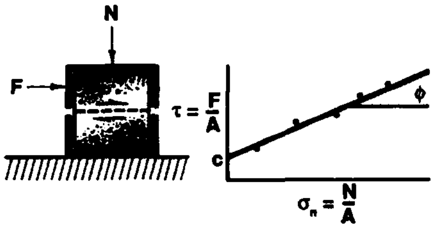


Figure 5. Direct shear test method and data analysis.

The test specimens for direct shear tests were obtained in several ways to get a range of soil conditions. Some samples were machined from frozen cores (similar to the triaxial test sample preparation) and then thawed overnight before testing at room temperature. Other samples were taken from the mobility test section as it thawed. These samples were taken by drive cylinders and then trimmed to the correct dimensions (6.35 cm diameter) or, when the samples did not survive transport, they were rebuilt to the correct sample size at the same density and moisture content as the undisturbed samples.

To duplicate more closely the conditions caused by a tire slipping on a soil surface, the samples were sheared at the fastest rate allowed on the test apparatus. This was 0.08 cm/s, which is still three orders of magnitude less than the typical shear rate caused by the slip of the wheel at peak traction (between 10 and 40 cm/s). Four different normal loads were applied to the sample. They were chosen to correspond to the load applied by the vehicle. The normal pressures ranged from 80 to 234 kPa. A different test specimen was used for each test.

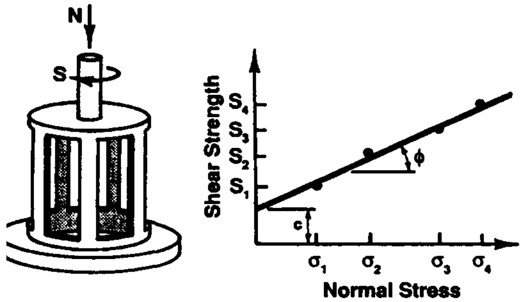
For each shear test, the shear force vs shear displacement was recorded. From such a graph, the peak shear stress and a residual shear stress can be chosen. The data obtained from all of the direct shear tests are shown in Table 2.

Shear annulus device

The shear annulus device is an instrument for measuring the shear strength of the terrain. A similar instrument, called a Bevameter, has been used in mobility work for many years. The shear annulus device used in these tests is shown in Figure 6. The basis of the apparatus is an annulus that rotates while a vertical load is applied. The annulus area is 127 cm^2, and it is coated with rubber. The torque caused by the shear resistance of the soil is measured with a torque cell located on the top of the annulus. A test sequence for determining the shear strength of the soil consists of performing three sets of tests where each set consists of a measurement at five different normal loads. The resulting normal stress applied to the soil surface ranges from 5.5 to 35.8 kPa. The annulus rotates at approximately 10 rpm, which is equivalent to shearing the soil at 4.2 cm/s at the midpoint of the annular ring. Although this is faster than the direct shear test, it is still an order of magnitude less than

Table 2. Data from direct shear tests. Data can be grouped by water content to calculate corresponding c' and ϕ'.

Sample no.	*Normal load (N)*	*Peak load (N)*	*Residual load (N)*	*Area (cm^2)*	*Water content (%)*	*Dry density (g/cm^3)*	*Total density (g/cm^3)*
12	243.48	146.78	93.41	30.53	21.5	1.501	1.823
8	243.48	179.25	160.13	30.61	12.6	1.573	1.772
tc12r	243.48	224.18	164.58	31.41	12.5	1.696	1.909
tc12	243.48	231.30	157.90	31.41	12.3	1.696	1.905
tc11	243.48	232.63	151.23	31.41	12.6	1.696	1.910
2	243.48	236.19	179.25	30.64	10.6	1.702	1.883
7	360.29	293.57	265.10	30.51	12.4	1.675	1.882
tc12	360.29	320.26	271.33	31.41	11.6	1.696	1.894
5	360.29	324.70	240.19	30.66	18.1	1.695	2.002
tc11	360.29	326.04	233.52	31.41	12.5	1.696	1.909
tc12r	360.29	346.94	263.32	31.41	12.3	1.696	1.905
4	360.29	373.63	272.22	30.35	16.9	1.735	2.028
6	556.00	389.20	345.61	30.75	20.5	1.470	1.772
11	556.00	411.44	350.06	30.51	10.6	1.631	1.804
9	556.00	422.56	341.16	30.53	19.1	1.614	1.922
tc12r	556.00	428.34	311.36	31.41	13.5	1.696	1.925
tc12	556.00	437.02	311.36	31.41	11.9	1.696	1.898
tc11	556.00	444.80	400.32	31.41	12.6	1.696	1.911
10	711.68	494.84	422.56	30.41	21.6	1.451	1.765
tc12	711.68	533.76	355.84	31.41	15.8	1.696	1.964
13	711.68	550.44	442.58	30.25	19.7	1.627	1.947
tc12r	711.68	551.55	389.20	31.41	11.5	1.696	1.892
tc12r	711.68	578.24	378.08	31.41	12.7	1.696	1.911
1	711.68	633.84	456.81	30.57	17.0	1.719	2.011



igure 6. Shear annulus device and data analysis.

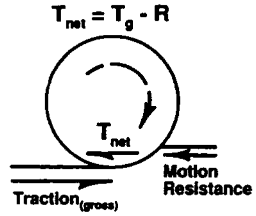


Figure 7. Net traction can be resolved into gross traction and motion resistance. Gross traction is the shearing force applied to the soil surface.

hear/slip caused by the tire. The data recorded with hear annulus device are analyzed in a fashion simi- o those obtained from the direct shear test in the ratory. The peak shear stress is determined for each nal stress. The shear stress and normal stress are ted to determine the c' and ϕ' of the soil (Fig. 6).

he shear annulus device was used to measure soil ngth in the test basin immediately prior to the ility tests with the CIV. The c' and ϕ' values calcu- d for each soil condition are listed in Table 3.

REL Instrumented Vehicle

ehicle mobility tests were performed in the Frost cts Research Facility using the CRREL Instrument- ehicle (CIV) described in Shoop et al. (1991) and op (1989). Briefly, the CIV is instrumented to mea- the forces at the front wheels in three perpendicular ctions. It also measures the speed of each of the front els and the true vehicle speed. Additional measure- its and instrumentation are included as desired. Both tion and motion resistance tests are performed. To sure traction, a braking force is applied to the rear els of the CIV while the front wheels are driven. The rator holds a constant vehicle speed as measured by a fifth wheel. Engine speed is gradually increased using the throttle, while the vehicle speed is held constant with the rear brakes. The resulting slip of the front wheels is recorded as the wheel-to-ground differential interface velocity (DIV). Traction is generally reported as the tractive coefficient: longitudinal force divided by vertical force. Motion resistance is measured by driving the vehicle at a constant speed and measuring the resisting force on the front, undriven wheels.

The soil strength parameters characterizing the failure caused by a slipping pneumatic tire were calculated from the vehicle traction and motion resistance data. The longitudinal force measured with the CIV during a traction test is equivalent to the net traction. The shear stress applied to the soil, however, is actually caused by the gross traction. Gross traction is obtained by summing the net traction from a traction test and the motion resistance from a resistance test (Fig. 7):

$$T_g = T_{net} + R \qquad (2)$$

where T_g = gross traction
T_{net} = net traction
R = motion resistance.

Table 3. c' and ϕ' calculated for each test sequence using the shear annulus, based on peak shear stress.

Date	c *(kPa)*	φ *(degrees)*	*Thaw depth (cm)*	*Water content (%)*	*Dry density (g/cm³)*	*Total density (g/cm³)*	*Saturation (%)*
Nov 9	4.44	33.5	3.81	20.0	1.509	1.811	67.9
Nov 10	0.88	36.5	10.16	23.4	1.546	1.907	83.9
Nov 10	0.30	37.9	10.16	23.4	1.546	1.907	83.9
Nov 10	0.92	36.6	10.16	23.4	1.546	1.907	83.9
Dec 20	0.90	38.4	*	13.0	1.699	1.920	58.9
Dec 20	1.54	37.9	*	13.0	1.699	1.920	58.9
Dec 27	2.82	36.8	*	9.0	1.611	1.756	35.6
Dec 27	4.13	34.8	*	9.0	1.611	1.756	35.6
Dec 27	3.17	33.5	*	9.0	1.611	1.756	35.6
Dec 28	2.27	33.1	3.81	24.2	1.516	1.883	82.9
Dec 30	3.72	29.9	5.08	27.0	1.547	1.965	97.0
Dec 30	0.25	30.7	5.08	27.0	1.547	1.965	97.0

* Soil totally thawed.

Table 4. c' and ϕ' calculated from CIV tests for each soil condition.

Date	c' *(kPa)*	ϕ' *(degrees)*	*Thaw depth (cm)*	*Water content (%)*	*Dry density* (g/cm^3)	*Total density* (g/cm^3)	*Saturation (%)*
Nov 9	16.39	28.0	3.81	20.0	1.5088	1.811	67.9
Nov 10	15.36	20.0	10.16	23.4	1.5456	1.907	83.9
Dec 20	37.34	21.6	60.96	13.0	1.6992	1.920	58.9
Dec 27	46.64	17.0	60.96	9.0	1.6112	1.757	35.6
Dec 28	12.88	23.3	3.81	24.2	1.5152	1.883	83.0
Dec 30	40.37	11.0	8.89	27.0	1.5472	1.965	97.0

As long as the peak traction occurs when slip sinkage is small and DIV is low (as was observed for our case), gross traction can be accurately obtained from the two separate tests using eq 2.

The maximum shear stress applied to the soil is the peak gross tractive force (measured at the tire/soil interface) divided by the contact area of the tire. The normal stress is the measured normal load on the tire divided by the tire contact area.

$$\tau = T_g/A \qquad \sigma_n = N/A \tag{3}$$

where τ = shear stress applied to soil
T_g = gross traction.
A = contact area of tire
σ_n = normal stress applied to soil
N = measured normal load.

Tire contact area was measured by making a print of the contact patch of the tire on a hard surface. As with T_g, A remains reasonably accurate as long as sinkage is small.

Traction tests were performed at two or more tire inflation pressures and with various normal loads to vary the contact area and normal stress. Similar to the other strength measurement test methods mentioned earlier, shear stress and normal stress were plotted, and c' and ϕ' were calculated based on the Mohr-Coulomb failure criterion (Fig. 8). Such a plot was generated for each soil condition tested.

Because the tractive force developed is the result of interaction between the vehicle and the soil, c' and ϕ' obtained from vehicle tests would not necessarily be expected to correspond to the c' and ϕ' parameters used in classical soil mechanics. But the stress conditions and failure mechanisms of a pneumatic tire on soil are exactly duplicated, therefore the c' and ϕ' obtained should be more representative of the strength parameters needed for mobility calculations and should yield more accurate predictions.

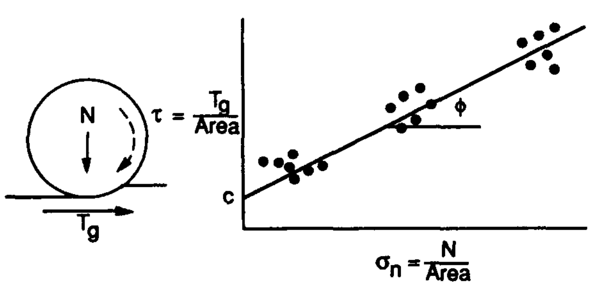


Figure 8. Vehicle traction test and data analysis.

Using the CIV mobility test results, c' and ϕ' were calculated for each set of soil conditions generated in the test basin. The results are listed in Table 4. (These are the same soil conditions tested using the shear annulus device, as mentioned earlier.)

DISCUSSION

The results of the strength measurements are analyzed in three ways:

1) comparison of test methods and the c' and ϕ' values obtained from each;

2) the effect of soil conditions on calculated strength parameters c' and ϕ'; and

3) the usefulness of c' and ϕ' from the different test methods for predicting traction.

Comparison of test methods

To compare the results of the different tests it is useful to recall that soil strength is nonunique. First, the term "strength" must be defined. For our case, the strength discussed is the peak shear strength. Second, and equally important, the measured strength depends on the conditions of the test, specifically on the loading conditions and stress distribution and the strain or deformation rate. (For the type of soil used in this study, a nonplastic silty sand, the strain rate has less effect on strength than the stress distribution.) The engineer generally specifies the type of strength test to be used so that real-world loading conditions are matched as closely as possible. Accordingly, it follows that, for vehicle mobility purposes, a strength test using a vehicle is sensible.

A comparison of the loading and deformation rate of the various soil strength test methods is shown in Table 5.

ble 5. Comparison of the loading characteristics of the ength test methods used.

	Normal stress (kPa)	*Deformation rate (cm/s)*	*Area of applied normal load (cm^2)*
ıxial	34–227	1.27	20.6
ect shear	80–234	0.08	31.6
ar annulus	5–36	4.2	126
rumented vehicle ıeel	124–200	10–40	387–581

llowing the design guidelines given above, since we using this information to predict vehicle perfornce, the test method chosen should match the loading ıditions caused by a vehicle. The deformation rates ›wn in Table 5 are measured with reference to the test paratus and are not those present on the actual soil ıture surface. The deformation rate listed for the trial test, for example, is the true axial strain on the sam- and not the deformation directly on the shear plane. e deformation rate imparted by the vehicle is the ferential interface velocity (the velocity of the wheel nus the velocity of the vehicle) and so indicates the e of the shear load application at the soil/tire interce. This is not necessarily the deformation rate on the ual shear failure plane in the soil.

Table 5 calls attention to notable differences in aped normal stress, deformation rate, and load area for test methods used in this study. The range of normal ess applied by the shear annulus is the lowest of all the t techniques and is considerably lower than the range plied by the test vehicle. The shear annulus device ed is a portable instrument; to apply higher stress the vice must be heavier and thus becomes quite cumberne. In addition, the deformation rate of the direct ear test was three orders of magnitude lower than the formation rate caused by the tire. This was the fastest e possible, however, using standard test equipment.

Since all of the tests were performed on Lebanon ıd under various thawing conditions, the tests from ch method were used to calculate an average c' and ϕ' the soil (for a range of moisture content and density). ese average failure envelopes are shown graphically Figure 9. The solid lines indicate the range of the rmal stress where the data were actually obtained. shed lines denote extrapolation of the failure envee beyond individual test limits.

It is easy to see from Figure 9 that both of the shear t methods (direct shear and shear annulus) yield a gher ϕ' and lower c' than the vehicle and triaxial test ta. This may be because the soil was tested under entially drained conditions for both of the shear tests cause of the relatively slow deformation rate and k of fluid confinement) and under undrained condi-

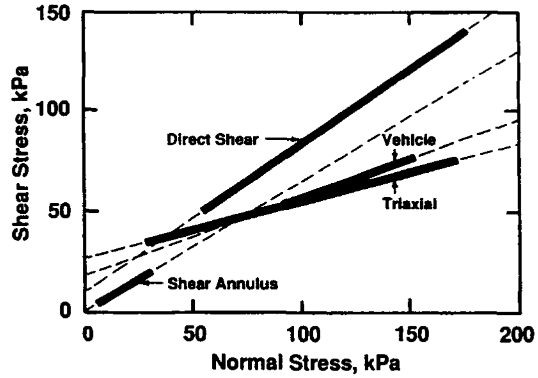


Figure 9. Comparison of failure envelopes for each test method. Solid lines mark the range of normal stress for each test.

tions for the vehicle tests (because of high strain rate) and triaxial tests. This figure also clearly shows that the shear annulus device operates at a much lower and more limited range of normal stress than the other tests, which may also lead to disagreement with the other test data. On the whole, the failure envelope from the triaxial test data most closely matches the failure envelope calculated from the vehicle tests.

When considering these various strength measurement methods, it is appropriate to mention some of the disadvantages associated with each. All of these tests are based on the assumption of a uniform stress distribution within the sample, at least within the zone of failure. In reality, this assumption is seldom satisfied. It is generally felt that the direct shear test is the worst offender. However, the triaxial test, the workhorse of a soils laboratory, suffers from stress concentrations at the end platens and variations in confining pressure from the flexible membrane around the soil. The shear annulus device tests actual field conditions but fails to duplicate the motion and loading of a tire. Although these features are duplicated exactly in the instrumented vehicle tests, the load applied by the tire and therefore the stresses in the soil, are nonuniform.

Because the shear annulus device and the vehicle tests were performed in exactly the same soil conditions, these two data sets can be examined more closely. The failure envelopes for the shear annulus and the vehicle for each of the soil conditions tested are shown in Figure 10. (The soil conditions corresponding to the dates labeled on the failure envelopes are given in Tables 3 and 4.) The ϕ' measured with the shear annulus is consistently higher than the corresponding vehicle failure ϕ'. This is quite reasonable when we recall that a typical failure envelope for earth materials is actually curved rather than linear and flattens at the higher stress levels (as shown in Fig. 3). The shear annulus data may be used to obtain a linear approximation of the failure

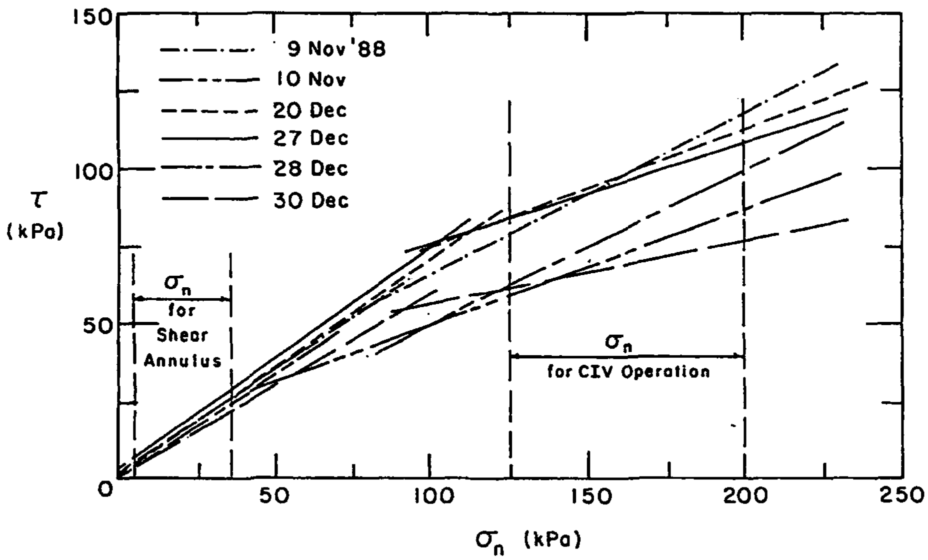


Figure 10. Failure envelopes from the shear annulus and the CIV for each set of soil conditions. Conditions correspond to those given in Tables 3 and 4.

curve at low normal stresses and the vehicle data to obtain a linear approximation that is representative of the higher normal stress. Together, then, these test results produce a failure curve of the shape typical for earth materials. When viewed in this way, the test results are compatible with each other and with the original Mohr failure theory.

Although the shear annulus has a much lower applied stress range than wheeled vehicles, this is not true for tracked vehicles. Thus the portable shear annulus may be quite useful in mobility studies of tracked vehicles.

Influence of soil conditions

In working with variably saturated thawing soils (or any layered soil of varying wetness), it is important to understand the effect of the soil conditions, such as moisture content and thaw depth, on the strength parameters. For all the soil conditions, c' remains very low while ϕ' varies. The soil condition with the most influence on strength was the moisture content. Figure 11 shows the effect of moisture content on ϕ' measured using the direct shear, shear annulus, and instrumented vehicle test methods. There were not enough data from the triaxial tests for a similar analysis. For each test method, the trend shows ϕ' increasing until the water content of the soil is near the liquid limit of the soil, and then dropping. (For the soil used in this study, liquid limit = 20%.) Similar results have been reported by others (Ayers 1987, Harrison 1966).

The same trend can also be seen in the vehicle traction data when tractive force is plotted against soil moisture content (Fig. 12). Traction increases or remains constant with increasing soil moisture until the moisture

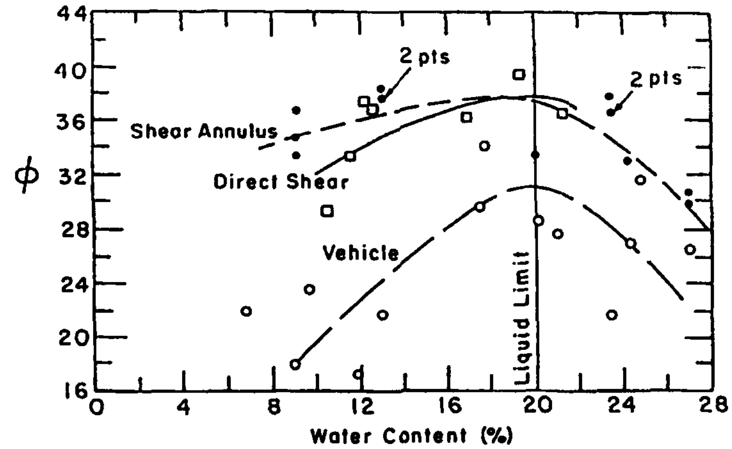


Figure 11. ϕ' increases with water content until the liquid limit is approached and then drops rapidly.

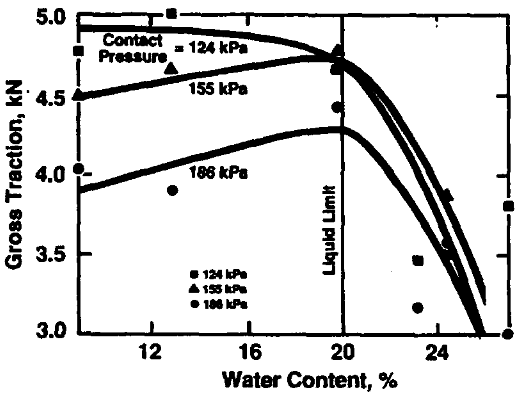


Figure 12. Traction increases with water content (as a function of contact pressure) and then drops sharply when water content reaches the liquid limit.

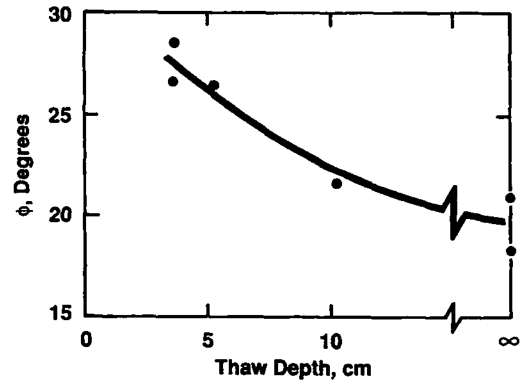


Figure 13. As calculated from the CIV, ϕ' decreases with thaw depth up to approximately 15 cm (the depth of influence depends on the soil and the vehicle).

content reaches the liquid limit, and then traction decreases rapidly. This trend exists for each of the tire contact pressures; however, the slopes and magnitudes vary notably at water contents below the liquid limit. At moisture levels greater than the liquid limit, tractive response is insensitive to contact pressure.

Changes in thaw depth also influence soil strength measurements. In the frozen and thawing soil, the strength tests are essentially a measure of the composite strength of the thawed layer and the underlying frozen ground, as detected by the measurement technique. Because of the nature of the laboratory tests and the test specimens, the effect of thaw depth cannot be determined in the laboratory. Of the field tests (shear annulus and instrumented vehicle), the effect of thaw depth is most apparent in the data from the vehicle. This is because the applied stress distribution caused by the vehicle load extends much deeper than the stress applied by the shear annulus.

The variation in $\phi'_{vehicle}$ with thaw depth can be seen in Figure 13. Clearly, ϕ' is most strongly influenced by thaw depth for shallow thaws. As thaw depth increases, ϕ' calculated from a tire shearing the soil surface soon becomes insensitive to changes in thaw depth. The depth at which the frozen layer no longer influences ϕ' is dependent on both soil type and the stress applied by the vehicle. Although soil density also affects strength, the density variation in this study was small and therefore the results are inconclusive.

Traction prediction

The knowledge of how the different soil strength tests compare with each other and how the soil conditions influence the strength is important if soil strength parameters are to be used in a model to predict vehicle traction. Rewriting the Mohr-Coulomb equation (eq 1) in terms of tractive force (using eq 3) we get

$$T = c'A + N \tan\phi' \qquad (4)$$

where T is the predicted maximum gross traction that a particular tire can produce based on soil strength. If we know A and N for a vehicle and measure c' and ϕ' for the soil with one of the test methods, peak traction can be predicted.

Since side-by-side measurements were made using the shear annulus device (for c' and ϕ') and the CIV (for traction), these traction values can be compared with traction values predicted (eq 4) using c' and ϕ' obtained from the shear annulus device. Figure 14 shows the resulting measured vs predicted traction values. The solid line indicates where the measured values equal the pre-

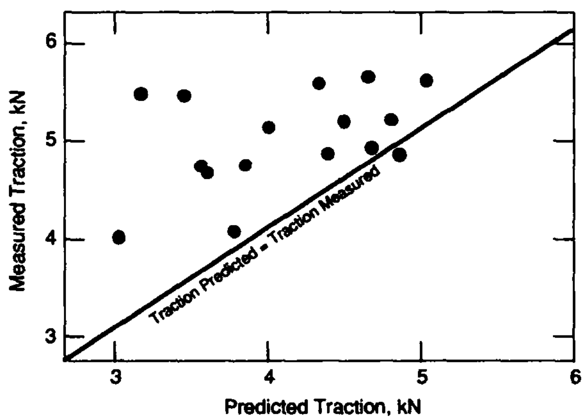


Figure 14. Traction predicted from the shear annulus overpredicts traction measured with the CIV because of the low normal stress applied with the shear annulus.

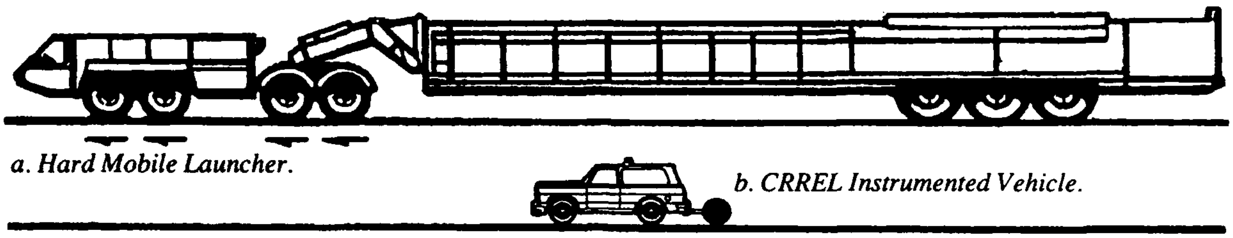


Figure 15. Comparison of the Hard Mobile Launcher (HML) and the CRREL Instrumented Vehicle (CIV) roughly to scale.

dicted values. It is immediately obvious that using eq 4 with c' and ϕ' from the shear annulus overpredicts peak vehicle traction. This was expected since the shear annulus measures c' and ϕ' in a lower range of normal stress than that applied by the vehicle (Table 5 and Fig. 9, 10), and thus is in a region where the slope of the failure curve is steeper, as discussed earlier. The predictions may have been better for a vehicle with lower ground contact pressure (i.e., a tracked vehicle).

To use the c' and ϕ' calculated from the CIV, independent traction measurements from another vehicle were necessary. No other vehicles were tested in the soil basin during this study, but Blaisdell et al. (1987) report side-by-side tests of the CIV and the Hard Mobile Launcher (HML), where both vehicles were tested on the same soil conditions and the tire pressure of the CIV was varied so that c' and ϕ' could be calculated. The HML weighs 47.2 kN and is 35 m long as compared with the CIV at 1.3 kN and approximately 5 m long. A schematic of the vehicles, roughly to scale, is shown in Figure 15. Vehicle–soil loading parameters and measured traction and resistance are given in Table 6.

Using the traction and resistance measured with the CIV, a c' and ϕ' of 69 kPa and 22.5°, respectively, is calculated. These terrain strength values can then be used in eq 4 to predict a peak gross traction provided by each of the driven wheels of the HML of 33.217 kN: since the HML has eight driven wheels, the total predicted gross traction for the vehicle is 265.733 kN. The measured gross traction calculated from the net traction plus the motion resistance (eq 4) is 240.392 kN. The difference between the predicted and measured gross traction is approximately 10%, which is remarkably low. Although only one example, this case indicates that an instrumented vehicle can be used to obtain accurate soil–vehicle strength parameters for predicting the traction of other vehicles.

CONCLUSIONS

The conclusions of this study can be summarized as follows:

1. An instrumented vehicle can be used to measure terrain strength parameters based on the Mohr-Coulomb yield criterion. The c' and ϕ' values obtained are comparable to those obtained using other soil (and soil/rubber interface) strength measurement techniques. Using an instrumented vehicle to characterize the terrain is the preferred technique for mobility studies, because the conditions created by a tire slipping on a soil surface are exactly duplicated.

2. Of the strength tests used, the failure envelope from the triaxial test was most similar to the failure envelope calculated from the CRREL Instrumented Vehicle.

3. The direct shear tests yielded the highest values of ϕ', much higher than ϕ' based on vehicle tests. This was probably because of the drained conditions and the very slow deformation rate of the direct shear test.

4. The ϕ' calculated using a portable shear annulus is also higher than ϕ' calculated from the instrumented vehicle. The higher ϕ' is a result of the low normal stress applied during the shearing tests (well below typical wheeled vehicle contact pressures) and the curved nature of the failure envelope at low normal stress (i.e., the failure envelope cannot be linearly extrapolated to a

Table 6. Tire loading and contact area of the CIV and the HML and corresponding traction and resistance measurements made in the same soil conditions (after Blaisdell et al. 1987).

Vehicle	*Tire inflation pressure (kPa)*	*Normal load on wheels (kN)*	*Tire contact area (cm^2)*	*Measured net traction (kN)*	*Measured resistance (kN)*
CIV	179	6.027	279.4	4.231	0.190
CIV	103	6.027	345.2	4.654	0.216
HML		49.133	1864.5	204.363	36.029

wheeled vehicle's normal stress range). Although the parameters calculated from the shear annulus overpredict the traction of the instrumented vehicle, they may be useful for predicting traction for low ground pressure or tracked vehicles.

5. All test results indicate that ϕ' is strongly influenced by soil moisture; it increases with moisture content up to the liquid limit of the soil, and then decreases rapidly with additional moisture.

6. Peak tractive force follows the same general trend as ϕ' with increasing moisture content. Below the liquid limit, reduced contact pressure and increasing moisture content result in improved traction. Above the liquid limit, traction decreases rapidly with increased water content, and the effect of contact pressure is negligible.

7. The ϕ' as measured by the vehicle is strongly influenced by the thaw depth of the soil. ϕ' rapidly decreases with thaw depth for shallow thaws, but becomes insensitive to thaw depth at deep thaws.

8. The CIV can be used to characterize the terrain for input into traction models such as those based on the Mohr-Coulomb failure criterion. With this information, the upper limit of traction for other vehicles such as the Hard Mobile Launcher can be predicted.

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13. ABSTRACT (*Maximum 200 words*)

The CRREL Instrumented Vehicle (CIV), shear annulus, direct shear, and triaxial compression devices were used to characterize the strength of thawed and thawing soil. These strength values can be used in simple traction models to predict the tractive performance of vehicles. Strength was evaluated in terms of the parameters c' and ϕ' based on the Mohr–Coulomb failure criterion. It is proposed here that an instrumented vehicle is best suited for terrain characterization for mobility studies because the conditions created by a tire slipping on a soil surface are exactly duplicated. The c' and ϕ' values from the shear annulus were found to overpredict traction because of the low normal stress applied by the annulus and the curved nature of the failure envelope. Of all the tests, the direct shear test yielded the highest ϕ' value, most likely because the test was run at a slow deformation rate under drained conditions. The triaxial test results were the most similar to those from the vehicle. All test methods show ϕ' increasing with soil moisture up to the liquid limit of the soil and then decreasing. As measured with the vehicle, ϕ' was also found to be strongly influenced by the thaw depth.

14. SUBJECT TERMS

Freeze/thaw	Thaw depth	Vehicle mobility
Shear	Traction prediction comparison	Water moisture content
Soil strength	Unsaturated soil	

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