Soil Cement Tensile Strength and Modulus as a Function of Unconfined Compressive Strength

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Abstract

In the past, the designers of DSM have analyzed various failure modes and then specified a minimum unconfined compressive strength (UCS) for the soil-cement. The specified minimum UCS reflected the compressive stress in the soil-cement under design loads and an appropriate factor of safety. With the increased use of finite element analysis for the design of DSM applications where allowable strain as well as stress are considered, there is a growing trend for designers to specify a modulus and occasionally a tensile strength for the soil-cement in addition to the UCS. This paper compares the relationship of the modulus and the tensile strength to the UCS for soil-cement from a recent DSM project with unique testing requirements. These results are compared to published data. The case is made that designers should utilize these published relationships to characterize the required strength and stiffness by a single acceptance criterion: UCS.

Introduction

As the use of DSM has increased in popularity so has the use of service state deformation analysis in lieu of more traditional failure mode analysis. Most DSM designers are interested in the appropriate modulus values and occasionally tensile strength values of soil-cement as well as simply the unconfined compressive strength (UCS) of soil-cement.

Although there are numerous published correlations between the UCS of soil-cement and the tensile strength and the modulus of soil-cement, some DSM project specifications are produced which have acceptance values for tensile strength, modulus, and UCS. If this specification of multiple strength properties is consistent with the nature of soil-cement, then there is really no harm except for the expenditure of client money on unnecessary testing. If however the multiple strength properties specified are inconsistent with the material properties of soil-cement, then the specifications can create the expectation that the DSM contractor can somehow create a custom soil-cement with tensile strengths and modulus characteristics which are unachievable.

This paper presents a brief summary of a project in Burnaby, B.C. which specified minimum values for the tensile strength, modulus, and UCS of the soil-cement. A comparison of those test results to published correlations between the UCS and the tensile strength is presented. Additionally, a comparison modulus derived from two different methods of testing is presented along with a comparison to published correlations between UCS and modulus for soil-cement.

Subsurface Conditions

A grid pattern of DSM was specified on a site in Burnaby, B.C. which was located adjacent to a small stream. The soil at the site consisted of several meters of peat over laying marine silts to a maximum depth of 15m. Below the marine silts was a dense granular till layer. The marine silt was soft to very soft. The surrounding topography graded slightly towards the adjacent stream.

Over the years, the surrounding area had been used as a landfill for the disposal of excavation spoils from projects in the surrounding region. It had been noted that fill placement of several meters would result in a bearing failure of the underlying marine silts.

Design

The two proposed commercial structures on the site were two stories in height. While the vertical loading from the structure was minor, the lateral loading from the design seismic event was significant. The expected lateral spread of the surrounding area during a seismic event resulted in a foundation design consisting of a grid pattern of DSM panels to resist the lateral spread while providing the necessary support to the vertical loads of buildings.

The significant difference in the magnitude of the vertical loads from the buildings and the magnitude of the lateral spread loadings from the design seismic event led the designer to evaluation the conditions separately. The vertical loads were divided by the area of the DSM panels and a factor of safety to determine a minimum UCS for the soil-cement. The lateral spread loads were applied to the end panel which was treated as a continuous beam across the ends of the shear panels to determine a minimum tensile strength in bending. A finite element analysis was performed to establish a minimum modulus for the soil-cement based on the acceptable lateral deformation of the entire composite gird system.

The divergent design methods and separate loading conditions resulted in the following minimum strength requirements for the project: UCS of 500 kPa, tensile strength of 300 kPa, and modulus of 300,000 kPa.

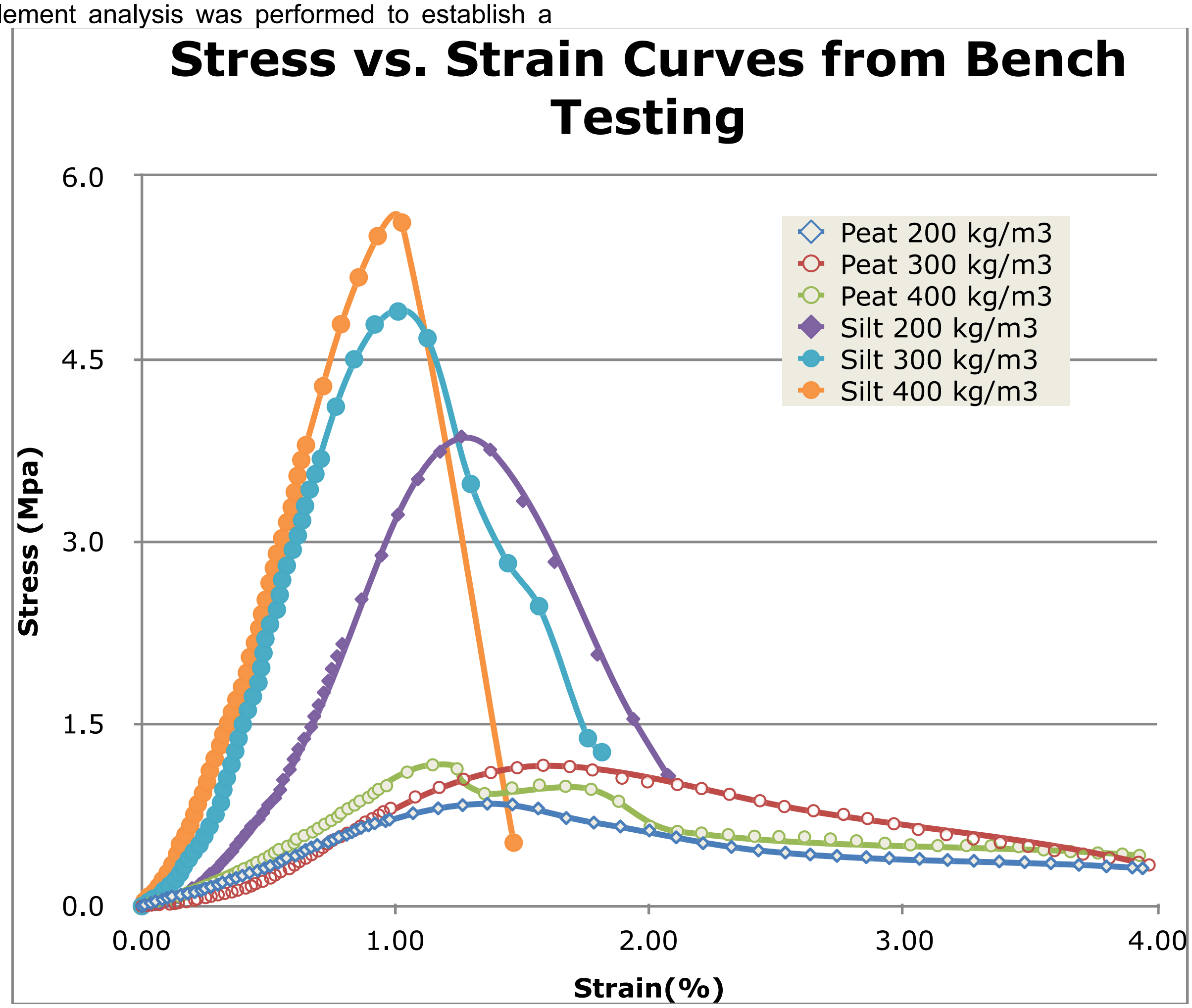


Figure 1. Bench Test Soil-Cement Compressive Stress-Strain Behavior

Bench Testing Results

Recognizing the fact that a soil-cement with an UCS of 500 kPa would not be expected to achieve a tensile strength of 300 kPa, the contractor performed extensive bench testing using peat and silt samples obtained from the site using a solid stem auger prior to mobilizing the DSM equipment to the site.

Based on the rule of thumb that tensile strength is approximately 10% of UCS for soil-cement, the contractor anticipated the need to achieve an UCS of 3,000 kPa in order to meet the minimum specified tensile strength of 300 kPa. Considering the initial UCS results from the bench tests shown in Figure 1, it is easy to observe the difference in the behavior of the soil-cement made from the silt versus the peat. The UCS results from the bench testing confirmed that the minimum tensile strength could be achieved in the silt and not in the peat.

Based on the UCS results for the peat in the bench trials, there was no small concern as to whether the minimum tensile strength could be achieved in the upper peat soils in the site. Preliminary tensile strength testing of the soil-cement samples made from the peat seemed to indicate that the pear produced soil-cement with a tensile strength to UCS ratio considerably higher than 10%. Additionally, the contract planned on pre-trenching the DSM alignment to a depth of 2m prior to mixing. This pretrenching would serve to remove a portion of the peat as well as provide a reservoir for the soil-cement soils during the DSM installation. Finally, the contractor was counting on some vertical mixing of the silt with the peat which was anticipated to result in higher UCS in the upper soil profile than was achieved with the 100% peat samples in the bench testing.

Modulus Testing

The specifications for the project required a minimum unconfined modulus E50 of 300,000 kPa. The specifications were silent on the testing method to be used and the local testing laboratory indicated that the modulus was typically obtained by measuring the displacement on the end platens during an ASTM C39 UCS test and using that displacement to calculate the strain on the sample. The derived strain and stress from a simple UCS test could then be used to calculate the E50.

Although this method of determining the E50 of soil-cement samples is relatively inexpensive and can be performed by most conventional material testing laboratories, it is inaccurate. As illustrated in Figure 2, the displacement measured at the end platens includes the conformance displacement of the end platens as they distort the ends of the soil-cement sample during loading as well as the strain of the sample. Since the displacement of the end platens does not differentiate between the sample strain and the conformance displacement, the recorded displacement is higher than the actual strain of the sample. The E50 calculated with the total end platen displacement is therefore too low by an unknown amount.

In order to determine an accurate value of E50 for soil-cement samples it is necessary to measure the strain of the sample directly during loading of the sample. The direct measurement of the strain can be achieved using ASTM C469. With this testing method, two collars are attached to

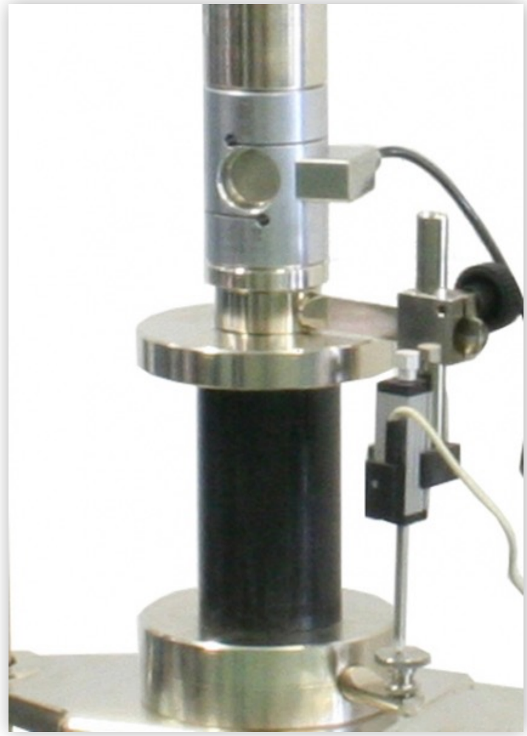


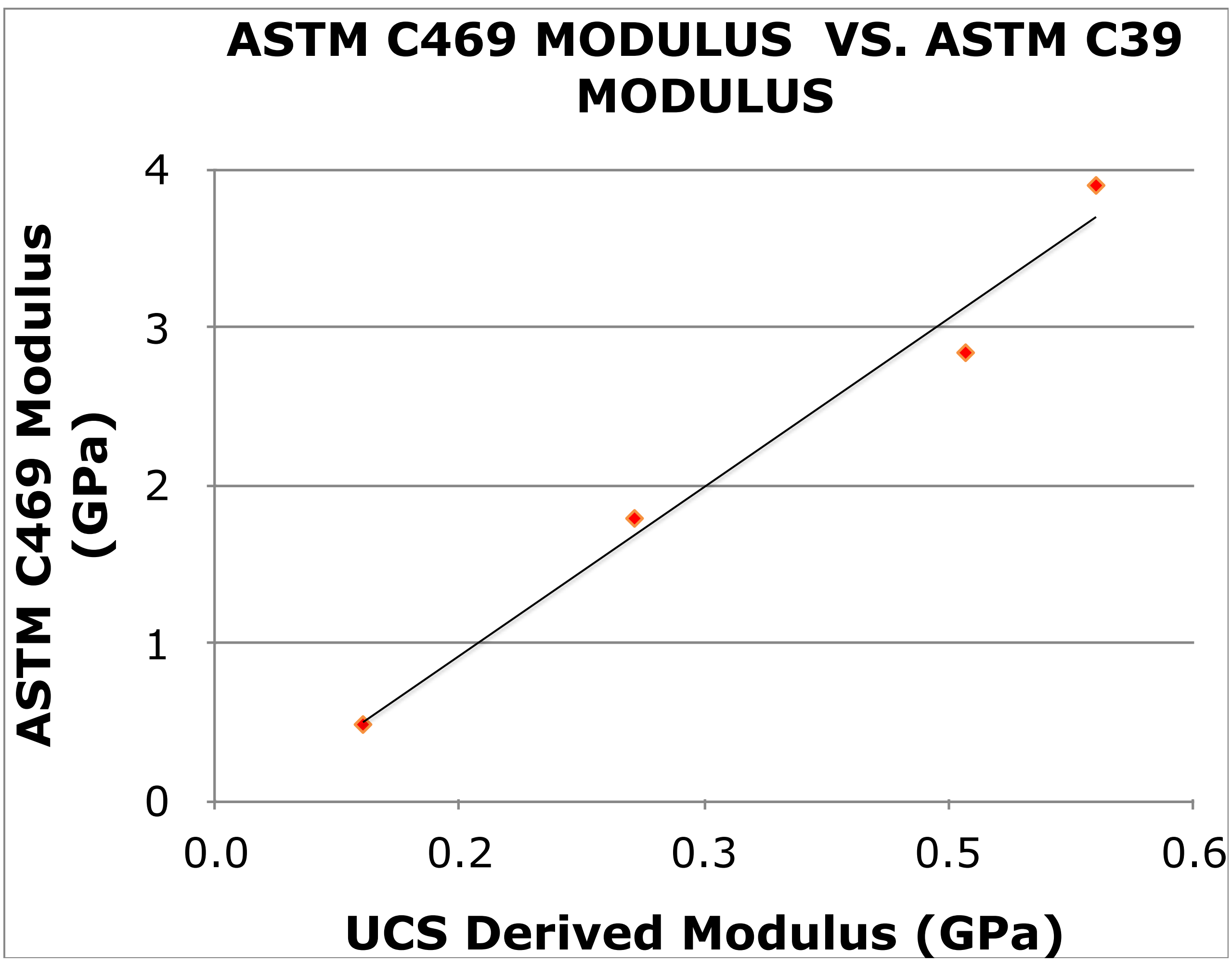
Figure 2. ASTM C39 Modulus Determination

Figure 3. ASTM C469 Modulus Determination

the soil-cement sample between the ends platens as shown in Figure 3. The displacement between the two collars is measured and recorded with LVDT's attached between the two collars. This method removes the erroneous displacement resulting from end compliance that is recorded during the C39 test and results in a more accurate calculation of the E50 of soil cement samples.

In order to determine the extent of the difference between the two testing methods for determining the E50 of soil-cement, the Contractor engaged a geotechincal testing laborary to perform side by side testing on cylinders taken from the same bench test sample using both the C39 and the C469 methods. Although the authors could not find any similar published data, it is widely recognized that the E50 deteremined from C469 is higher than those determined from C39 tests.

The graph of the four sets of parallel modulus test results are shown in Figure 4. The linear trendline on the graph indicates that the E50 value determined from the ASTM C469 test is 6.8 times greater than the E50 value determined from the C39 test method. Since the samples were not tested at the same date, a portion of the difference can be attributed to the strength gain with age of the soil-cement samples. However, even when the results are normalized to account for the difference in the age and strength of the samples, the ASTM C469 test mehods yields a modulus value roughly six times higher than the moduluc value derived form ASTM C39 testing with end platen displacement measurement.



Published Modulus to UCS Correlations for Soil-Cement

A literature search by the authors during the initial bench testing of this projection yielded two published correlations for E50 as a function of the UCS for soil-cement.

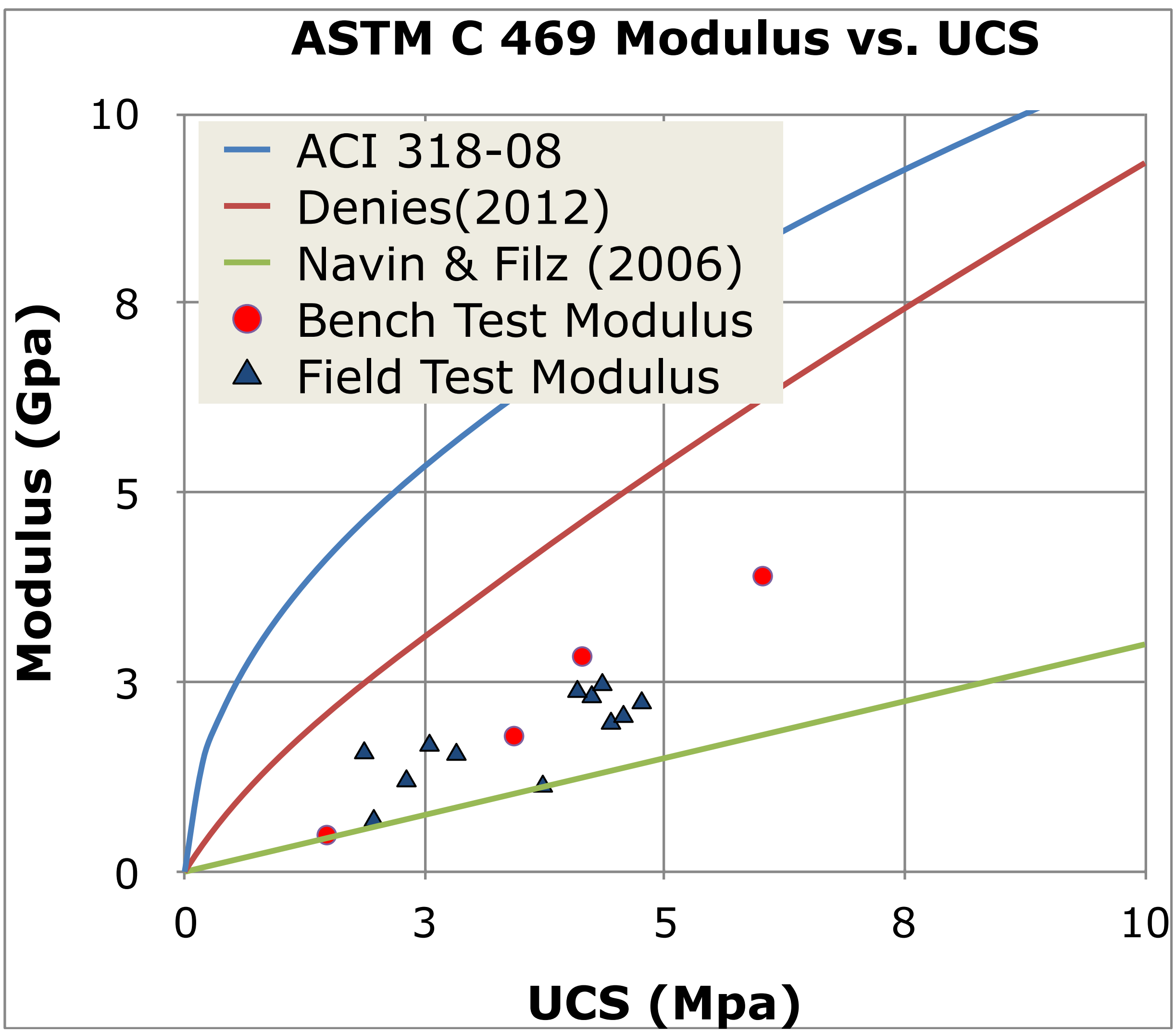
$E_{50} = 300 \times UCS$ (Navin & Filz, 2006)

$E_{50} = 1482 \times (UCS)^{0.8}$ (Denies et al, 2012)

The C469 test data from this project is plotted against the UCS in Figure 5. For comparison the two correlations noted above have also been plotted along with the ACI relationship for normal strength concrete.

It can be seen in the graph, that the Navin & Filz correlation consistently underestimates the E50 based on the UCS of the soil-cement. In personal communication with the authors of that correlation, we understand that the data used to develop that correlation was derived from ASTM C39 modulus test results. Based on the earlier discussion about the two test methods, it is understandable why that correlation would underestimate the modulus based on UCS test results.

The correlation presented by Denies et al consistently overestimates the modulus based on the test data from this project. The authors have no plausible explanation as to why this correlation overestimates the modulus so much compared to both the test data and the other published correlation. It is noteworthy that the Denies et al correlation is not much lower than the ACI correlation which is based on normal strength concrete data. It may be that the Denies et al relationship was developed from higher strength soil-cement test data possibly from jet grout samples than that used by Navin & Filz.



Tensile Strength Testing

The specified minimum tensile strength of 300 kPa was determined on the project using a splitting method, not a flexural beam method. The splitting method involves applying a vertical line load along length of the test cylinder or sample until the sample splits as depicted in Figure 6 below. The maximum load applied is used along with the dimensions of the cylinder to calculate the splitting tensile strength using the following equation:

Splitting Tensile Strength = 2 x P / (π x L x D)

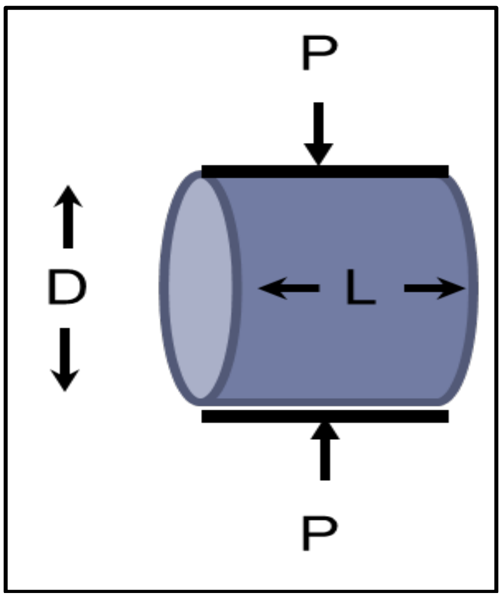


Figure 6 – Illustration of Splitting Test

ASTM C496 Splitting Tensile Strength for Cylindrical Concrete Specimens utilizes a test cylinder with a length to diameter ratio of 2 and loading rate of 0.7 to 1.4 MPa/min. The testing apparatus for ASTM C496 is shown in Figure 7.

ASTM D3967 Splitting Tensile Strength of Intact Rock Core Specimens is essentially the same type of test except the specimen has a length to diameter ratio of 0.2 to 0.5 and the specimen is loaded at 3 to 21 Mpa/min.

Based on the designer's requirements, the soil-cement samples on this project were tested using the Brazilian Testing Method which is a variation on the ASTM D3967 method. There are two distinguishing features between the two ASTM testing methods. First, the concrete cylinder splitting test utilizes a much longer sample for splitting which in the case of soil-cement may serve to develop more of an average tensile strength due to the length of the sample than the smaller disk used in the rock core or Brazilian method. In the case of soil-cement cores, only the highest strength material would be expected to survive the coring process as well as the sample preparation process which involves cutting the core to achieve the required L/D ratio of 0.2 to 0.5. Second, the rock core or Brazilian test method utilizes a much higher loading rate which would be expected to yield a higher splitting tensile load based on the higher rate of loading as compared to the concrete cylinder testing method.

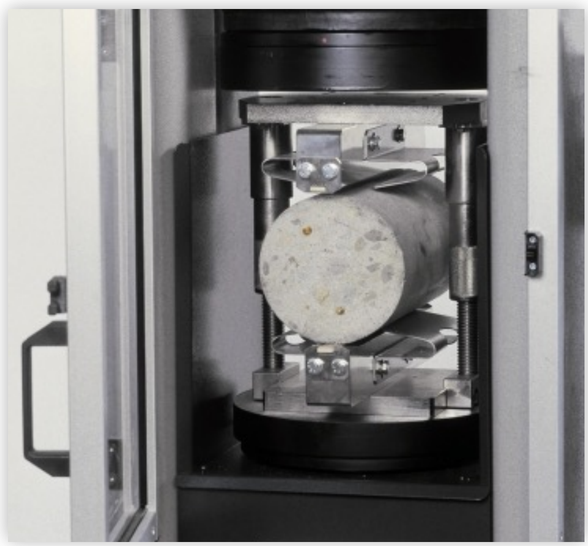


Figure 7. ASTM C469 Concrete Cylinder Tensile Testing Apparatus

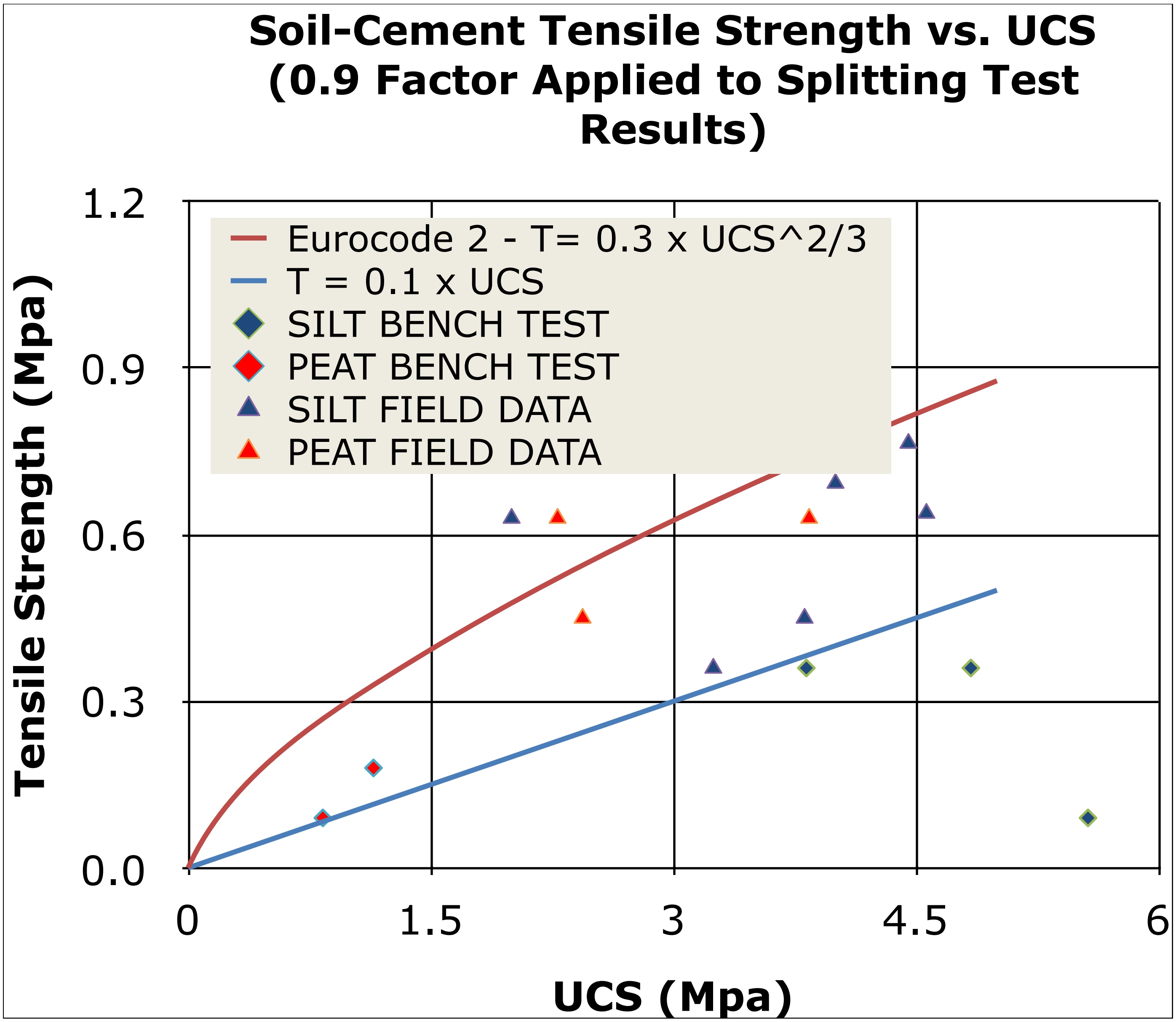
As with all ASTM test methods, there is no guidance on how to determine the actual tensile strength of soil-cement one should be using in design calculations from the splitting tensile strength determined directly from the test. The Eurocode (EN 1992-1-1) recommends using 90% of the splitting tensile strength as the actual tensile strength of the concrete being tested. Noting that there is no specific recommendations for the reduction factor for soil-cement in the literature, the authors have used this correlation for the data presented from the splitting tensile test on this project.

Published Tensile Strength to UCS Correlations for Soil-Cement

A literature search by the authors yielded two published correlations for tensile strength as a function of the UCS for soil-cement or concrete.

Ta = (0.1 to 0.15) x UCS (Porbaha et al 2002)

Figure 8 presents a plot of the tensile strength versus UCS for both bench test cylinders and production core samples that were tested on this project using the Brazilian splitting test. The UCS was obtained from separate cylinders prepared from the same wet sample in the case of the bench tests and from the same core sample in the case of the field tests.



Ta = 0.3 x UCS 2/3 (EN 1992-1-1)

As is expected, the test results for the soil-cement show a considerable amount of scatter which is a testament to the variability of soil-cement strength as well as the impact of discontinuities in the individual cylinders and cores tested.

Conclusions

Although a designer may be tempted to take analysis results for tensile strength, modulus, and UCS insert those minimum strength properties directly into the specifications, the authors suggest that the more prudent approach would be to ask a simple question: are the strength requirements from the analysis consistent with the properties of soil-cement?

In order to answer this question, the designer is forced to compare the results of analysis with known correlations between UCS and the modulus or tensile strength of soil-cement. If the results of the original analysis are inconsistent material properties, the analysis should be rerun using a set of soil-cement properties which are internally consistent.

Once a consistent set of soil-cement properties are developed, they can be scaled up or down to provide the desired performance of the DSM system within the design methodology being used by the designer. The designer can then simply specify the required UCS for the contractor and avoid creating a contradictory set of strength requirements that could potentially result in litigation and that will inevitably result in unnecessary testing costs for the client.

Further research is needed to determine a more accurate correlation between the UCS and the E50 value of soil-cement. As shown by the testing on this project, the use of conventional end platen displacement during UCS testing to calculate the modulus significantly underestimates the E50 of soil-cement.

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