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16. Abstract

Researchers at the Texas Transportation Institute developed the Tube Suction Test (TST) for assessing the moisture susceptibility of granular base materials. The moisture susceptibility ranking is based on the mean surface dielectric value of compacted specimens after a 10-day capillary soak in the laboratory. The Adek Percometer™ is employed in the test to measure the dielectric value of specimens. Based on promising results of the test, the Texas Department of Transportation (TxDOT) began implementation of the TST statewide during 2001. This report provides an overview of research performed to develop and evaluate the criteria used for ranking materials in the test, describes recommended revisions to the test protocol, and details the proposed implementation plan.

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TUBE SUCTION TEST—INTERIM REPORT AND RECOMMENDATIONS

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Research Project Title: Development of a Test Procedure for the Tube Suction Test (TST)

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Transportation Institute (TTI), the Texas Department of Transportation (TxDOT), or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. Trade names were used solely for information and not for product endorsement. The engineer in charge of the project was Tom Scullion, P.E. #62683.

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INTRODUCTION

The Tube Suction Test (TST) was developed in a cooperative effort between the Finnish National Road Administration and the Texas Transportation Institute (TTI) for assessing the moisture susceptibility of granular base materials (*1*). The moisture susceptibility ranking is based on the mean surface dielectric value of compacted specimens after a 10-day capillary soak in the laboratory. This report provides an overview of research performed to develop and evaluate the criteria used for ranking materials in the test, describes recommended revisions to the test protocol, and details the proposed implementation plan.

CRITERIA DEVELOPMENT AND EVALUATION

The Texas Department of Transportation (TxDOT) originally funded research on the relationship between electrical and strength properties of aggregate base materials to assist in utilizing ground-penetrating radar (GPR) for non-destructive evaluation of pavements (*2*). In this study, dielectric values of 11 aggregates of known field performance were compared with strength properties at different moisture contents and densities. Strength was measured with resilient modulus testing and in terms of CBR using a dynamic cone penetrometer (DCP). Researchers also investigated the dielectric properties of frozen specimens.

Because dielectric values for three-phase mixtures of aggregate particles, water, and air are most sensitive to the volumetric percentage of unbound water in the aggregate matrix, and because water directly affects the mechanical properties of soil and aggregate materials, researchers were able to readily identify correlations between the electrical and strength properties of aggregates in the project. Relative changes in resilient modulus values, variations in CBR values measured with DCP, and differences in unfrozen water contents qualitatively inferred from electrical properties of frozen specimens were used to classify the aggregates into three categories based on dielectric value. The researchers reported increasing amounts of unfrozen water and descending trends of CBR and resilient modulus with increasing dielectric value. Especially in the first case, the amount of unfrozen water inferred in frozen specimens increased markedly for samples with dielectric values greater than 10 before freezing. For poor performing aggregates, especially those with dielectric values above 16, results showed decreases in resilient modulus of up to 75 percent from the dry to the wet states, where the latter was the equilibrium moisture content achieved after subjection to capillary rise (*3*). On the other hand, good aggregates did not imbibe substantial amounts of water and so did not experience significant strength loss.

Based on these findings, researchers developed an early version of the TST in a second TxDOT project (*4*). In the study, the dielectric values of soaked specimens were correlated with Texas triaxial strength values and compared with mineral components identified in the aggregate fines. The effects of stabilizers on improving the moisture resistance of specimens were also investigated. General findings of this project were that logical trends existed between dielectric values in the TST and the physical and chemical properties of the tested aggregates, the TST was adequately repeatable, and the test was sufficiently sensitive to the addition of additives known to improve the properties of the fines fraction of the aggregate matrix. The project resulted in the recommendation of the TST as a supplement to Item 247 of *Standard Specifications for Construction of Highways, Streets, and Bridges*. After subsequent discussion with TxDOT personnel, TTI researchers reduced the height of TST specimens from almost 300 mm to about 200 mm to be more consistent with existing TxDOT sample preparation techniques.

With this modification, two additional projects performed at TTI evaluated the ability of the TST to assess the frost susceptibility of aggregate base materials. A preliminary study investigating both unconfined compressive strength and frost heave showed that materials with higher dielectric values at the end of the TST exhibited lower strengths and experienced greater frost heave than materials with lower dielectric values (*5*). A follow-up effort then evaluated 35 specimens representing 10 aggregate base materials from Indiana, Minnesota, Pennsylvania, Texas, and Virginia (*6*). The results provided strong evidence that the TST can be used as a viable tool for specifying premier aggregate base materials in cold climates. Materials ranked as "good" in the TST imbibed significantly less water and experienced significantly less frost heave upon freezing than high-dielectric specimens. These good performers were characterized by lower fines contents and lower porosity, on average, than specimens with higher dielectric values. The findings suggest that aggregate base materials with dielectric values less than 10 in the TST may be confidently ranked as neither moisture nor frost susceptible.

A Finnish study further demonstrated that low-dielectric specimens have higher void ratios and experience significantly less permanent deformation than samples with higher dielectric values in the TST (*7*). In summary, the final dielectric value achieved by specimens in the TST generally corresponds to the void ratio, CBR, unconfined compressive strength, resilient modulus, permanent deformation, freezing characteristics, and frost heave behavior of aggregates. Based on these promising correlations of test results to engineering parameters, TxDOT began implementation of the TST statewide during 2001 (*8*).

RECOMMENDED PROTOCOL REVISIONS

The draft TST protocol has been given in an earlier report on this project and generally requires compaction of the aggregate sample at optimum moisture in four lifts to a finished height of about 200 mm inside a 152 mm diameter plastic mold (*8*). In order to accommodate triaxial strength testing of TST specimens immediately after soaking, this report recommends an important change in the compaction and testing procedures currently employed in the test.

Rather than compacting the moistened sample inside a plastic cylinder, the sample should be constructed inside a steel cylinder and extruded as described in TxDOT Test Method Tex-113-E. The bottom of the specimen should then be capped with a plastic base of 50 mm height, pre-drilled with the same hole pattern detailed in the draft TST procedure (*8*). A Texas triaxial cell should then be installed over the top of the specimen so that only the lower 25 mm of the base cap remains exposed, and drying and capillary soaking should be performed with the triaxial cell in place. Afterwards, if triaxial strength testing is desired, the cap should be carefully removed and the test performed. With an additional two or three 10 mm holes drilled in the plastic base cap, this testing arrangement will also accommodate seismic laboratory testing at any time during drying or soaking with the free-free resonant column apparatus developed at the University of Texas at El Paso (*9*). These changes are reflected in the revised protocol given in the appendix at the back of this report.

IMPLEMENTATION PLAN

Implementation of the revised TST protocol given in this report will be accomplished mainly through training seminars conducted by TTI personnel. Visits to at least six participating districts will entail brief explanations about the significance of the test, detailed presentations of the test protocol, demonstrations of the testing procedure, hands-on experience for TxDOT engineers and technicians, and arrangements for follow-up evaluations.

The latter two activities will be facilitated as part of a round-robin test plan designed to evaluate the interlaboratory variability, or reproducibility, of the TST. TTI researchers will use the results of the round-robin testing to formulate a precision statement following the American Society for Testing and Materials (ASTM) E 691-99 designation, "Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method." An evaluation of the repeatability of the TST has already been performed at TTI and will be included in this statement. However, because accepted reference values for TST results obtained from various materials are not available, a bias statement cannot be developed for this test.

Two granular base materials have been obtained for inclusion in the round robin test program proposed for this implementation plan. The materials have been divided into quantities of identical gradations sufficient for each laboratory to construct three TST samples of each aggregate for evaluation. Participating laboratories will use the forms for data collection and analysis presented in the appendix of this report. Upon completion, copies of these forms will be returned to TTI for a complete statistical review. The research report prepared at the conclusion of this implementation project will present a thorough analysis and discussion of results. In coordination with the TTI Information and Technology Exchange Center (ITEC), a training video will also be produced during this project. The video will be made available to TxDOT for use in future training of additional districts as necessary.

Because of the success of the TST in discriminating between good- and poor-performing aggregate base materials, this report recommends inclusion of the TST among the requirements for flexible base listed in Item 247 of *TxDOT Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*. This report proposes two alternatives by which this may be accomplished.

The first option would create a new "premium" grade of aggregate, which would include all of the requirements listed for the existing Grade 1 specification, as well as a dielectric value less than 10 in the TST. The engineer in charge would determine whether specification of a premium base material was warranted for a particular project. The second choice would add a new entry to the existing physical requirements listed for Grade 1 and Grade 2, where a dielectric value less than 10 might be required in the former, and a dielectric value less than 16 in the latter, for example. As in the triaxial class requirements, Grade 3 might remain unspecified. In this case, all Grade 1 and Grade 2 materials would be necessarily ranked in the TST as "good" or "marginal," respectively. Considering the fact that not all areas of the state have high water tables or problems with moisture susceptibility, the first option may be preferred. Further discussion with TxDOT personnel is needed on this topic.

CONCLUSION

Several projects discussed in this report have verified the meaningful applicability of the ranking criteria suggested for the TST to the problem of assessing the moisture and frost susceptibility of granular base materials. The revised protocol presented in this report allows integration of the TST with standard triaxial strength testing and the free-free resonant column apparatus developed at the University of Texas at El Paso. The incorporation of these tests will promote better characterization of the detrimental effects of moisture ingress on the mechanical properties of aggregates.

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TUBE SUCTION TEST

This test method evaluates the moisture susceptibility of granular base materials used in pavements.

Significance and Use

The selection of base materials with adequate resistance to damage under traffic and environmental loading is important in maximizing the life of a pavement. Moisture ingress is a primary catalyst for pavement damage, and moisture susceptibility, or the degree to which moisture ingress degrades the engineering properties of aggregates, plays a key role in the performance of these materials in the field.

Research studies demonstrate that moisture susceptibility is related to the matric and osmotic suction properties of aggregates. Matric suction is mainly responsible for the capillary phenomenon in aggregate layers, and osmotic suction is the suction potential resulting from salts present in the pore water of an aggregate matrix.

The Tube Suction Test (TST) rates the resistance of aggregates to moisture damage as good, marginal, or poor. This moisture susceptibility ranking is based on the final surface dielectric values of compacted specimens after a 10-day capillary soak in the laboratory. The Adek Percometer™, a 50 MHz dielectric probe, is employed in the test to measure the dielectric values of specimens.

The dielectric value of a three-phase system comprised of aggregate particles, air, and water depends on the volumetric percentages and dielectric values of each constituent. The dielectric value of dry aggregate particles generally varies from 4 to 6, and the dielectric value of air is 1. The dielectric value of water depends on its state of bonding in the aggregate matrix. Tightly bound, or adsorbed, water has a dielectric value of about 3 or 4, but the dielectric value of unbound water is substantially higher at 81. Unbound water can migrate within the pavement structure to balance changes in suction caused by chemical contaminations, changes in the pore structure, or fluctuations in the water content.

For materials with high suction potential and sufficient permeability, substantial amounts of unbound water rise within the aggregate matrix during soaking and lead to higher dielectric values in the test. Conversely, non-moisture-susceptible materials maintain a strong moisture gradient throughout the test, with little moisture reaching the surface, and have lower dielectric values at the end of testing. Beneficiation techniques such as stabilization, blending, or reducing the fines content should be considered for effectively reducing the moisture susceptibility of poor-performing aggregates.

Apparatus

- Apparatus outlined in Test Method Tex-101-E, Part II
- Apparatus outlined in Test Method Tex-103-E, Part I
- Apparatus outlined in Test Method Tex-113-E
- Triaxial cells, lightweight stainless steel cylinders
- Cylindrical plastic molds with inside diameter of 152.4 mm (6 in.) and minimum height of 50.8 mm (2 in.)
- Power drill with 1.5 mm (1/16 in.) drill bit
- Drying oven maintained at 40 ± 5 °C (104 ± 9 °F)
- Flat-bottomed plastic pan, wide and shallow, for soaking specimens
- Adek Percometer™

Materials

- Distilled water

Sample Preparation

Prepare the sample as in Test Method Tex-101-E, Part II.

Test Record Forms

Record sample preparation and testing data on the Tube Suction Test Data Collection Form (Figure 1). After tests are completed, summarize results on the Tube Suction Test Data Analysis Report (Figure 2).

Procedure

Step	Action
1	Use Test Method Tex-113-E for determining the optimum moisture content (OMC) and maximum dry density (MDD) of the material for molding the test specimens.
2	Obtain three cylindrical plastic molds. At approximately 6 mm (1/4 in.) above the outside bottom of each mold, drill 1.5 mm (1/16 in.) diameter holes around the circumference of the mold at a horizontal spacing of 12.7 mm (1/2 in.). This equates to 38 or 39 holes around the mold base. Also drill one 1.5 mm (1/16 in.) diameter hole in each quadrant of the bottom of the mold about 50 mm (2 in.) from the center. Trim the cylinder as necessary to a height of 50 mm (2 in.) to create a reusable plastic base cap. Make two vertical cuts in each base cap, equally spaced around the circumference as shown in Figure 3, to enable easier installation and removal. Weigh the caps to the nearest 1 g (0.0022 lb.) and record as W_{CAP}.

3	Obtain a representative sample of prepared material in sufficient quantity to prepare three specimens. Bring the material to optimum moisture using distilled water. (Ions in regular tap water can influence the results of the test by increasing the osmotic suction component of the aggregate.)
4	Compact three specimens at optimum moisture and maximum dry density according to Test Method Tex-113-E. The specimens should be 152.4 mm (6 in.) in diameter and 203.2 ± 6.4 mm (8 ± 0.25 in.) in height and should be wetted, mixed, molded, and finished as nearly identical as possible. The surface of each specimen should be made as smooth as possible after compaction. Remove or reposition any coarse aggregate protruding from the specimen surface and fill any large voids as necessary. (Application of fines across the whole specimen surface should be avoided, however.)
5	After removal of specimens from the compaction sleeve, install a base cap on the bottom of each specimen. Weigh three clean, dry triaxial cells to the nearest 1 g (0.0022 lb.), and record as W_{CELL}. Slide the triaxial cell down over the specimen so that only the lower 25 mm (1 in.) of the base cap remains exposed. Weigh the specimen with the base cap and triaxial cell to the nearest 1 g (0.0022 lb.) and record as W_{OMC}.
6	Place the specimens in an oven maintained at 40 ± 5 °C (104 ± 9 °F) for 96 ± 4 hours.
7	Remove the specimens from the drying oven and weigh each specimen with base cap and triaxial cell to the nearest 1 g (0.0022 lb.) and record as W_{DRY}. Use the Adek Percometer™ to take six initial dielectric readings on each specimen surface as shown in Figure 4. Five should be equally spaced around the perimeter of the specimen, and the sixth should be in the center. Press down on the probe with a force of 9.1 ± 2.3 kg (20 ± 5 lb.) to ensure adequate contact of the probe on the specimen surface. This pattern should be followed each time dielectric values are measured.
8	As illustrated in Figure 5, place the samples in a flat-bottomed plastic pan on a level surface in a laboratory room maintained at 25 ± 5 °C (77 ± 9 °F) and fill the pan with distilled water to a depth of 12.5 ± 3.2 mm (1/2 ± 1/8 in.). The water bath should be maintained at this temperature and depth throughout the testing. Avoid splashing the specimen surfaces with water during the test. (Metal pans should not be used because of the possibility of contaminating the bath water with metal ions.)
9	Take six dielectric readings on each specimen surface once a day for 10 days. If the water content is to be monitored through time, the sample weight should be recorded daily to the nearest 1 g (0.0022 lb.) and recorded as W_{WET} at each time interval. Wipe the bottom of the mold dry before weighing.
10	The test is completed when the elapsed time exceeds 240 hours. Measure and record final surface dielectric values and weights. If triaxial strength testing is desired in this soaked condition, carefully remove the base cap and perform the test.
11	Determine the final moisture content of each specimen according to Test Method Tex-103-E, Part I, but use the entire sample in the procedure. Wash all aggregate particles from the base cap and interior of the triaxial cell, as well as from any porous stones used in triaxial testing, into the drying pan. Record the weight of the oven-dry aggregate particles as W_S. Though the moisture content determined in this way after triaxial testing may not represent the moisture content at the conclusion of soaking, the value of the latter can be calculated using W_S as shown in the next section.

Aggregate ______________________ Technician ______________________

Source ______________________ Year ________ Lab. No. ________

Specimen Preparation		Test Day	0	1	2	3	4	5	6	7	8	9	10
OMC, %		Date, mm/dd											
MDD, kg/m^3 (pcf)		Time, hr:min											

Specimen No.		W_{WET}, g (lb.)												
Specimen Testing		Dielectric Value	1											
W_{CAP}, g (lb.)			2											
W_{CELL}, g (lb.)			3											
W_{OMC}, g (lb.)			4											
W_{DRY}, g (lb.)			5											
W_S, g (lb.)			6											

Specimen No.		W_{WET}, g (lb.)												
Specimen Testing		Dielectric Value	1											
W_{CAP}, g (lb.)			2											
W_{CELL}, g (lb.)			3											
W_{OMC}, g (lb.)			4											
W_{DRY}, g (lb.)			5											
W_S, g (lb.)			6											

Specimen No.		W_{WET}, g (lb.)												
Specimen Testing		Dielectric Value	1											
W_{CAP}, g (lb.)			2											
W_{CELL}, g (lb.)			3											
W_{OMC}, g (lb.)			4											
W_{DRY}, g (lb.)			5											
W_S, g (lb.)			6											

Figure 1. Tube Suction Test data collection form.

Aggregate		Technician	
Source		Year	Lab. No.

Test Day	0	1	2	3	4	5	6	7	8	9	10
Total Time, hr											
Specimen No.	Average Dielectric Value										
Specimen No.	Gravimetric Water Content During Soaking, %										

Average Final Dielectric Value	
Moisture Susceptibility Ranking	

Average Final Gravimetric Water Content, %	
Average Water Loss in Drying, % of OMC	

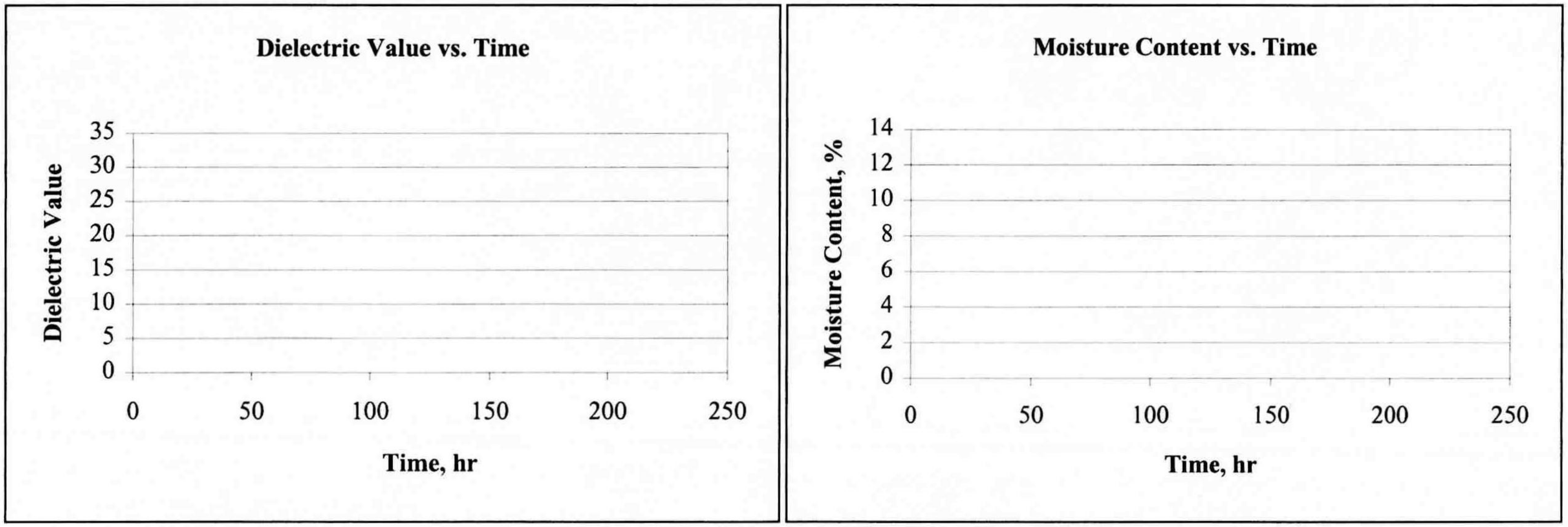

Figure 2. Tube Suction Test data analysis report.

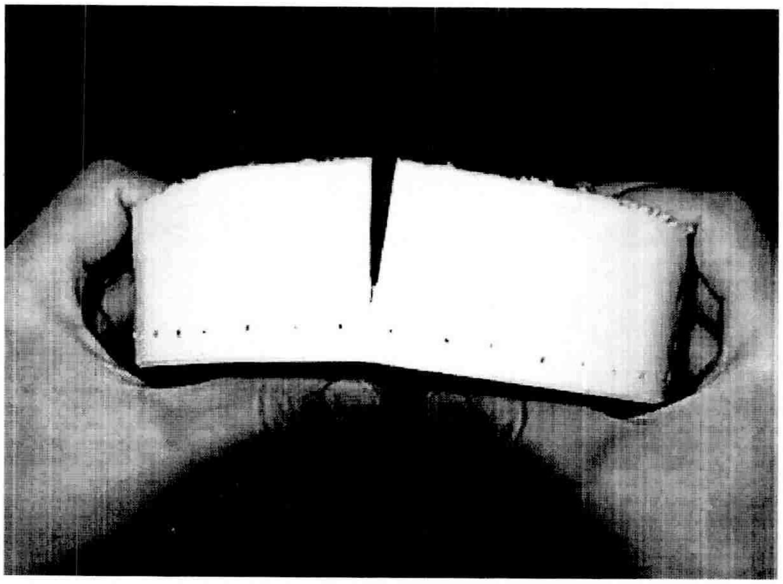

Figure 3. Finished base cap.

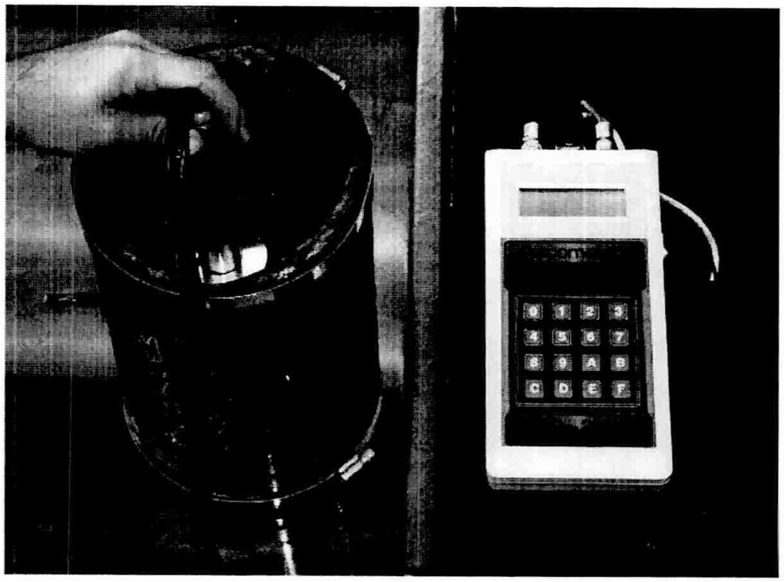

Figure 4. Using the Adek Percometer™.

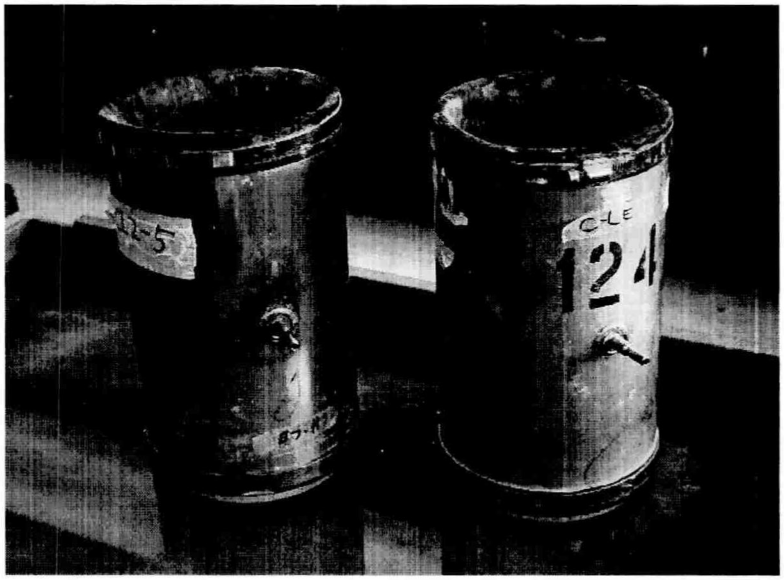

Figure 5. Typical TST arrangement.

Calculations

- Calculate the actual gravimetric water content (WC_{OMC}, %) of each specimen just after compaction at the optimum moisture content,

$$WC_{OMC} = 100\ (W_{OMC} - W_{CAP} - W_{CELL} - W_S) / W_S$$

Where:

W_{OMC} = weight of specimen with base cap and triaxial cell just after compaction, g (lb.)
W_{CAP} = weight of plastic base cap, g (lb.)
W_{CELL} = weight of clean, dry triaxial cell, g (lb.)
W_S = weight of oven-dry aggregate particles, g (lb.)

- Calculate the gravimetric water content (WC_{DRY}, %) of each specimen just after the four-day drying period,

$$WC_{DRY} = 100\ (W_{DRY} - W_{CAP} - W_{CELL} - W_S) / W_S$$

Where:

W_{DRY} = weight of specimen with base cap and triaxial cell after four-day drying period, g (lb.)
W_{CAP} = weight of plastic base cap, g (lb.)
W_{CELL} = weight of clean, dry triaxial cell, g (lb.)
W_S = weight of oven-dry aggregate particles, g (lb.)

- Calculate the percentage of water loss (P_{LOSS}, % of OMC) for each specimen during the four-day drying period,

$$P_{LOSS} = 100 \left((W_{OMC} - W_{DRY}) / W_S \right) / WC_{OMC}$$

Where:

W_{OMC} = weight of specimen with base cap and triaxial cell just after compaction, g (lb.)
W_{DRY} = weight of specimen with base cap and triaxial cell after four-day drying period, g (lb.)
W_S = weight of oven-dry aggregate particles, g (lb.)
WC_{OMC} = gravimetric water content just after compaction, %

- Calculate the average percentage of water loss for the three specimens.

- Calculate the gravimetric water content (WC_{WET}, %) of each specimen at each time interval during the soaking period,

$$WC_{WET} = 100 (W_{WET} - W_{CAP} - W_{CELL} - W_S) / W_S$$

Where:

W_{WET} = weight of specimen with base cap and triaxial mold at time of interest during soaking period, g (lb.)
W_{CAP} = weight of plastic base cap, g (lb.)
W_{CELL} = weight of clean, dry triaxial cell, g (lb.)
W_S = weight of oven-dry aggregate particles, g (lb.)

- Calculate the average gravimetric water content of the three specimens at the end of the soaking period.

- For each specimen at each time interval, discard the highest and lowest dielectric readings. Calculate the average dielectric value from the remaining four readings for plotting against time.

- Calculate the average final mean dielectric value of the three specimens to determine an overall moisture susceptibility ranking. Aggregates with final dielectric values less than 10 are expected to provide good performance, while those with dielectric values above 16 are expected to provide poor performance as base materials. Aggregates having final dielectric values between 10 and 16 are expected to be marginally moisture susceptible.

Graphs

- Plot the dielectric-time curve for each specimen.
- Plot the moisture-time curve for each specimen if requested.

Test Report

Report the average final dielectric value after soaking and the corresponding moisture susceptibility ranking of good, marginal, or poor.

Also, report the average final gravimetric water content of the specimens after soaking and the average percentage of water loss with respect to OMC during the four-day drying period. The former is indicative of the water content this aggregate may attain in the field given the availability of water, and the latter, if less than 50 percent, suggests that special construction considerations may be required in moist conditions to avoid trapping water in the pavement.