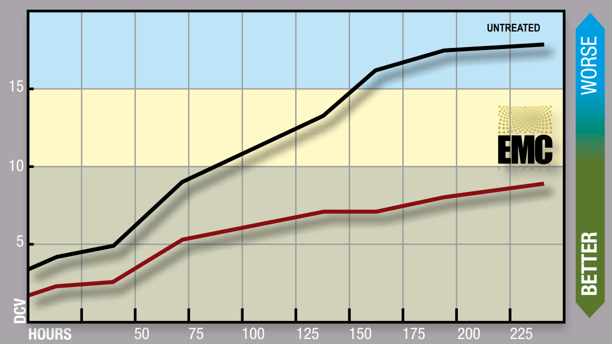
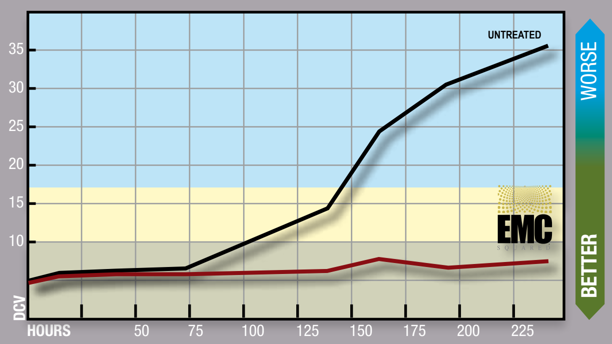
Treatment of Moisture and Frost Susceptibility

Field and Laboratory Studies

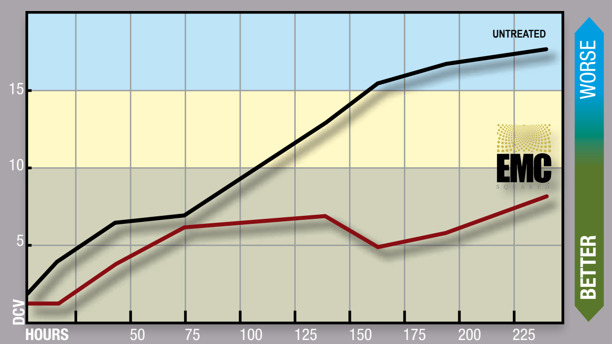
ALASKA ELLIOTT HIGHWAY



NEW MEXICO CITY OF GALLUP



NEVADA MOUNTAIN ROAD



EMC SQUARED®
Untreated

Stabilization Products LLC

ABSTRACT

Three aggregate materials were evaluated in a laboratory research study conducted at the Texas Transportation Institute. They were obtained from original supply sources for three road construction projects located in cold climate areas with severe winter conditions where aggregate materials are subjected to freeze-thaw cycling as well as seasonal fluctuations in temperature and moisture conditions. In previous field installations of each of the three aggregate materials (in the absence of stabilization treatment), it was evident that they were moisture susceptible and subject to loss of stability in wet weather and freeze-thaw conditions. On each of the three road construction projects, the aggregates were treated with EMC SQUARED® Stabilizer, a concentrated liquid stabilization treatment, and placed into service as aggregate surface courses, providing running surfaces for vehicles and heavy trucks. During this time, months in one case and years in the others, the stabilized aggregates provided excellent running surfaces requiring little to no maintenance and with no evidence of moisture penetration or frost damage. The stabilized aggregate surface courses were eventually utilized as stabilized or "bound" bases for asphalt pavements and a bituminous surface treatment, having first proven effective while directly subjected to the full range of environmental conditions, to heavy truck traffic and to winter snow plowing operations.

Given the well-established field performance history of these three aggregates from three different regions (first as untreated and then as stabilized materials), the group of aggregates provided a unique opportunity to demonstrate the effectiveness of Suction and Dielectric laboratory procedure itself as a performance based test methodology for identification of moisture susceptible aggregate materials and for evaluation of a specific stabilization product in treatment of a specific aggregate material. In the case of these three aggregate materials, the Suction and Dielectric testing provided excellent correlation with the field performance history. Testing of the untreated aggregates predicted accurately that they were moisture sensitive and highly frost susceptible. Testing of the stabilized aggregates accurately confirmed that they were non-moisture sensitive and non-frost susceptible in service for road surface and highway base course applications.

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Field Performance and Laboratory Results Confirm Successful Treatment of Moisture and Frost Susceptible Aggregate Materials for Severe Service Applications in Alaska, New Mexico, and Nevada

SUCTION AND DIELECTRIC TESTING (Adsorption and Tube Suction)

According to research conducted by the Finnish National Road Administration (FNRA) and the Texas Transportation Institute (TTI), electrical properties can be used to classify the strength properties of base course aggregates.[1] The studies showed that the dielectric value and electrical conductivity related to both the strength and deformation properties and the frost susceptibility of base course aggregates. The dielectric value correlates well with the California Bearing Ratio (CBR) value of compacted base materials. Further study showed that Suction and Dielectric Testing[2] can be utilized to identify aggregate base course materials (also described as flexible base or granular base materials) which are moisture sensitive and frost susceptible and consequently prone to significant reduction in resilient modulus, shear strength and flexural strength in the actual service environment.

It is well known that moisture infiltration reduces the strength and stiffness of most aggregate base materials and contributes to many pavement failures. With research now available also documenting failures of heavily cement treated base materials[3] resulting from unsuccessful treatment of aggregate moisture susceptibility, it becomes increasingly apparent that the standardized index tests traditionally used to evaluate untreated aggregates and chemically bound aggregate materials carry significant risk when relied upon for pavement designs in the absence of test methods effective in the evaluation of moisture susceptibility.

It appears that the recently developed Suction and Dielectric Testing methodology provides the advanced performance based test method needed to directly measure the moisture susceptibility of aggregate base materials and to evaluate the effectiveness of chemical stabilizers with specific aggregate materials in regards to treatment of moisture susceptibility. The research conducted by the Texas Transportation Institute with sponsorship from Texas Department of Transportation (TxDOT) and the U.S. Department of Transportation, Federal Highway Administration (FHWA), was focused on using electrical properties for the classification of strength properties of base course aggregates. The Minnesota Department of Transportation's (Mn/DOT's) Minnesota Road Research Project (Mn/ROAD) used this testing methodology in their program, and it was incorporated in the National Cooperative Highway Research Program's (NCHRP's) study, "Performance Related Tests of Aggregates for Use in Unbound Pavement Layers."

THREE CASE STUDIES

Three aggregate materials evaluated in an additional Suction and Dielectric laboratory research study conducted at TTI were obtained from original supply sources for three road construction projects located in cold climate areas with severe winter conditions where aggregate materials are subjected to freeze-thaw cycling as well as seasonal fluctuations in temperature and moisture conditions. In previous field installations of each of the three aggregate materials (in the absence of stabilization treatment), it was evident that they were moisture susceptible and subject to loss of stability in wet weather and freeze-thaw conditions. Each of the aggregate materials were treated with the **EMC SQUARED®** Stabilizer (1000), a concentrated liquid stabilizer (CLS) utilized for treatment of aggregate and soil materials. The EMC SQUARED Stabilizer (1000) product is a complex non-ionic formulation, relatively neutral in pH, added at a standard treatment rate to the compaction water and applied as a dilute solution during the normal moisturization and mixing operations used to bring aggregate and soil materials to optimum moisture content for compaction.

[1] Saarenketo, T. and Scullion, T., Using Electrical Properties to classify the Strength Properties of Base Course Aggregates, NTIS: FHWA/TX-97/134-2 (TTI Research Report 1341-2), 1996.

[2] Also described as Adsorption and Tube Suction Testing.

[3] Saarenketo, T. and Scullion, T., Op. Cit.

On each of the three road construction projects, the treated aggregates were first placed into service as aggregate surface courses, providing running surfaces for vehicles and heavy trucks. During this time, months in one case and years in the others, the stabilized aggregates provided excellent running surfaces requiring little to no maintenance and with no evidence of moisture penetration or frost damage. The stabilized aggregate surface courses were eventually utilized as stabilized bases for asphalt pavements and a bituminous surface treatment, having first proven effective while directly subjected to the full range of environmental conditions, to heavy truck traffic and to winter snow plowing operations. Given the field performance history of these three aggregates from three different regions (first as untreated and then as treated materials), the group of aggregates provided a unique opportunity to demonstrate the effectiveness of Suction and Dielectric laboratory procedure itself as a performance based test methodology for identification of moisture susceptible aggregate materials and for evaluation of a specific stabilization product in treatment of a specific aggregate material. In the case of these three aggregate materials, the Suction and Dielectric testing provided excellent correlation with the field performance history. Testing of the untreated aggregates predicted accurately that they were moisture sensitive and highly frost susceptible. Testing of the treated aggregates accurately confirmed that they were non-moisture sensitive and non-frost susceptible in service for road and highway base applications.

The Suction and Dielectric testing methodology is unique among test methods in its focusing specifically on moisture susceptibility. It provides a demonstration of stabilization products which are particularly effective in treatment of moisture susceptibility problems, and it provides a method to identify chemical treatments which pass the standardized benchmarks of conventional index tests, but fail to effectively treat moisture susceptibility, a problem which is now widely recognized as a precursor to leaching and reversal of stabilization benefits.

The performance of the **EMC SQUARED**® treatment in the laboratory testing and project case histories described below has been impressive, particularly in light of the low cost of these applications in comparison to cement and lime treatment.

SUCTION & DIELECTRIC TESTING RESULTS

Results of the testing are summarized in the table below.

AGGREGATE BASE ROCK SAMPLES	CONTROL (Untreated)	CONTROL + EMC SQUARED (treated)
Alaska Aggregate	17.5	6.0
New Mexico Aggregate	35.0	7.1
Nevada Aggregate	17.3	7.7

For the purpose of general classification using dielectric measures of aggregates, a dielectric value greater than 15 indicates that the aggregate is wet or water saturated and extremely frost susceptible. A dielectric value in the range 10 to 15 indicates that a significant amount of free water has accumulated within the aggregate during the testing period and is a warning signal that the material is moisture sensitive and frost susceptible. Aggregate materials with a dielectric value of less than 10 are considered non-moisture sensitive and non-frost susceptible in service for road and highway base applications. Typical dielectric constant values for highway materials are tabulated below.

MATERIAL	DIALECTRIC CONSTANT
Dry Aggregates	4-6
Asphalt Concrete	5-7
Portland Cement Concrete	7-9
Flexible Base	6-20*
Subgrades	0-25*

*Depends upon Moisture Content

NOTE: The EMC SQUARED Stabilized Aggregates tested in the same range as asphalt and concrete pavement materials

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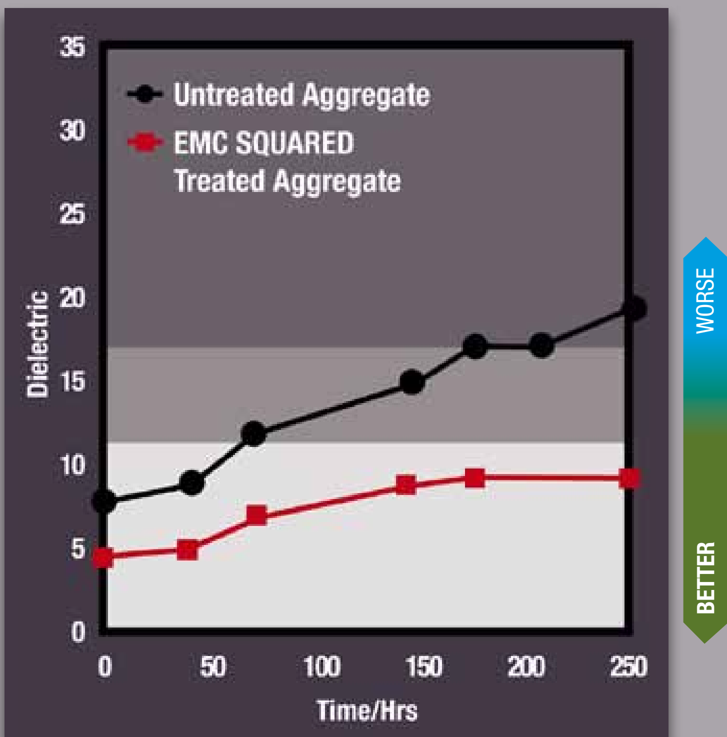
FIELD PERFORMANCE & OTHER RELATED TESTING

In each of the discussion sections which follow, the Suction and Dielectric Test results for the aggregate are presented first, followed by a report of field performance and summary of other lab testing.

ALASKA - ELLIOTT HIGHWAY



The Alaska aggregates were obtained from the stockpile used to supply a Federal Highway Administration (FHWA) Experimental Feature Project on the Elliott Highway, beginning north of Fairbanks at the transition point from asphalt to gravel road. Nicknamed "the Haul Road" (the Elliott Highway ties into the Dalton Highway), this gravel surfaced highway system provides access to the Prudhoe Bay oil fields. Alaska truckers were driving approximately 17,000 truckloads a year up to Prudhoe Bay, operating on a year-round schedule. An aggregate surface course treated with the **EMC SQUARED**® Stabilizer serviced haul truck traffic for over four years before this section of the road was upgraded with an experimental bituminous treatment placed over the stabilized base course section. This project, constructed under the direction of the Alaska Department of Transportation & Public Facilities (ADOT&PF), is more fully covered in Transportation Research Record 1589.

Prior to placement of the **EMC SQUARED** Stabilized Aggregate running surface this section of the Elliott Highway was graded and retreated with a dust palliative product each summer. The material treated with the dust palliative was subject to constant potholing, washboarding, and gravel loss and required regular maintenance grading. After the second year of service, the stabilized section was described as essentially maintenance free with only minor touch-up required in the super-elevated curves. Involved ADOT&PF staff unanimously gave the stabilized road section an excellent performance rating after servicing many thousands of heavy truck loads in all weather conditions. The state's regional geotechnical engineer in his memorandum of final evaluation commented that the **EMC SQUARED** Stabilizer also outperformed the dust palliative treatment in regards to dust control effectiveness and that it was less expensive to apply.[5] This project also included evaluation of the effectiveness of two different mixing methods in applying this stabilization technology. The aggregate for the first stabilized section was mixed in a portable pugmill unit located at the aggregate stockpile and then hauled in bottom dump trucks to the project location. The second section was treated after the aggregate was placed on the road in a mixed-in-place operation using a motor grader equipped with scarifier teeth for mixing and processing. In both cases, the thickness of the treated aggregate materials was approximately 150 mm

[4] Randolph, R., Earth Materials Catalyst Stabilization for Road Bases, Road Shoulders, Unpaved Roads and Transportation Earthworks, Transportation Research Record 1589, 1997.

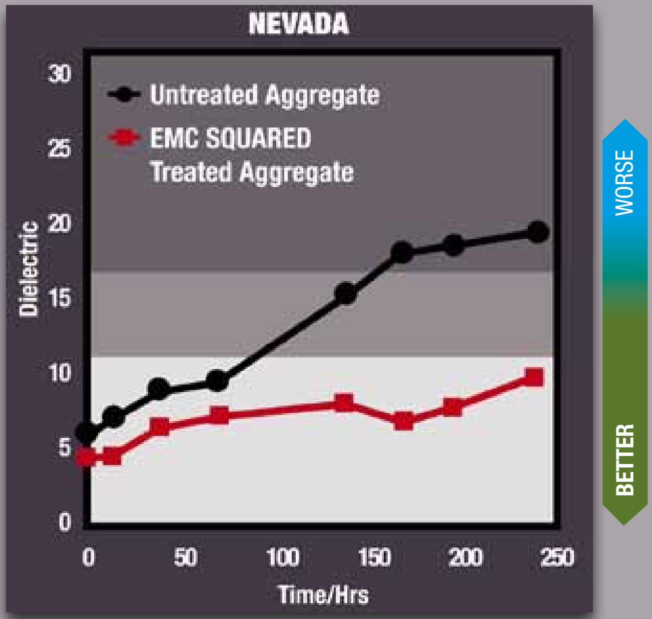
[5] McHattie, R.L., Final Evaluation of Experimental Features - Projects AK8701S and AK8701B. Departmental Memorandum, Alaska Department of Transportation & Public Facilities, Jan. 1994.

(6 inches). Over the evaluation period, no difference in performance was observed between these two stabilized sections. The memorandum of evaluation included as an attachment a report of independent laboratory testing comparing untreated with treated aggregate specimens. ASTM D 2166 unconfined compressive strength tests were conducted after 14 days of curing, resulting in a strength measure of 1,850 kPa (269 lb/in^2) for the untreated material and 2,900 kPa (421 lb/in^2) for the treated material.[6]

The laboratory supervisor of the independent materials testing laboratory involved in monitoring the FHWA experimental feature project on behalf of the supplier of the **EMC SQUARED**® product, made two site visits following the third summer, to obtain additional aggregate from the stockpile and to provide a video record of the stabilized and control sections. He reported only a few small potholes on the stabilized section, located in the worst stress area of the super-elevated curves. The potholes were no larger than “half a grapefruit.” He was able to drive the legal speed limit, approximately 90 km/hr (55 mph) on the stabilized section but had to reduce driving speed to less than 40 km/hr (25 mph) on the control section, which had been retreated with the dust palliative only 4 months previously. Numerous potholes of 2 to 3 m (6 to 10 feet) diameter were observed in the control section.

[6]Ibid

NEVADA-MOUNTAIN ROAD



The Nevada Aggregate material was provided by an aggregate production and supply company which had utilized the **EMC SQUARED** Stabilizer for a project upgrading the access road to their mountain production facility. The production schedule required placement of the aggregate base materials on the road grade in late fall and then a delay of six to eight months until temperature conditions warmed to be fully suitable for hot mix asphalt placement operations. The winding access road reached over 6,000 feet in elevation and had switchbacks and grades as steep as 13%. The road provided year round access for 200 or more daily trips by triple trailer trucks weighing approximately 60 tons fully loaded.

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The project owners were aware that their untreated aggregate surfacing was moisture and frost susceptible and would require constant grading maintenance. They were also aware that it would need daily watering in dry weather in order to survive the truck traffic preliminary to paving. They hired a materials testing laboratory to confirm the effectiveness of the **EMC SQUARED®** Stabilizer in treatment of this specific aggregate material. The treated material tested with an R-Value of 86,[7] well above the 80 R-Value used in some state design manuals as the required strength for CTB Class B Cement Treated Bases, considered as high stability layers capable of reducing structural section requirements in replacement of aggregate base materials.[8]

Once laboratory testing was completed, the aggregate materials were placed on the road and then treated with the stabilizer solution in a mixed-in-place operation conducted with a motor grader and a tractor drawn agricultural disk unit. The 150 mm (6 inch) thick stabilized aggregate surface was placed into service immediately. The treated road was well preserved after half a year of use and company management reported that paving operations were able to proceed with minimal need for grading or trimming of the stabilized aggregate surface. The road was attacked several times in the following years by winter flooding at a creek crossing. Reports indicate that unstabilized aggregate road shoulder materials were swept away clear to the vertical edge of the stabilized road surface. The asphalt pavement layers were also swept away, but the stabilized base layer remained in place without any visible erosion, looking much like a concrete slab. These flooding events provide further testimonial that the treated aggregate layer which survived years of freeze-thaw cycling, snow melt and wet weather conditions, was indeed highly resistant to moisture intrusion. It is also interesting to note that the laboratory testing series conducted at TTI indicated that the aggregate material obtained from this same production source, following treatment with the **EMC SQUARED** Stabilizer, had a dielectric of 7.7, similar to the typical dielectric constant values for Portland Cement Concrete (7 to 9).

[7]Vineis, Steven, Resistance Value Test Data, SHB AGRA, Inc., Sparks, Nevada, 1993.

[8]Highway Design Manual, California Department of Transportation, page 600-13, July 1, 1995, Fifth Edition

The performance of this stabilized aggregate during the time it served as a road surface on a steep and winding mountain road, supporting trucks with loaded weights permitted on only a few state highways systems, was impressive.

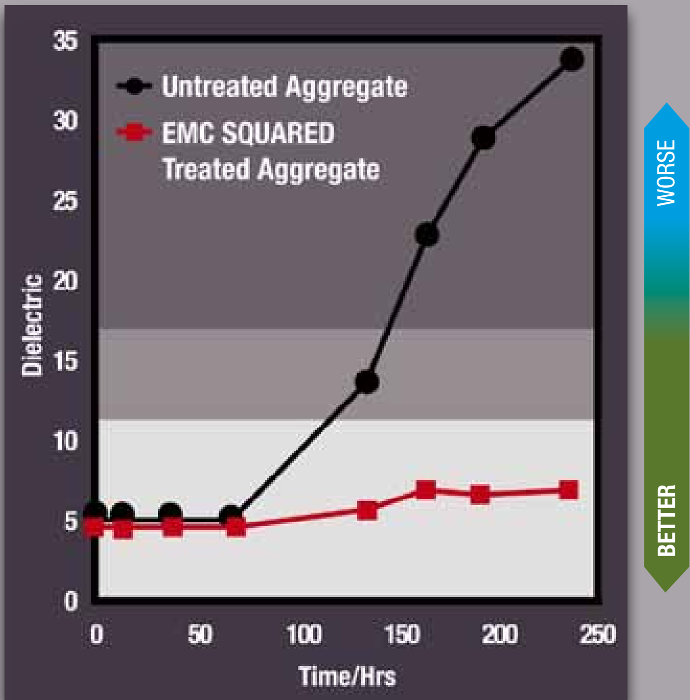
While the 86 R-Value referenced earlier is the only strength index measurement test performed in conjunction with this field installation of an **EMC SQUARED** Stabilized Aggregate material in the mountains of central Nevada, additional perspective is provided by reviewing the results of more sophisticated modern matierals laborary tests that have been performed in conjunction with other highly sucessful **EMC SQUARED** Stabilized Aggregate field installations.

For example, an **EMC SQUARED** Stabilized Aggregate material was sampled from another stabilized aggregate base course project in Nevada and subjected to Resilient Modulus testing. The stabilizer treatment increased the modulus of the untreated aggregate by a factor of over five times. According to the research engineer in charge of the study, the Resilient Modulus test results indicated that the **EMC SQUARED** Stabilized Aggregate had a Layer Equivalency Factor of 0.35, the same design factor used for hot mix asphalt materials.[9] Dynamic Modulus and Repeated Load Triaxial (RLT) testing of **EMC SQUARED** Stabilized Aggregate materials have shown an increase of the modulus value by a factor of approximately ten times, producing a strong and resilient layer superior to typical hot mix asphalt materials in retention of strength (no loss of strength in warm or hot weather conditions) and resistence to permanent deformation.[10] As demonstrated by the laboratory studies summarized in this publication, there is a strong materials engineering basis behind the outstanding field performance capabilities of **EMC SQUARED** Stabilized Aggregate materials.

[9]Yahn, R., Kleinfelder, Inc., Strength Test Data, State of California Project, Santa Rosa, CA, December 1997.

[10]Parks, B., Inter-Department Memporandum, Mississippi Department of Transportation, Jackson, MS, April 1995.

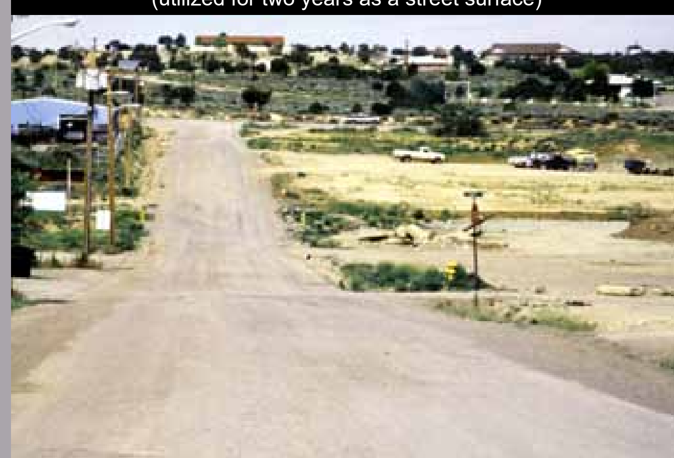
NEW MEXICO — CITY OF GALLUP



The New Mexico aggregate material was obtained from a Gallup area aggregate producer that had supplied aggregate base rock materials for City of Gallup projects including sections of a stabilization project in Gallup's South Annex. The City had recently taken over responsibility for over four and a half miles of distressed chip seal surfaces and aggregate surfaced streets that had deteriorated to the point that winter access had become problematic even for four wheel drive vehicles and trucks. The City of Gallup is located at relatively high altitude just west of the Continental Divide in the southern end of the Rocky Mountains. With severe winter conditions and frequent freeze-thaw cycling, compounded by low bearing capacity clay subgrade soils, City staff were actively looking for construction procedures and product technologies that could extend the service life of the city streets.

Asphalt Millings (RAP) Stabilized with EMC SQUARED® Stabilizer
(utilized for five years as a street surface)

Aggregate Stabilized with EMC SQUARED® Stabilizer
(utilized for two years as a street surface)



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The City of Gallup had previously field tested the **EMC SQUARED**® Stabilizer during reconstruction of the access road to their street maintenance office and yard complex, applying the treatment in a mixed-in-place operation following full depth milling of the existing distressed asphalt pavement and the contaminated base course materials. After proving out the 225 mm (9 inch) thick stabilized layer under daily truck traffic, the City placed a new asphalt pavement directly on the treated base. Faced with the South Annex street improvement project, the City selected the **EMC SQUARED** Stabilizer over cement treatment as the delivered cost for cement was more than five times the cost and required more elaborate construction operations as well as immediate protection with a pavement surface course. The asphalt reclaimer/rotary mixer unit was again utilized to pulverize existing chip seal surfaces and distressed areas and for mixing of the stabilizer solution. A new surface course of aggregate base rock was then placed to a 150 to 200 mm (6 to 8 inch) thickness and also stabilized with a mixed-inplace operation. The stabilized aggregate streets serviced industrial and commercial businesses, public schools and residential neighborhoods. The street superintendent reported that the stabilized aggregate streets required almost no maintenance and mentioned that the only complaint came from contractors cutting utility trenches through the stabilized aggregate surface course as they were unable to cut through the stabilized layer with tractor mounted backhoe equipment. Similar to their experience with cement treated base materials, cutting the utility trenches required use of jackhammer equipment to penetrate the stabilized layer.

The City of Gallup subsequently expanded use of the **EMC SQUARED** System for stabilization of clay subgrade soils in replacement of lime treatment and for treatment of asphalt millings. With an extensive supply of asphalt millings made available from nearby state highway reconstruction projects, the City maintenance crew experimented on their own initiative with use of the **EMC SQUARED** Stabilizer as a treatment for asphalt millings placed as street surfacing. Satisfied with their initial installations, once the additional asphalt millings became available, they proceeded to place a 75 mm (3 inch) surface course over the entire South Annex street system with a mixed-in-place operation using the asphalt reclaimer for repulverization of the millings and the addition of the stabilizer solution. After five years of service, the streets remained in excellent condition and were overlayed with hot mix asphalt as funding became available.

In preparation for the overlay with hot mix asphalt, the City's Street Superintendent reported that they had to fill no more than a dozen very small potholes in the entire four-and-a-half-mile length of city streets that were surfaced with the stabilized asphalt millings. Several days prior to placement of the hot mix asphalt overlay, local geotechnical engineering firm AMEC Earth & Environmental Inc. cored the stabilized asphalt millings pavement in a number of locations as well as coring through the stabilized base course layer at one location. As the core sample of the stabilized asphalt millings and stabilized aggregate base course pictured on the previous page illustrates, the **EMC SQUARED** System treatment was effective in producing strongly bound layers that were moisture and frost resistant as well as being wear resistant under vehicular and truck traffic.

SUMMARY

The three aggregate materials discussed here presented a rare opportunity to compare laboratory predictions with field performance for both treated and untreated samples. The electrical measures of the Suction and Dielectric procedure, or Tube Suction Test, indicate relative levels of moisture susceptibility which proved to be accurate predictors of field performance. In addition, measures taken of treated and untreated samples of each aggregate indicated that the **EMC SQUARED** treatment was highly effective in eliminating aggregate moisture and frost susceptibility problems.

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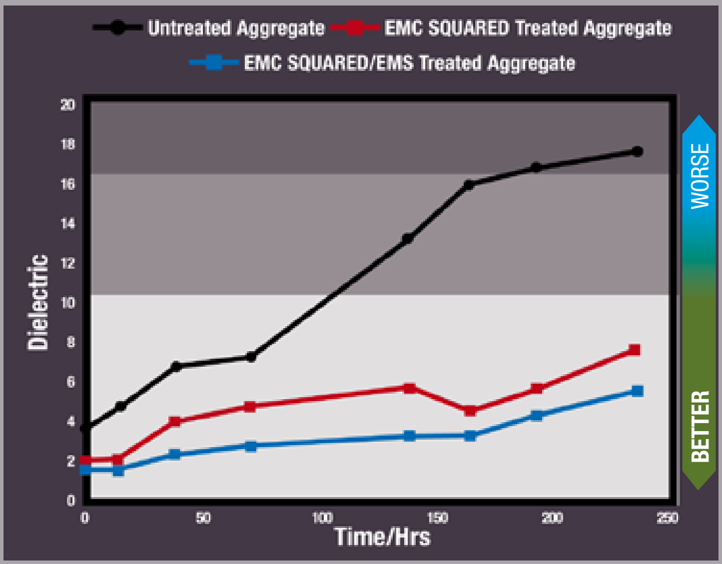
EMC SQUARED®/EMS® Dual Component Treatment

While the **EMC SQUARED** Stabilizer cost effectively met project requirements as a sole treatment, the **EMS** booster is available to further expand the range of performance benefits, the range of material types, and the variety of site specific problems which can be addressed using the **EMC SQUARED** System products. Available for use in combination with **EMC SQUARED** Stabilizer products and applied as a single step process, the **EMS** Earth Materials Sealant product provides designers, materials testing engineers, contractors and owners with an additional option for treatment of moisture sensitive aggregate and soil materials. In cold climate regions, the Dual Component Treatment may also be effective in further reducing or eliminating frost susceptibility.

While the Suction and Dielectric Testing series conducted at Texas Transportation Institute graphed below (see notes at right) indicated that use of the **EMS** booster treatment further reduced the moisture sensitivity and frost susceptibility of this aggregate material, previous field evaluation of the **EMC SQUARED** Stabilizer applied as a sole treatment verified that it fully met project requirements both as a gravel road stabilizer and as a stabilized or bound base course treatment supporting the hot mix asphalt pavement that was placed at a later date as part of this incremental or staged construction project in Nevada.

The additional improvement with the **EMC SQUARED/ EMS** Dual Component System added to the Nevada aggregate is shown in the graph below.



SUCTION AND DIELECTRIC TESTING

According to research conducted by the Finnish National Road Administration (FNRA) and the Texas Transportation Institute (TTI)[1], Suction and Dielectric Testing[2] can be utilized to identify aggregate base course materials (also described as flexible base or granular base materials) that are moisture sensitive and frost susceptible and consequently prone to significant reduction in resilient modulus, shear strength and flexural strength in the actual service environment (see description of categories below). In the testing series conducted at TTI and graphed at the left, measurements were taken from both untreated aggregate specimens, aggregate specimens treated with the **EMC SQUARED** Stabilizer and aggregate specimens treated with the **EMC SQUARED/EMS** Dual Component Treatment.

16+ A Dielectric Value of 16 or greater indicates that the aggregate is wet or water saturated and extremelyfrost susceptible

15-10 A Dielectric Value range of 10 to 15 indicates that asignificant amount of free water has accumulatedwithin the aggregate during the testing period and isa warning signal that the material is moisture sensitiveand frost susceptible

<10 Aggregate materials with a Dielectric Value of less than10 are considered non-moisture sensitive and non-frost susceptible in service for road and highway applications

For sake of reference, typical dielectric constant values for highway materials are tabulated below:

MATERIAL	DIELECTRIC CONSTANT
Dry Aggregate	**4-6**
Asphaltic Concrete	**5-7**
Portland Cement Concrete	**7-9**
Flexible Base	**6-20***
Subgrades	**10-25***

*** Depends on Moisture Content**

[1] Scullion,T. And Saarenketo, T. Using Suction and Dielectric Measurements as Performance Indicators for Aggregate Base Materials.Transportation Research Record 1577, 1997.

[2] Also described as Absorption and Tube Suction Testing.

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APPENDIX

The Suction and Dielectric Testing (Tube Suction) study that was summarized earlier in the Treatment of Moisture and Frost Susceptibility Field And Laboratory Studies publication, to which this Appendix is attached, was conducted under the direction of Dr. Tom Scullion, a Highway Research Engineer at the Texas Transportation Institute (TTI). This study was focused on three moisture and frost susceptible crushed aggregate materials from three different cold climate locations where these problematic aggregate materials were effectively stabilized with the **EMC SQUARED®** Stabilizer product. The stabilized aggregate materials were utilized for the construction of road projects that were upgraded incrementally. The stabilized aggregate materials first functioned as road running surfaces before two were paved with hot mix asphalt, while the third had a bituminous surface treatment applied. The stabilized aggregate surface courses were re-purposed as stabilized base courses.

Having access to these three moisture and frost susceptible aggregate materials that were known to have been successfully treated in field service also provided an opportunity for the research engineer. He was able to evaluate the effectiveness of the laboratory test method itself as a diagnostic tool for measuring the improvements provided by application of a stabilizer product to problematic aggregate materials. Subsequent to the original study, Dr. Scullion and his associate at TTI, Mr. Imran Syed, conducted follow on research that was funded by the Texas Department of Transportation (TxDOT). The follow on study included mineralogical evaluations of the three aggregate materials using X-Ray Diffraction testing (XRD). The results of this additional study were prepared as a technical paper that was presented during the Annual Meeting of the Transportation Research Board (TRB) of the National Research Council (NRC). The report was published in the TRB's peer-reviewed Transportation Research Record (TRR) and is included in this appendix.

The two research engineers added a fourth problematic aggregate material to the follow on laboratory study. It was previously used as a base course under an asphalt pavement in field testing by TxDOT. The pavement rapidly failed and they determined that this was due to water ingress into the moisture susceptible gravel base course material. The researchers confirmed that this lime treated pit run gravel mixture was highly moisture susceptible in their laboratory testing. This material was significantly different from the three crushed aggregate materials evaluated in the original study. This material was from a warm climate location in Texas. Rather than being a "manufactured" or crushed aggregate, it was a pit run gravel dug out of a natural deposit, mixed with low-quality limestone fines, known locally as "caliche", and 1.5% chemical lime.

The research engineers treated the Texas pit run gravel mixture with the **EMC SQUARED** Stabilizer and subjected the specimens to the same laboratory testing regime. While the pit run gravel mixture failed the test within hours, they reported that the pit run gravel mixture treated with the **EMC SQUARED** Stabilizer remained "essentially dry" for three full day. After more than four days, the treated pit run gravel mixture began taking on what the researchers defined as an unacceptable amount of water. It is worthy of note that the **EMC SQUARED** Stabilizer treatment extended the ability of the pit run gravel mixture to remain in the researcher's target zone for excellent performance by a factor of approximately 16 times. The researchers also had access to another **EMC SQUARED** System treatment option using the **EMS®** Earth Materials Sealant product in what is known as the Dual Component Treatment (see previous page). While the Dual Component Treatment had been evaluated in the original testing series with the same Nevada aggregate material and found to be even more effective in treating moisture and frost susceptibility problems than use of the **EMC SQUARED** Stabilizer product alone, they missed the opportunity in this follow on laboratory series to evaluate this more powerful combination of stabilizer products for treatment of their highly problematic Texas pit run gravel.

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Paper No. 00-1147

Tube Suction Test for Evaluating Aggregate Base Materials in Frost- and Moisture-Susceptible Environments

Imran Syed, Tom Scullion, and Robert B. Randolph

A simple tube suction test has been developed by the Finnish National Road Administration for evaluating unstabilized granular base material. The test consists of monitoring the capillary rise of moisture within a 150-mm-diameter by 200-mm-high cylinder of compacted aggregate. A probe is used to measure the dielectric constant at the surface of the sample. The dielectric constant is a measure of the free, or unbound, water within the aggregate sample. It is this unbound water that is thought to be directly related to the strength of the material and its ability to withstand repeated freeze-thaw cycling. Measurements of dielectric constants are made over a period of 10 days. The poorest performing materials are those that rapidly reach saturation and exhibit high surface dielectric values. A study was conducted on four marginal aggregates from Alaska, Nevada, New Mexico, and Texas. These aggregates have been reported to be poor performers in their environments. Each aggregate failed the tube suction test. A mineralogical evaluation was performed to identify the mineral composition of each aggregate and to explain their high affinity for moisture. Subsequently the aggregates were treated with a concentrated liquid stabilizer. Upon treatment the aggregates showed improved performance in the tube suction test. The Alaska, Nevada, and New Mexico aggregates were then used in construction projects. Initial performance reports have been promising. The tube suction test described in this research has the potential to identify moisture-susceptible aggregates and to serve as a guide in selecting the optimal stabilizer type and amount.

Free moisture is frequently the root cause of damage to flexible pavements. Although the sources of water and the mechanics of how moisture damages a pavement are understood, these principles are not widely incorporated into design. The primary source of moisture in pavement structures is rainwater, which infiltrates through the surface of the pavement. Moisture can also enter a pavement from subsurface sources, including lateral seepage from a drainage ditch or subsurface flow from a high water table, spring, or wet subgrades. It is well known that moisture infiltration reduces the strength and stiffness of most aggregate base materials and is particularly damaging in severe climates, contributing to many pavement failures. The freeze-thaw process can have a dramatic influence on the permanent and resilient deformation of pavement structures (*1*). Recent documented failures (*2*) of both flexible and stabilized bases indicate that the standardized index tests traditionally used to evaluate untreated aggregates and chemically bound aggregate materials can carry significant risk when relied upon for pavement designs in the absence of test methods to evaluate moisture susceptibility.

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STUDY GOALS

This study focuses on four reported problem aggregates from the states of Alaska, Nevada, New Mexico, and Texas. Performance problems were compounded due to extreme freeze-thaw conditions in Alaska, Nevada, and New Mexico. The base course in Texas was in a region of wet subgrades and high rainfall. Each aggregate was tested using the AASHTO Classification System (AASHTO M145-87 or AASHTO M283-83) that included particle size distribution and Atterberg Limits. It is important to note that, barring the aggregate from New Mexico, each aggregate passed current AASHTO M145-87 and individual state specifications.

The study had the following goals:

- Determine whether the tube suction test could be used to identify moisture-susceptible granular materials.
- Identify mineral components within problem materials.
- Determine whether poorly performing materials can be improved by adding a concentrated liquid stabilizer.
- Verify laboratory results by actual field performance studies.

AGGREGATES USED IN THE STUDY SITES

Alaska

The aggregate used in Alaska came from the stockpile used to supply a 1991 FHWA Experimental Feature Project on Elliott Highway, beginning north of Fairbanks, Alaska, at the transition point from asphalt to gravel road. An unbound granular material, the aggregate had performed poorly and was subject to constant potholing, washboarding, and gravel loss. It required regular maintenance grading (*3*).

Nevada

The aggregate used in Nevada had been placed on a road in the late fall. There was a subsequent delay of 6 to 8 months until temperature conditions warmed enough to be fully suitable for hot-mix asphalt placement operations. The unsurfaced access road, which had switchbacks and grades as steep as 13 percent, provided year-round access for 200 or more daily trips by triple-trailer trucks weighing approximately 60 tons fully loaded. The project owners recognized that they had a moisture-susceptible aggregate that required constant grading maintenance and daily watering in dry weather in order to service the truck traffic prior to paving.

New Mexico

The aggregate used by the city of Gallup, New Mexico, for paving projects, exhibited poor performance over 4.5 mi, including distressed chip seal surfaces and paved streets that had deteriorated to the point that winter access had become problematic even for four-wheel drive vehicles and trucks. Gallup experiences severe winter conditions and frequent freeze-thaw cycling, compounded by low-bearing-strength clay subgrade soils.

Texas

The Texas aggregate material was a mixture of siliceous river gravel mixed with locally available "caliche" (low-quality limestone) fines. To reduce the plasticity index, this material was treated with 1.5 percent of lime. The aggregate was used as base course material in a pavement section that was subjected to accelerated pavement testing using the Texas Mobile Load Simulator (TxMLS). Testing was conducted on a frontage road, US-59 in Victoria, Texas, in the Texas Department of Transportation (TxDOT) Yoakum District. Detailed results of the accelerated pavement test were reported by Hugo et al. (*4*). Rutting and cracking developed quickly during testing, resulting in generally poor performance. The poor performance of this pavement test section was attributed to water ingress into the base.

CURRENT CLASSIFICATION METHODS

Two AASHTO designations were used to classify the four aggregate materials based on the AASHTO Classification System: AASHTO M145-87, Recommended Practice for the Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes; and AASHTO M 283-83, Standard Specification for Coarse Aggregate for Highway and Airport Construction. In addition, the classification systems used by the state highway departments in Alaska, Nevada, New Mexico, and Texas were used to classify aggregate materials. Results are reported in Tables 1 and 2.

PROPOSED CLASSIFICATION METHOD USING THE TUBE SUCTION TEST

According to research conducted by the Finnish National Road Administration and the Texas Transportation Institute (TTI) (*1*), electrical properties can be used to classify the strength properties of base course aggregates. Studies showed that the value of dielectric constant and electrical conductivity related to both strength and deformation properties as well as the frost susceptibility of base course aggregates. Moisture affects the mechanical properties of all pavement materials and soils. However, the magnitude of these effects depends on the physical and chemical properties, moisture content, and even the saturation history of the materials. Both positive and negative pore-water pressures in a soil have a major effect on shear strength and volume change (*5*). Negative pore pressure is often described by the term "suction," which is also used to describe the Gibbs free energy—a thermodynamic quantity that generates tension in the pore water between soil particles (*6*). Total suction is composed of two components: matric and osmotic suction (*7*). In base materials with low moisture content, suction can increase the resilient modulus of aggregates (*8*, *9*), but when moisture content increases, the effect of suction decreases (*7*).

Based on ultramicroscopic observations, it has been concluded that because of the very small size of the particles, powdered clay particles dissolve in water and form a colloidal solution (*10*). Water molecules are bipolar and are attracted to the negatively charged clay particles. The height of capillary water (h) in cm is given by following equation:

$$h = \frac{2\sigma\cos\alpha}{r\rho_w g}$$

where

σ = surface tension in dynes/cm r,
α = contact angle in degrees between the liquid and surface α,
ρ_w = density of the liquid in g/cm^3,
g = acceleration due to gravity in cm/s^2, and
r = capillary radius in cm.

TABLE 1 Atterberg Limits

Materials	Liquid Limit	Plasticity Index
Alaska	25	10
Nevada	28	10
New Mexico	22	8
Texas	23	6

TABLE 2 Engineering Classification

Materials	Classification Grade Based on State DOT & AASHTO Specifications					
	Alaska	Nevada	New Mexico	Texas	M 145	M 283
Alaska	C-1/D-1	1-A/1-B	NA†	1	A-2-4	NA†
Nevada	C-1/D-1	1-A/1-B	NA†	1	A-2-4	NA†
New Mexico	C-1/D-1	1-A/1-B	NA†	1	A-2-4	NA†
Texas*	NA†	1-A	III-SB/IV-SB	1	A-1	NA†

† NA: Not acceptable as a base/subbase material.

* Specifications call for untreated base materials. However, the Texas aggregates were treated with 1½ % of lime.

The contact angle α for water against most soils is very small, so

$$\cos\alpha \approx 1$$

Also, if we substitute ρ_w for water = 1 g/cm^3, σ = 73 dynes/cm, and g = 981 cm/s^2, we arrive at the simplified equation

$$h = \frac{0.15}{r}$$

It is thus evident that the height of the capillary rise is inversely related to the radius of the capillary. In current laboratory testing procedures, there is no capability to quantify the volumetric water that is held by capillary forces within pavement base materials. The tube suction test is a promising laboratory testing technique that needs further evaluation.

Setup and typical results of the tube suction test are shown in Figure 1. The test measures the suction dielectric properties of materials by monitoring the capillary rise of moisture within a 200-mm-high cylinder of compacted aggregate. Moisture conditions of the aggregate surface are monitored with a probe that measures the dielectric constant. The value of the dielectric constant is a measure of free, or unbound, water near the surface of aggregate sample. The test is not a simple measure of moisture content of the material but rather an assessment of the state of bonding of water within fine aggregates.

MINERALOGICAL EVALUATION

Pretreatment and Fractionation

To identify component minerals, the base sample was separated into different fractions based on particle size: sand (2 mm to 50 μm), silt (2 μm to 50 μm), coarse clay (0.2 μm to 2 μm), and fine clay

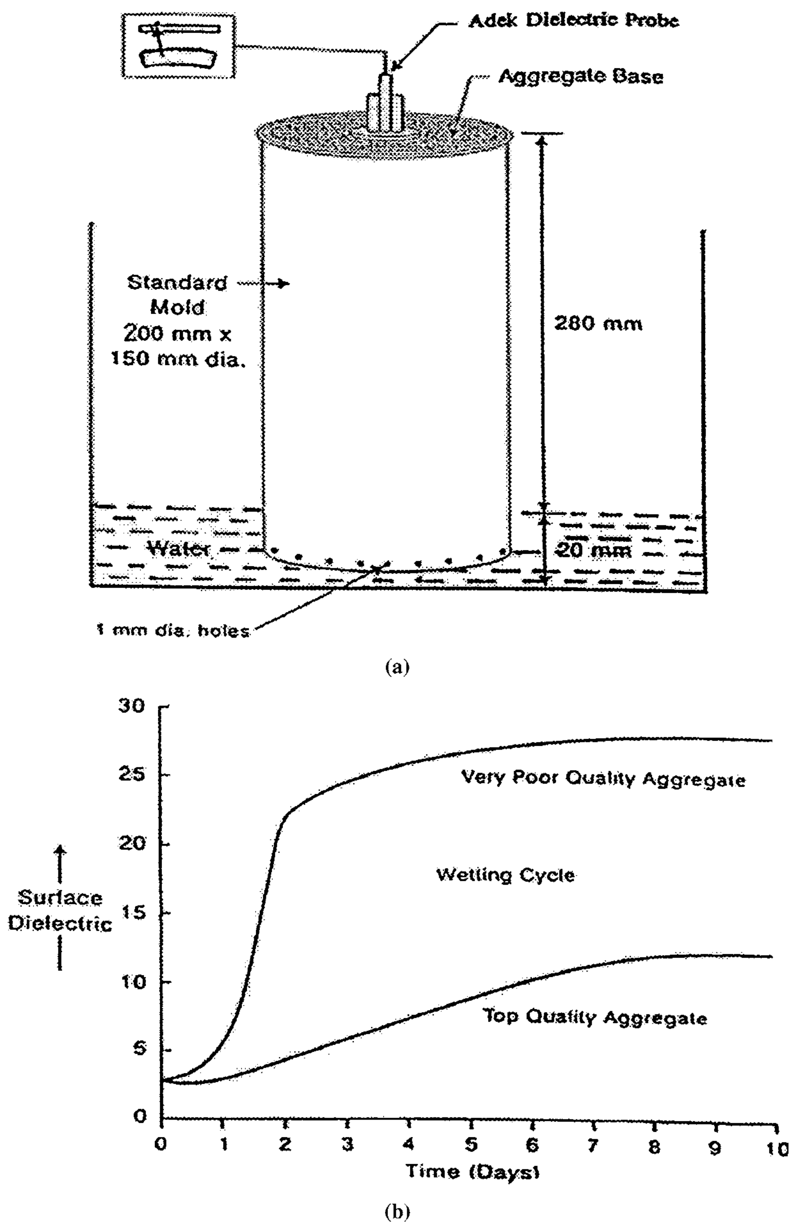


FIGURE 1 Tube suction test (*17*): (*a*) setup, (*b*) typical results.

(<0.2 µm). The bulk soil sample was air-dried, crushed, and sieved with a 2-mm sieve. A pH 5, 1 N sodium acetate solution was used to remove carbonates and achieve sodium saturation of the sample. Organic matter and manganese dioxide were removed with hydrogen peroxide. Dispersion was achieved with pH 10 water. Sand, silt, coarse clay, and fine clay fractions were separated by wet-sieving, gravity sedimentation, centrifugation, decantation, and flocculation. The sand, silt, and coarse clay fractions were then oven-dried. The fine clay fraction was freeze-dried to maintain sample integrity (*11*).

X-Ray Diffraction

Sand and silt fractions were mildly ground with acetone to pass through a 180-mesh sieve. The sample was backmounted in an aluminum holder to maintain random grain orientation. The coarse and fine clay fractions were saturated with magnesium (Mg) and potassium (K). Each Mg-saturated fraction was mounted on glass, and each K-saturated fraction was mounted on vycor slides. Both coarse and fine clay fractions were subjected to different treatments: Mg-saturation (25°C), Mg-ethylene glycol (25°C), K-saturation (25°C), and K-saturation heated to 300°C and 550°C (Figure 2). Cation saturation is needed because *d*-spacings for expansive minerals such as vermiculite and smectite are highly variable without a known exchange cation. Additional treatment of the Mg-saturated slide with ethylene glycol aided in detecting the presence of smectite. Consistency of *d*-spacings allowed for recognition of interstratified phyllosilicates and facilitated a more quantitative interpretation of X-ray diffraction (XRD) patterns for samples with interstratifications. Heat treatments of the K-saturated slide aided in detection of chlorite, hydroxy-interlayered phyllosilicates, kaolinite, and mica (*11*).

MINERALOGICAL ANALYSIS

Mineralogical analysis was performed with a Rigaku X-ray diffractometer using CuKα radiation. All XRD peaks were confirmed with the Hanawalt search manual and cards from the *Mineral Powder Diffraction File* databook prepared by the Joint Committee on Powder Diffraction Standards (JCPDS) (*12*). XRD aggregate patterns are shown in Figure 2*a–d*.

Alaska Aggregate

The sand and silt fraction was comprised of quartz and feldspar. The coarse clay fraction consisted of mica (discrete illite), kaolinite, and vermiculite as major constituents, with minor smectite possibly interstratified with illite. The fine clay fraction was predominantly smectite, kaolinite, and mica.

Nevada Aggregate

The sand and silt fraction was primarily composed of sodium-rich feldspar. The coarse clay fraction was composed of mica and kaolinite. The remaining XRD peaks could not be completely identified; further study is under progress to identify those peaks. The fine clay fraction was predominantly smectite, kaolinite, and mica.

New Mexico Aggregate

The sand and silt fraction was dominated by the presence of quartz, calcite, and feldspar. The coarse clay was dominated by randomly interstratified illite (10)/smectite with minor kaolinite and discrete illite. The fine clay fraction was predominantly smectite, kaolinite, and mica.

Texas Aggregate

The sand and silt fraction was comprised of quartz and microcline. The coarse clay fraction was made up of quartz, kaolinite, mica, and smectite. The fine clay fraction was comprised of kaolinite, mica, and smectite.

CONCENTRATED LIQUID STABILIZERS

In a research study sponsored by the U.S. Department of Transportation and the Federal Highway Administration (FHWA-FLP-92-011) (*13*), several of the commercially available concentrated liquid stabilizers (CLS) are described. The study reviewed the applications and performance of CLS used with subgrade soils, aggregate bases, and aggregate surface courses in low-volume roads and in highway construction. One of the commercially available CLS products, EMC-Squared, reviewed by Scholen (*13*), had recently been reported to have successfully stabilized similar moisture-susceptible aggregates (*14*). One advantage of this CLS is that its pH ranges between 5 and 9, which is very close to that of rainwater. Hence, from a geoenvironmental standpoint, the use of this chemical is encouraging. Reactions that normally take place are those that occur during the process of decomposition of clay in a natural environment.

Because the four aggregate materials exhibited poor performance in terms of resistance to moisture susceptibility, it was decided to treat these materials with the CLS. The tube suction test was used to check for moisture susceptibility of the treated aggregate materials.

RESULTS AND DISCUSSION

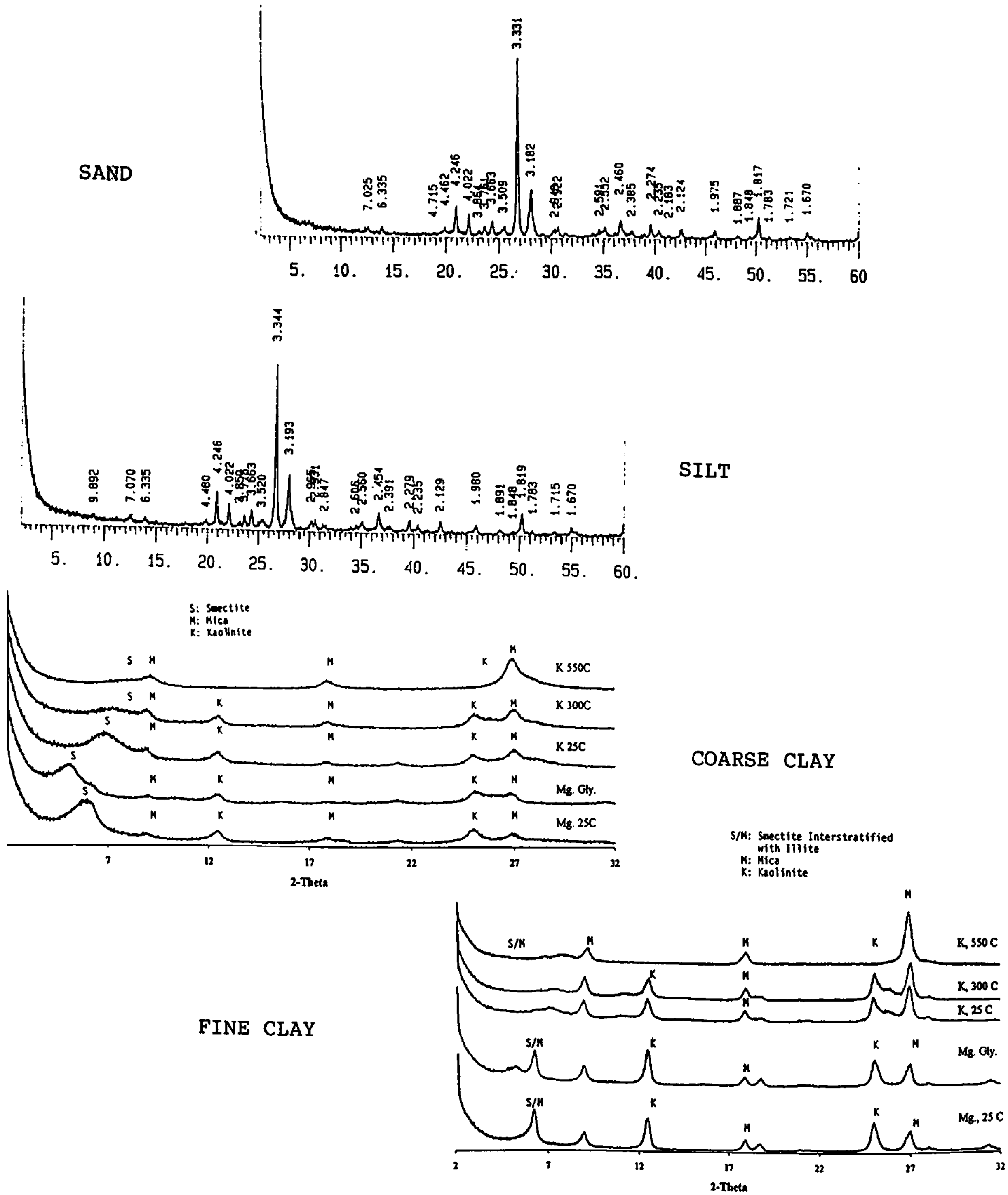
Untreated Aggregates

Engineering Classification

Particle size distribution is shown in Figure 3. Atterberg Limits are tabulated in Table 1 and the engineering classification is tabulated in Table 2. Figure 4 shows the results of the tube suction test. Dotted lines in Figure 4 indicate the tube suction test results on the untreated aggregates, while solid lines indicate tube suction test results on CLS-treated aggregates.

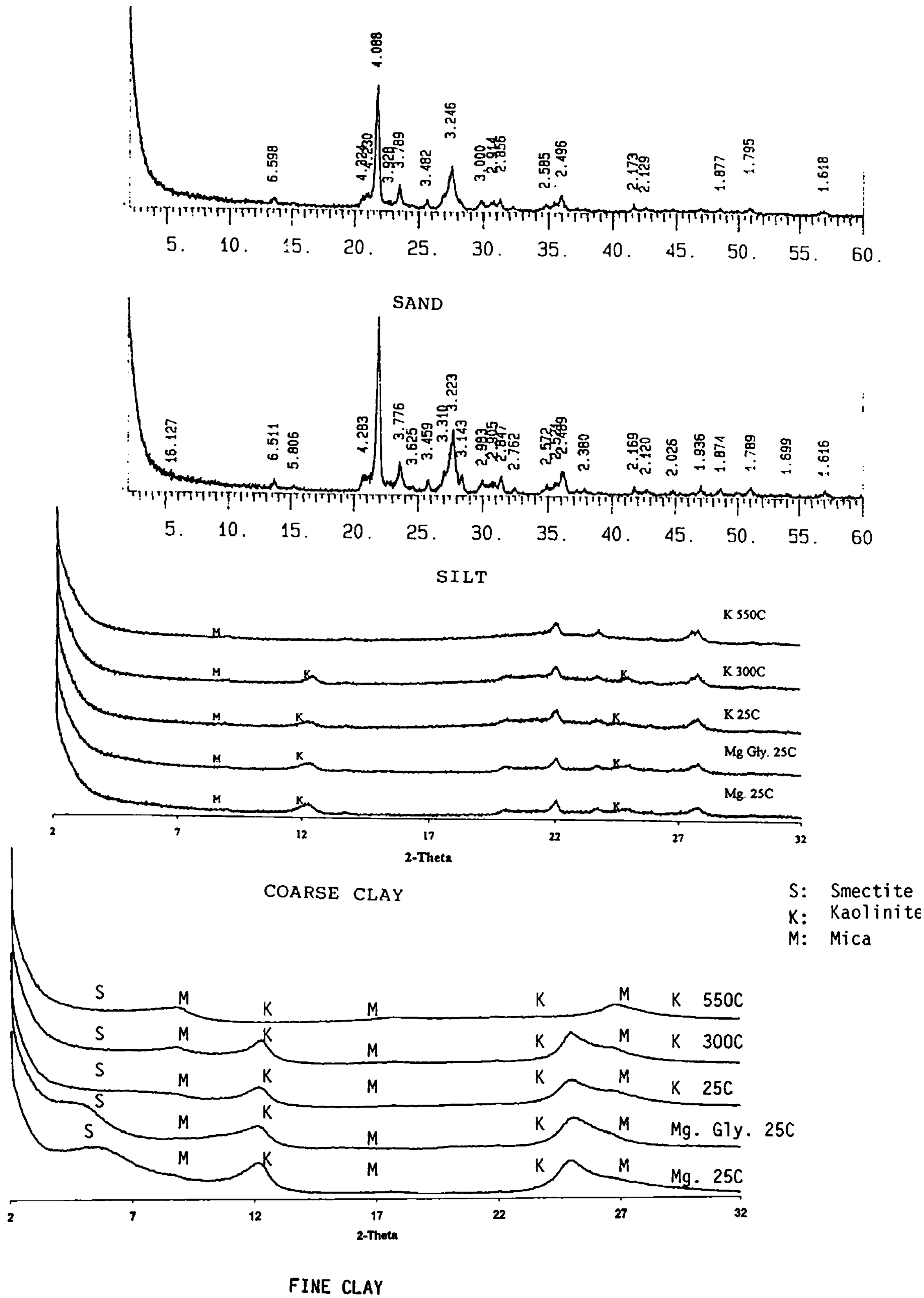
Based on engineering classification, it is clear there is no consistency in the different specifications used by various states for granular materials that can be used as base/subbase materials.

As per AASHTO M283 and New Mexico Department of Transportation specifications, none of these materials are acceptable for base courses. The reason is that these specifications restrict the maximum permissible plasticity index to a value of 6 percent. Rollings and Rollings (*15*) showed that the California bearing ratio values measured on soaked and unsoaked base course aggregate samples



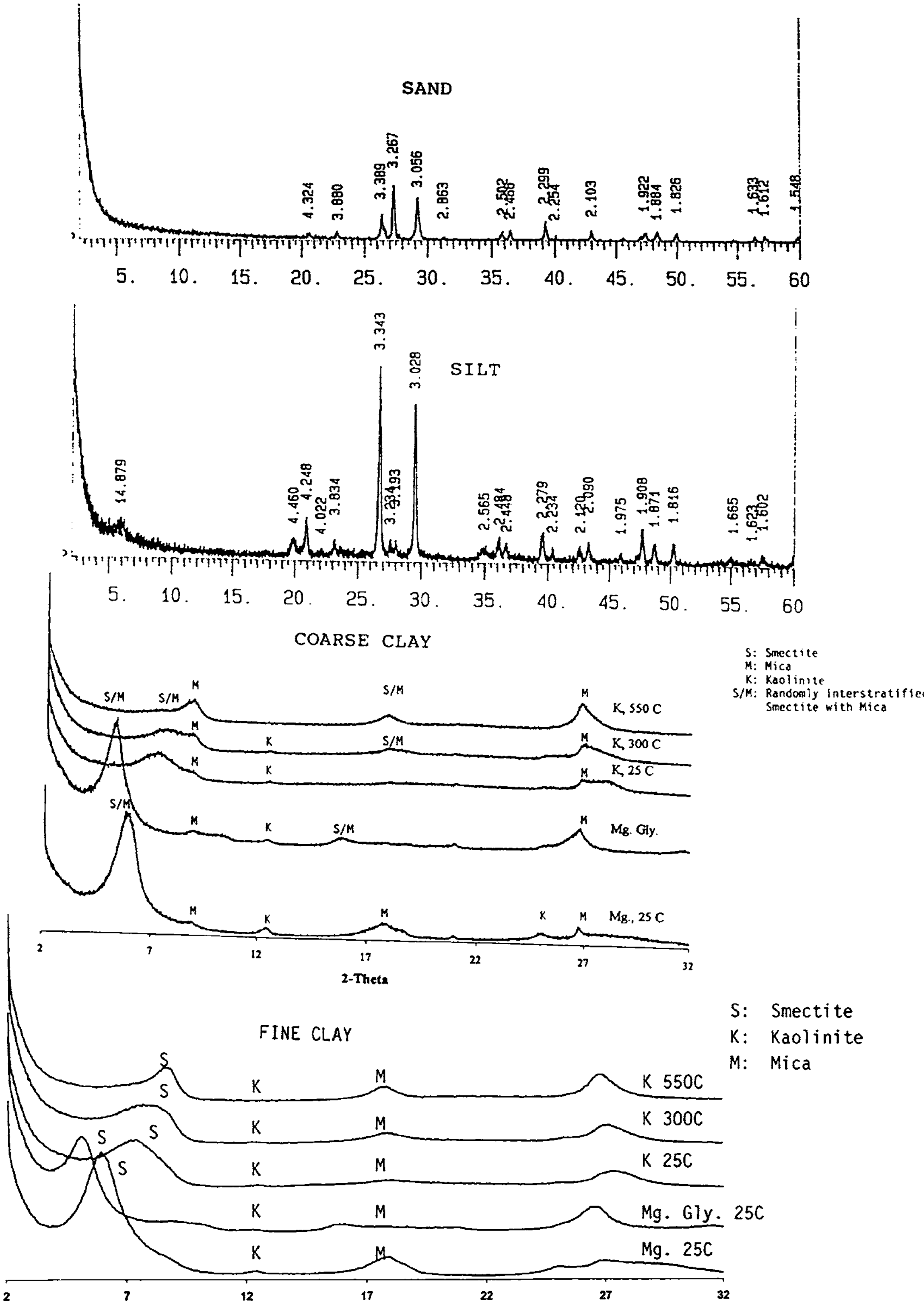
(a)

FIGURE 2 X-ray diffraction pattern for sand, silt, and clay: (*a*) Alaska aggregate. (*continued on next page*)



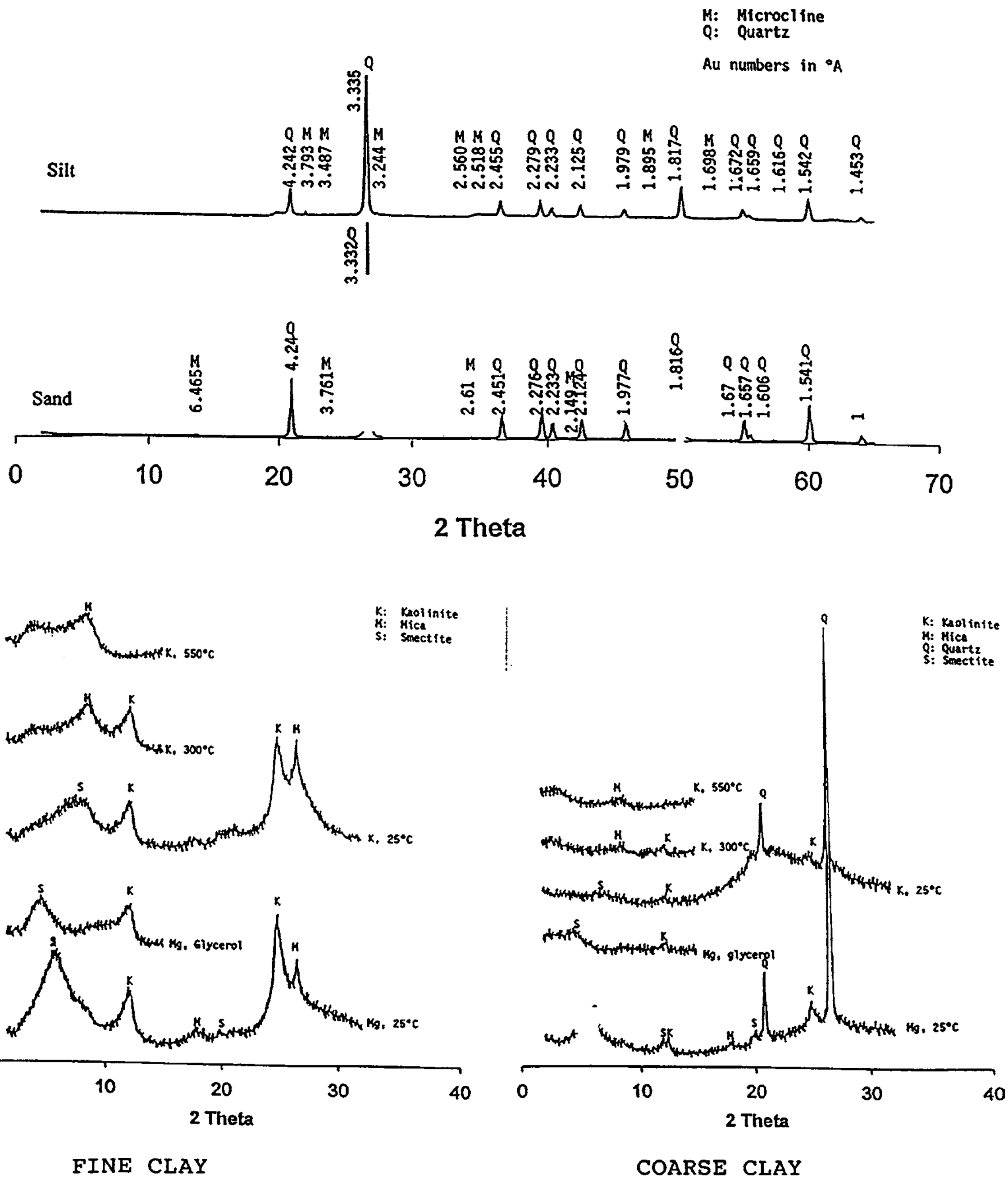
(b)

FIGURE 2 *(continued)* X-ray diffraction pattern for sand, silt, and clay: *(b)* Nevada aggregate. *(continued on next page)*



(c)

FIGURE 2 *(continued)* X-ray diffraction pattern for sand, silt, and clay: *(c)* New Mexico aggregate. *(continued on next page)*



(d)

FIGURE 2 (*continued*) X-ray diffraction pattern for sand, silt, and clay: (*d*) Texas aggregate.

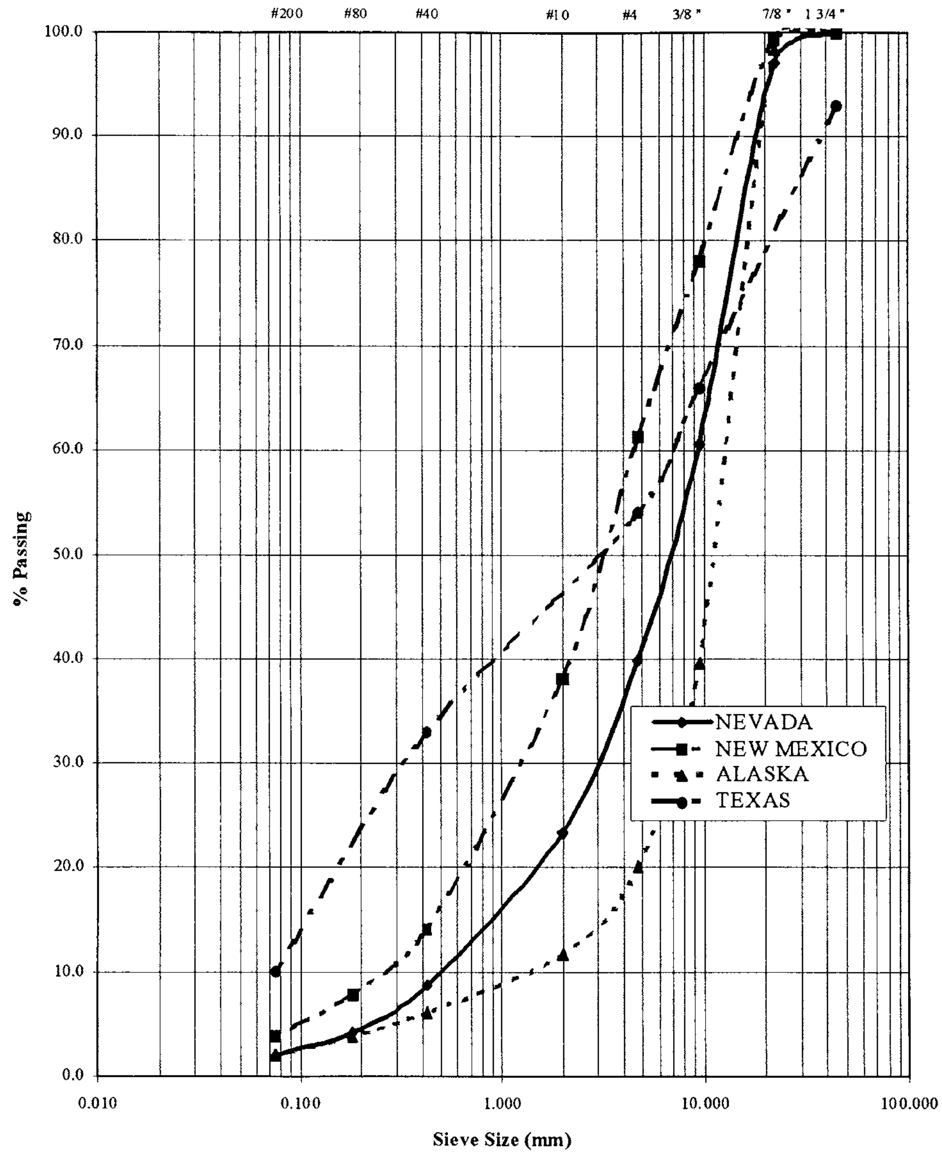


FIGURE 3 Particle size distribution.

from 10 airports in the southeastern and southwestern United States decreased with increasing plasticity index. A plasticity index of 6 percent has been a traditionally accepted dividing point between plastic and nonplastic behavior (*16*), and many specifications set the maximum allowable plasticity index between 4 and 6 percent for materials to be used in base and subbase of pavements.

All four aggregate materials were classified as acceptable as base courses per AASHTO M145 and the Department of Transportation (DOT) specifications of Nevada and Texas. Only Texas and Nevada DOT specifications found the four aggregate materials acceptable.

Tube Suction Test

Scullion and Saarenketo (*17*) suggested a maximum permissible dielectric constant of 16 for granular materials. This was based on the research study, *Using Electrical Properties to Classify the Strength Properties of Base Course Aggregates* (*1*). Measured values of surface dielectric constants at completion of the tube suction test were greater than 16 for all four aggregate materials. Based on the tube suction test, all the materials were classified as poor performers, and this was also reflected in their reported field performance.

Mineralogical Evaluation

Aggregates from Alaska, New Mexico, and Texas were comprised of expansive clay minerals such as smectite and vermiculite. Interstratification of the clay minerals smectite, mica, and vermiculite was also observed. Mixed-layered clay minerals are very common in soil environments, with illite-smectite being the most widespread. Minerals such as smectite and vermiculite have very high surface charge, very high surface area, and very high cation exchange capac-

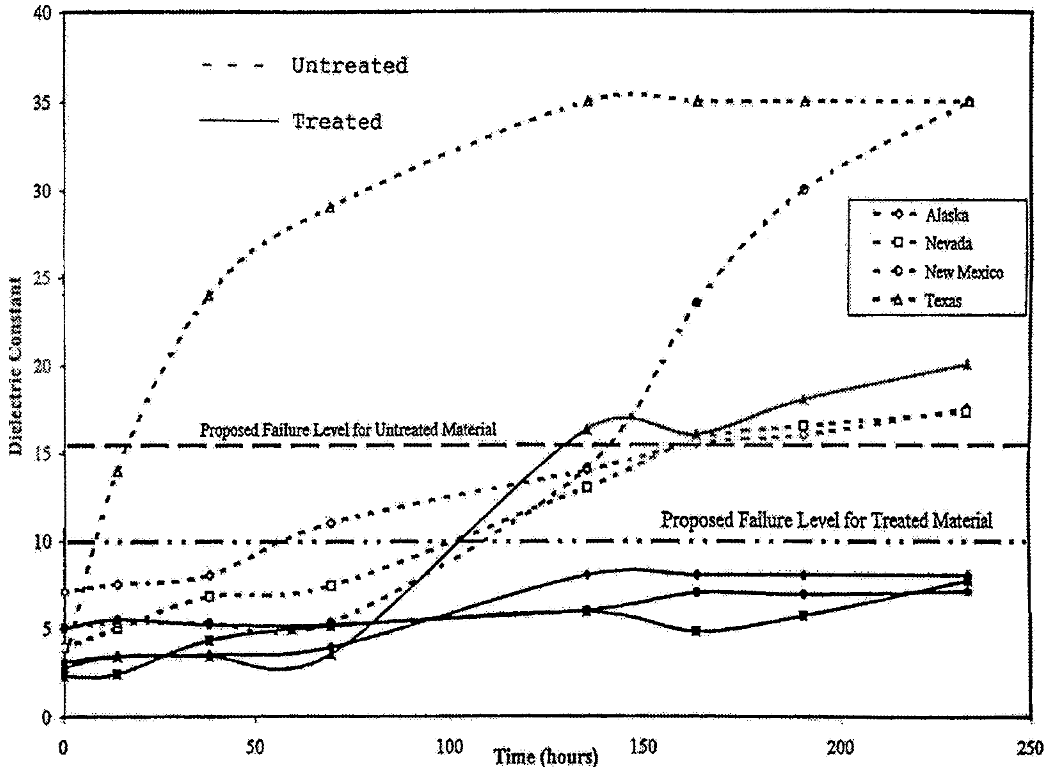


FIGURE 4 Tube suction test results.

ity. These minerals have medium-to-high potential for swelling or shrinking, plasticity, and affinity for water (*18*). For the above mentioned reasons, granular materials that have an abundance of these minerals will have extremely small clay particles. As shown earlier, the height of the capillary is inversely proportional to the radius of the capillary. Hence, if a sufficient amount of such minerals is present in a base material, then matric suction properties of that material will be enhanced. These base materials will therefore have a very strong affinity for water, which explains the high surface dielectric constant readings measured in these materials upon completion of the tube suction test.

Nevada aggregate material is particularly noteworthy. The sand and silt fraction shows an abundance of sodium-rich feldspar but an absence of quartz. The coarse clay fraction showed no expansive clay mineral. However, the fine clay fraction showed a dramatic amount of smectite, kaolinite, and mica, as shown in Figure 2*b*. The presence of large amounts of smectite in the fine clay fraction contributed to failure of this material in the tube suction test.

Treated Aggregates

Saarenketo and Scullion (*1*) concluded that, based on their laboratory study and field data in Texas and Finland, if the dielectric constant exceeds a value of 10, the granular material is susceptible to moisture-related damage. Based on the research carried out at the Texas Transportation Institute during the past 5 years, a maximum dielectric constant of 10 is tentatively recommended for stabilized base materials (*2*).

After treatment with CLS, Figure 4 shows that for materials from Alaska, Nevada, and New Mexico, the measured surface dielectric constant at completion of the tube suction test was less than 10. Thus, materials for the pavement base/subbase course were classified as acceptable. However, although showing significantly improved performance exceeding a value of 10 for surface dielectric constant, the Texas aggregate did not pass the tube suction test. Scholen (*13*) states that CLS combines with large organic molecules to form a reactant intermediary, which exchanges with the clay lattice and breaks down the clay structure, thereby causing the coverup effect that prevents further sorption of water or the resultant swelling with loss of density. CLS treatment of aggregates showed an improvement in resistance to moisture susceptibility for all four aggregate materials, although the extent of improvement varied.

Materials from Alaska, Nevada, and New Mexico showed excellent results and were subsequently used in pavement construction. However, the Texas aggregate failed the test. Further work is underway to study the mechanisms involved in CLS treatment of these aggregates. The goals of this effort are to understand the chemical reactions that occur when CLS is added to aggregates and to explain the variability observed in improvement to moisture resistance among different aggregates.

FIELD EVALUATION

For road construction projects in Alaska, Nevada, and New Mexico, treated aggregates were first placed into service as aggregate surface courses, providing running surfaces for vehicles and heavy trucks. During this time, stabilized aggregates provided excellent running surfaces, requiring little to no maintenance and showing no evidence of moisture penetration or frost damage. The stabilized aggregate surface courses were eventually utilized as stabilized bases for bituminous surface courses.

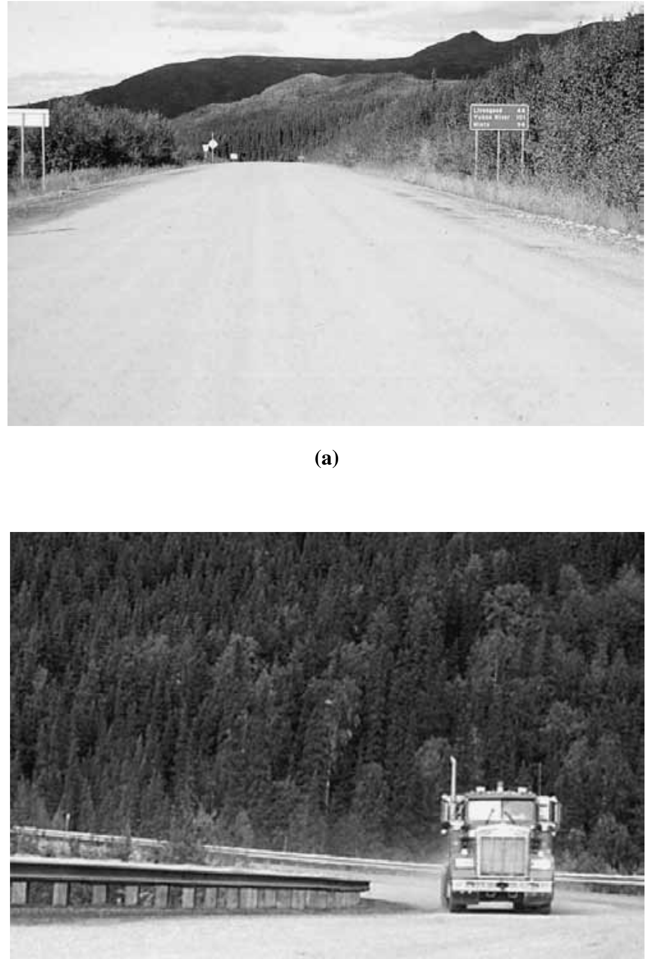
Alaska Aggregate

CLS-treated Alaska aggregate was used in a project by the Alaska Department of Transportation and Public Facilities in early June 1991. The project is more fully covered elsewhere (*14*). After the project's second summer, the stabilized section (Figure 5*a*) was described as essentially maintenance-free, with only minor touch-up required in the super-elevated curves. At the end of the third summer, it was reported that only a few small potholes had been found on the stabilized section, located in the worst stress area of the super-elevated curves (Figure 5*b*) and no larger than "half a grapefruit." Numerous potholes of 2- to 3-m-diameter were observed in the control section.

Nevada Aggregate

Aggregate materials were placed on the road and then treated with the CLS solution in a mixed-in-place operation conducted with a motor grader and a tractor-drawn agricultural disk unit. The 150-mm-thick stabilized aggregate surface was placed into service immediately. After 6 months of use, the treated road was well preserved, and company management reported that paving operations were able to proceed with a minimal need for grading or trimming of the stabilized aggregate surface.

The performance of this stabilized aggregate during the time it served as a road surface on a steep and winding mountain road (Figure 6*a*), supporting trucks with loaded weights permitted on only a few state highways systems, is impressive.



(a)

(b)

FIGURE 5 Elliot Highway, Alaska: (*a*) stabilized aggregate course 15 months after construction, (*b*) truck rounding curve on stabilized aggregate surface course.

New Mexico Aggregate

The asphalt reclaimer/rotary mixer unit was used to pulverize the existing chip seal surfaces and distressed areas and also for mixing the stabilizer solution. A new surface course of aggregate base was then placed to a 150-to-200-mm thickness and also stabilized with a mixed-in-place operation. The stabilized streets serviced industrial and commercial businesses, public schools, and residential neighborhoods and required almost no maintenance (Figure 6*b*).

Texas Aggregate

Historical performance of the pit run gravel as a flexible base for TxDOT highways had not been satisfactory, and tube suction testing results indicated that the dielectric constant of the surface increased by a factor of 7 within 24 h of commencing the test, attaining a final value of over 35. As part of an ongoing study at TTI, this pit run gravel was also tested with the CLS treatment. The CLS treatment essentially maintained the aggregate in its dry state for the first 3 days of testing before the dielectric began its eventual climb to a final dielectric value of 20. While resistance of the gravel to initial wetting was significantly improved, the final value of the dielectric constant fell short of meeting the goal of the treatment program—a value of dielectric constant less than 10, which the test method defines as the upper limit for non-moisture-sensitive and non-frost-susceptible road base service. As demonstrated in this testing series with pit run gravel, the tube suction test procedure is capable of identifying aggregates that are problematic for stabilization treatments as well as verifying applications that are successful.

Given the field performance history of these four aggregates (as untreated and treated materials) from three different regions, the aggregate group provided a unique opportunity to demonstrate the effectiveness of tube suction testing as a performance-based test methodology for identification of moisture-susceptible aggregate materials and for evaluation of a specific stabilization product in treatment of a specific aggregate material. In the case of the four aggregate materials, tube suction testing provided excellent correlation with field performance history. Testing of the untreated aggregates predicted accurately that they were moisture-sensitive and

(a)

(b)

FIGURE 6 Stabilized aggregate: (*a*) 6 months after construction, Canyon Way Road, Nevada; (*b*) 5 months after construction, South Annex Street, Gallup, New Mexico.

highly frost-susceptible. Testing of the treated aggregates indicated that they were non-moisture-sensitive and non-frost-susceptible in service for road and highway base applications.

CONCLUSIONS

- There is a wide variation in the current engineering classification of aggregate materials to be used as base/subbase materials. Current methods focus more on particle size distribution and the plasticity index, but this methodology may not be entirely suitable for identifying poorly performing aggregate bases/subbases.
- Free moisture within base materials can cause serious problems. Current testing methods do not address the problem of moisture susceptibility of base/subbase materials.
- The tube suction test is a suitable candidate for inclusion as part of laboratory testing and specifications for design and construction of pavements. This test should be part of the aggregate acceptance test for design and construction of future pavement projects.
- ACLS selected for its history of successful stabilization of moisture-susceptible aggregates was used to chemically treat the four aggregates. The tube suction test on the treated materials showed marked improvement in moisture susceptibility of the three aggregates from Alaska, Nevada, and New Mexico. However, the CLS was only partially successful in improving moisture susceptibility of the Texas aggregate.
- Field performance of the three roads in Alaska, Nevada, and New Mexico also showed improvement upon treatment with CLS. This was a result of improved resistance of the treated material to moisture susceptibility, indicated by the tube suction test in the laboratory.

FOLLOW-UP STUDY

Future work is needed to evaluate the stabilizing mechanisms of the CLS. There was a significant improvement in moisture susceptibility of aggregates from Alaska, Nevada, and New Mexico. The Texas aggregate showed marginal improvement. Although moisture susceptibility of the CLS-treated Texas aggregates was less than that of the untreated aggregates, it still fell short of required levels. This is intriguing, because the mineralogical evaluation of all four aggregates indicated the presence of smectite as the main cause of concern. Future research needs to address basic causes of CLS's success in improving moisture susceptibility of the three aggregates and its lack of similar success in improving moisture susceptibility of the Texas aggregate.

ACKNOWLEDGMENT

This work was funded by the Texas Department of Transportation (TxDOT). The support of Dar-Hao Chen of the TxMLS Data Analysis Program in the Pavement Design Section of TxDOT is greatly appreciated. The authors also wish to gratefully acknowledge the assistance of J. B. Dixon, G. N. White, and J. P. Harris in carrying out the mineralogical evaluations.

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Publication of this paper sponsored by Committee on Frost Action.