1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-01/0-1707-1		

4. Title and Subtitle	5. Report Date
LITERATURE REVIEW FOR LONG-TERM RESEARCH ON BITUMINOUS COARSE AGGREGATE	January 2001 Resubmitted: July 2001
	6. Performing Organization Code
7. Author(s) Dallas Little, Joe Button, Priyantha Jayawickrama, Mansour Solaimanian, and Barry Hudson	8. Performing Organization Report No. Report 0-1707-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project No. 0-1707
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin Texas 78763-5080	13. Type of Report and Period Covered Technical Report: Jan. 2000 – June 2000 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Long Term Research on Bituminous Coarse Aggregate

16. Abstract

The Soils and Aggregates Branch of the Construction Division of the Texas Department of Transportation (TxDOT) has the primary responsibility for overseeing aggregate quality issues. An overall process review of selected testing and monitoring protocols used within the branch is needed to ensure that the needs of TxDOT and the state of Texas are continuously met. Two key areas are addressed in this review: (1) a review and upgrade of the Aggregate Quality Monitoring Program (AQMP) and (2) a review and upgrade of the proposed Surface Aggregate Classification System.

The assessment of the AQMP includes evaluation of other tests that might be required as replacements and/or supplements for the tests currently used to monitor quality. The study also includes an assessment of the frequency and protocol of testing and suggests changes where necessary. The Surface Aggregate Classification System evaluation will involve defining the best tests and protocols to ensure excellent wet weather skid properties (level 1) and to ensure excellent overall hot-mix quality (level 2) for a safe and durable hot-mix surface. The project also includes a long-term field-monitoring program to ensure that selected tests and protocols correlate with field experience.

17. Key Words	18. Distribution Statement
Magnesium Sulfate Soundness, Polish Value, Los Angeles Abrasion, Skid Resistance	No Restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	54	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

LITERATURE REVIEW FOR
LONG-TERM RESEARCH ON BITUMINOUS COARSE AGGREGATE

by

Dallas Little
Senior Research Fellow
Texas Transportation Institute

Joe Button
Senior Research Engineer
Texas Transportation Institute

Priyantha Jayawickrama
Associate Professor
Texas Tech University

Mansour Solaimanian
Research Engineer
Center for Transportation Research

and

Barry Hudson
Consultant

Report 0-1707-1
Project Number 0-1707
Project Title: Long Term Research on Bituminous Coarse Aggregate

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

January 2001
Resubmitted: July 2001

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

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 Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. Additionally, this report is not intended for construction, bidding or permit purposes.

ACKNOWLEDGMENTS

Special thanks are given to Ms. Caroline Herrera of TxDOT's Austin District for her assistance in the development of this strategy selection process. We also extend our thanks to the representatives of the Texas Department of Transportation for their assistance in conducting the research and development of this literature review. Thanks also to the FHWA for its support.

TABLE OF CONTENTS

Page

BACKGROUND AND SIGNIFICANCE OF WORK

AQMP PROGRAM: RESEARCH NEEDS

TxDOT's current Aggregate Quality Monitoring Program (AQMP) prequalifies aggregate sources based on the aggregates' performance in polish value, five-cycle magnesium sulfate soundness and Los Angeles (LA) abrasion tests. The sampling and testing of these aggregates follow a regular schedule. This approach minimizes the need for stockpile testing at the project site for aggregate qualification. This program, therefore, has achieved its goal by minimizing both costs associated with stockpile testing and possible delays from aggregate testing and acceptance at the project site. However, the effectiveness of the program has been questioned in a number of different areas. The following concerns have been raised:

1. The character and quality of the material produced at some aggregate sources show significant variations. Can we adequately characterize the material with the current sampling and testing frequency (every three or six months)?
2. One of the drawbacks in the current program is that it follows a regular schedule of sampling and testing. In a quarry that produces material with variable quality, the supplier may adjust the quarrying sequence so that sampling produces the best quality material. Therefore, should TxDOT consider sampling at random time intervals?
3. Another deficiency in the current program is that it does not provide a mechanism to ensure the quality of the aggregate that is received at the jobsite. Are there other test protocols that may be used at the project site to test the aggregate stockpile and, hence, achieve better quality control (QC) at the project level?
4. There can be a considerable time lag between the beginning of the data gathering period and the date on which the Rated Source Quality Catalog becomes effective. Such a time lag is not desirable when dealing with aggregate sources with large variation in quality. Can this variation be corrected or minimized?

5. The current AQMP program relies on PV five-cycle MSS and LA Abrasion tests for quality control purposes. Are there other test methods superior to these in terms of: (a) time and cost associated with testing, (b) reproducibility of test results, and (c) ability to relate to actual field performance?

6. By using AQMP and method specification, TxDOT assumes the responsibility for controlling and maintaining quality of materials. Can the program be revised so that the producers share some of this responsibility?

Several landmark studies have been completed in the area of aggregate testing related to hot-mix asphalt (HMA) performance over the last several years. These include the following TxDOT-sponsored studies: a) Center for Transportation Research (CTR) at University of Texas in Austin, Texas, research project 0-490, which focused on skid resistance of seal coat pavements; b) Center for Multidisciplinary Research in Transportation, at Texas Tech University, Lubbock, Texas, research project 0-1459, which focused on skid resistance of hot-mix asphalt concrete pavements project 438-1F, which focused on the durability properties of aggregates and current research project 0-1771, which addresses aggregate durability of a suite of 60 different aggregates; and c) TxDOT's in-house research project 7-3994, which was a follow up to the previous projects. Non-TxDOT studies include: National Cooperative Highway Research Program (NCHRP) project 10-12, NCHRP report 405, and the International Center for Aggregates Research (ICAR) report 404011-1 on evaluation of superpave aggregate angularity specification and the Aggregates Handbook. Although other pertinent reports exist, these studies provide a wealth of information and provide a primary and immediate source of information.

A review of the above-mentioned studies, i.e., the testing procedure, the results, and the conclusions on the performance of the aggregates in HMA, are discussed in the following part of this report.

RESEARCH STUDY: CTR-490

Report Title: Implication of Aggregates in the Construction and Performance of Seal Coat Pavement Overlays

Report Date: August 1992

Sponsoring Agency: Texas Department of Transportation (in cooperation with United States Department of Transportation (USDOT) and Federal Highway Administration (FHWA)

INTRODUCTION

Many variables have been identified as the cause for wet weather skidding accidents, with pavement frictional resistance being recognized as the primary factor. It is nearly impossible to provide adequate frictional resistance for the design life of a pavement surface without the development of numerous maintenance techniques aimed at correcting deterioration in surface friction. The factors influencing the surface frictional resistance include frictional characteristics of the coarse aggregates, construction design variables and practices, traffic volume, and environment. In Texas, the Materials and Tests Division of the State Department of Highways and Public Transportation (SDHPT) employs the polish value (PV) test to determine the aggregates to be incorporated in pavement surfaces and skid resistance tests to measure the frictional resistance of pavement surfaces, referred to as friction number (FN). The current requirements based on average daily traffic (ADT) are as follows:

ADT	PV
Where specified in the plans	35
Greater than 5000	32
5000 to 2000	30
2000 to 750	28
Less than 750	No requirements

OBJECTIVES OF THE STUDY

The following objectives were used to investigate and develop design criteria to provide and maintain adequate pavement friction:

- develop a comprehensive, long-range strategic research plan that addresses all aspects of pavement friction, and
- investigate the relationship between laboratory frictional properties of coarse aggregates (PV) and frictional performances of roads built with these aggregates (FN).

In this research, the frictional resistance of 59 seal coat test sections in Texas was investigated, as seal coat overlays were used in the rehabilitation of pavements of all classes.

SCOPE OF THE STUDY

The ultimate aim of this research, as highlighted below, was to formulate statistical models for predicting the frictional resistance of the seal coat rehabilitation method in terms of the hypothesized factors influencing either the microtexture or macrotexture components of surface friction:

- relate the laboratory properties of aggregates used in seal coat construction to the frictional performance of this rehabilitation method and thus establish criteria for evaluating expected aggregate performance,
- evaluate the effects of different construction spreading rates and gradation of aggregates on the frictional performance of seal coat overlays constructed with aggregates of common laboratory properties,
- determine the influence of environment and other climatic variables on seal coat frictional performance, and
- quantitatively study the interaction between traffic and the performance of various aggregate materials.

FINDINGS/RECOMMENDATIONS

Laboratory Studies

Correlation studies revealed no correlation between the polish value test and soundness, LA abrasion, and insoluble residue (AIR) test for aggregates on which data were available. However, good correlations were found between polish value test and soundness and LA abrasion tests for the limestone group. The LA abrasion test could better distinguish among natural aggregates and between the hard aggregates and the limestones with low polish value. For uncoated aggregates, poor overall correlations were noticed between the polish value test and all other tests. Excellent correlations were observed between the polish value test and the specific gravity and absorption tests. A moderate correlation coefficient was obtained for the correlation between the polish value and Texas degradation tests.

The aggregate durability index test was found to have no correlation with the LA abrasion test, while a moderate overall correlation was observed between the LA abrasion and Texas degradation tests. Low and high PV values were associated with aggregates having high percentages of matrix-supported and grain-supported texture particles, respectively. The polish value tests also failed to reflect the effect of the hardness of the minerals constituting an aggregate. The presence of a large amount of tightly compacted carbonate grains in grain-supported texture particles did not produce a high polish value. High soundness loss was associated with the presence of numerous voids in grain-supported texture particles or high porosity in matrix-supported particles.

Field Studies

A correlation existed between average texture depth and British pendulum number (BPN). Frictional numbers (FN) were found to be independent of average texture depth for a high level of British pendulum numbers (lightweight aggregates). A correlation between frictional numbers and the average texture depth could not be detected for low levels of British pendulum numbers, however, frictional numbers were found to be related to average texture depth for two medium levels of British pendulum numbers.

The performance of aggregates with high polish value and soundness losses (carbonate aggregates) was inferior to that of aggregates with high polish value and low soundness losses (non-carbonate aggregates). The level of performance for the former was found to be dependent on the level of ADT, as the polishing action of this variable interacted with the amounts of rejuvenation by weathering action.

Porous aggregates, particularly some lightweight and limestone rock asphalt, maintained excellent rejuvenated surfaces in the area characterized by temperature freeze-thaw cycling. The level of construction aggregate spreading rate explained much of the variation in many of the groups identified. The performance of low-polish value aggregates that possessed some porosity or had high contents of non-carbonate minerals was better than that of the other low polish value aggregates.

Statistical Model

Correlations among laboratory and field tests were studied. The performance data were graphed to detect the sources of variations and were grouped according to the different considered variables. The grouping gave insights into which variables controlled the observed differences in frictional performance. The grouping of aggregates along with the aggregate spreading rate and region variables explained about 85 percent of the variation in performance. A general multivariable regression model was formulated using all friction measurements.

RESEARCH STUDY 0-1459

Report Title: A Comprehensive Methodology for Predicting Field Skid Resistance of Bituminous Aggregates Based on Laboratory Test Data as Well as Their Past Skid Performance

Report Date: September 1998

Sponsoring Agency: Texas Department of Transportation (in cooperation with USDOT and FHWA)

INTRODUCTION

A hot-mix asphalt concrete (HMAC) pavement should be designed to provide adequate surface frictional resistance against sliding, commonly expressed as a skid number (SN). This safety-related property of the pavement surface is achieved through proper selection of materials, design, and construction. The skid resistance of a pavement is influenced by its microtexture and macrotexture properties. Microtexture properties can be controlled through the selection of aggregates with desirable polishing behavior, determined by the PV test in the laboratory. Macrotexture properties depend upon the size, shape, and gradation of coarse aggregates, as well as the construction technique, bituminous mix, and environmental factors.

TxDOT adopts two rating procedures for aggregate qualification: rated source polish value (RSPV) and skid performance history. However, some shortcomings of these methods have resulted in a need for revision of the existing bituminous aggregate qualification procedures.

OBJECTIVES OF THE STUDY

This research was initiated to conduct a comprehensive evaluation of the current TxDOT aggregate qualification procedures with recommendations. The tasks involved in the work plan are as follows:

- Conduct a nationwide survey on the current qualification procedures adopted by other state DOTs.
- Select 50 to 60 test pavement sections that represent aggregate types, mix designs,

and climatic regions within Texas for skid resistance monitoring, with a few test sections monitored more frequently because of seasonal variations.

- Conduct laboratory tests on coarse aggregates used in the construction of test pavement sections.
- Perform statistical analysis to conclude the following: (a) relative significance of microtexture versus macrotexture, (b) laboratory test procedures that provide better correlation with aggregate field performance, and (c) significance of seasonal factors in terms of the variability of SN measurements.

RESEARCH METHODOLOGY

The research involved both a detailed laboratory test program and a field test program to determine the performance of the selected aggregates. The laboratory test program involved PV test, AIR test, petrography analysis (PA), LA abrasion test, and MSS test, as these were some of the tests commonly adopted by most state DOTs. To ensure representative aggregate sources used in the pavement test sections the aggregate samples tested were obtained from cylindrical core samples taken along the length of the pavement test sections.

The field test program involved monitoring 54 selected pavement test sections, which represented various aggregate types, mix designs, and climatic regions within Texas, for skid resistance monitoring over a 3-year period. Field skid tests were conducted on the pavement surface once every year, and a mini-texture-meter was used to record the pavement surface macrotexture. A British pendulum tester was used at three different points along the pavement test section to measure the British pendulum number. Six pavement test sections were monitored at more frequent intervals to record the effects of seasonal variations on field SN. SN at 64 km/h was taken at five locations, l00 m apart on each test section, in the direction of the left wheel path along the outside lane.

CONCLUSIONS

The type and quality of coarse aggregates used in the mix controlled the skid resistance performance of bituminous pavements. The skid performance behaviors are as discussed below:

- The aggregates were divided into three categories that showed differences in skid performance:
  Category I — carbonates with low hard mineral content — exhibit rapid deterioration of SN with increasing vehicle passes per lane (VPPL) (poor skid resistance performance),
  Category II — carbonates with high hard mineral content — maintains better SN, and
  Category Ill — non-carbonates — maintains better SN (best skid resistance performance as a group).
- The current RSPV approach is not able to correctly identify poor performance aggregate sources or vice versa. This is also confirmed by the poor statistical correlation between skid performance rating (SPR) and RSPV ($R^2 = 0.176$).
- A single laboratory test parameter may not serve as a predictor, and the poor correlation obtained for all of the lab parameters suggests that the difficulty lies in measuring the field skid performance of aggregates. The statistical analysis shows that none of the other laboratory test parameters provided a correlation that is clearly better than that obtained for RSPV.
- There is an improvement in the correlation between SPR and RSPV if the aggregates are categorized based on AIR. Since the correlation was still unsatisfactory, the RSPV is still the best predictor of the field skid performance.

RECOMMENDATIONS

The following recommendations are made for future implementation of the findings from this study.

- Two other tasks are pertinent prior to the implementation of this study. The first involves verification of the proposed methodology, and the second involves careful analysis of its impact on each TxDOT district.
- In order to verify the proposed methodology, monitoring of the test pavement sections must be continued until sufficient data have been collected. This will enable the presently adopted SPR, used in this study, to be replaced by the terminal skid number thus verifying the proposed methodology.

- Aggregate rating based solely on historical field performance is not suitable due to the large variability in skid number measurements. There is a need for additional resources to perform field skid testing to identify the variability of aggregates from similar sources with time.
- The findings from this study can be implemented at various levels. The lowest level will involve classification based on AIR and PA, with the following regression models shown in Table 1.

Table 1. Relationship between Aggregate Groups and Skid Performance Rating

Aggregate Group	R^2	SPR	p-Value	Overall p-Value
Low AIR Carbonates	0.3251	-7.110 + 0.279 (RSPV)	0.0211	0.0211
High AIR Carbonates	0.4318	-2.416 + 0.140 (RSPV)	0.0107	0.0107
Non-Carbonates	0.5051	0.4740 + 0.102 (RSPV)	0.0002	0.0002

According to this model, the threshold RSPV values used by TxDOT will be adopted as scales for differing aggregate categories: low AIR carbonates, high AIR carbonates, and non-carbonates. Although this approach may overcome some of the shortcomings of the current procedures, reliability still may not be satisfactory. The recommended approach combines both laboratory and past skid performance data. This approach, which is more technical and rational, can be easily performed using the SKIDRATE software. The program can predict the SPR for any selected aggregate source based on the laboratory test and historical skid performance data. The user can also specify the desired level of reliability.

REPORT NO: 438-1F

Report Title: Evaluation of the Four-Cycle Magnesium Sulfate Soundness Test

Report Date: November 1987

Sponsoring Agency: Texas State Department of Highways and Public Transportation (in cooperation with USDOT and FHWA)

INTRODUCTION

When road aggregates are tested for their suitability as road construction materials, the intention is to obtain material with performance adequate to last the design life of the road. The performance of these aggregates is affected by many variables, such as aggregate mineralogy, pavement type, pavement design, subgrade conditions, maintenance practices, traffic characteristics, and weather conditions. Several tests have been developed to assess the performance of these aggregates, but the four-cycle MSS test has successfully predicted aggregate performance.

The study used 41 aggregates for laboratory testing (14 limestones, 12 sandstones, 13 siliceous gravels, and two synthetic lightweight) from 33 quarries in Texas, Oklahoma, and Arkansas, representing the most common or problem materials used by Texas districts.

The MSS test is a laboratory method for evaluating aggregates in HMAC and seal coats. Although the repeatability of the test is very low, 16 Texas districts specify the MSS test either for hot mixes and/or seal coats. The majority use a limit of 30 percent loss for aggregate rejection, while others may specify lower or higher limits. The study focused on examining the relationship of the soundness test to aggregate performance.

OBJECTIVES OF THE STUDY

The objectives of the study were to: (1) investigate the four-cycle MSS test in the laboratory; (2) evaluate the four-cycle MSS as a laboratory method to predict performance of aggregates when used in HMAC and seal coat surface applications; (3) determine the most appropriate parameters for the soundness test considering aggregate type, pavement type, region, and traffic; (4) investigate the relationship between the MSS test and other material tests in an effort to identify a better method for evaluating durability of aggregates; and (5) develop a specification addressing the four-cycle MSS or a better method for evaluating aggregate behavior in the field.

RESEARCH METHODOLOGY

The research involved was divided into four tasks:

1. Literature Search – A search of related literature and interviews with Texas district maintenance and laboratory engineers was performed. Other related literature on the use and development of other material tests was gathered as well.
2. Laboratory Evaluation – Forty-one aggregates representing the most widely used or problem sources from all regions of the state were gathered, and their physical properties were determined. A statistical analysis was performed to determine the relationship of the MSS to other tests.
3. Field Evaluation – Hot mix and seal coats that were constructed with eight of the aggregate sources tested in the laboratory were examined in five districts, and their performance was evaluated.
4. Specification – Laboratory and field evaluations were compared then analyzed together with the experience of districts, and specific recommendations were made for the evaluation of aggregate durability.

CONCLUSIONS

The conclusions from this study are as follows:

1. The four-cycle MSS test was the best among seven laboratory methods in predicting the performance of aggregates in HMAC and surface treatments.
2. The MSS test is successful in eliminating soft, absorptive, weakly cemented limestone and sandstone aggregates. These materials crack, crumble, split, shell, and wear readily during construction from rolling or in service due to traffic and the environment.

3. All siliceous gravels, because of low absorption and high durability, exhibited very small soundness loss.
4. Aggregates used in seal coats are more prone to disintegration than aggregates used in hot mixes because they are subjected to higher wheel stresses, are more exposed to weathering, and are more influenced by design and construction variables.
5. There was some evidence that aggregate breakdown was more affected by magnitude of load rather than repetition of load. Repetition primarily affects wear of aggregates.
6. After implementing the soundness test, most districts have experienced improved road performance.
7. Districts have reported that Los Angeles abrasion, wet ball mill, and decantation tests do not eliminate problem aggregates.
8. There is evidence that a soundness test should be specified in conjunction with a polish value test for satisfactory performance in terms of aggregate resistance to both breakdown and wear. Also, frictional evaluation of several hot mix projects has revealed that high durability, as determined by the four-cycle MSS test, does not guarantee a high frictional performance if an aggregate has a low PV.
9. Specifying the PV test alone does not prevent the use of unsound materials.
10. Economics (material, availability, haul, and prices) govern the level of specification limits for soundness in some districts.
11. A 30 percent soundness limit on hot mixes and 25 percent soundness limit on seal coats are likely to improve performance of roadways. Most districts will not be affected by these limits.
12. Four districts in central-west Texas stated that a 25 percent soundness limit on seal coats would create a material shortage and/or raise prices.
13. Three districts stated that a 30 percent soundness limit on hot mixes would create a material shortage and/or raise prices; two other districts stated that the limit would allow the use of unacceptable material.

14. Roads constructed with a soundness limit greater than 30 percent showed extensive signs of surface disintegration.
15. Laboratory tests on aggregate blends or on aggregates consisting of particles of varying quality are misleading if aggregates contain significant amounts of very soft particles.
16. Repeatability of the soundness test was better than that of procedure A of aggregate durability index and approximately equal to procedure C of the same test. Texas degradation had the highest repeatability.
17. All aggregate tests showed a good correlation with the soundness test at soundness losses less than 20. At higher losses, tests were insensitive to changes in soundness.
18. The minus No. 10 loss in the Texas degradation test had the best correlation with the soundness test with the model describing the relationship of the two tests as:

    $\ln MSS = 1.5627 + 0.7628(SS) + 1.6906 \ln (TDT10)$, with $R^2 = 0.718$.
19. The combination of Texas degradation sediment and specific gravity tests gave the best two variable relationship with the soundness test in the model describing it as;

    $\ln MSS = 13.1305 + 0.8294 \ln (TDTSED) - 4.8298\ SG$, with the $R^2 = 0.776$.
20. There was strong evidence that the Los Angeles abrasion test permits the use of unacceptable aggregate.
21. Freeze-thaw, aggregate durability index, and Texas degradation had a very high correlation.
22. Texas degradation furnishes information helpful in determining the resistance of aggregates in HMAC and seal coats to producing clay-like fines.

RECOMMENDATIONS

The recommendations of this study are as follows:

1. The four-cycle MSS test should be used to evaluate quality of aggregates for use in HMAC and surface treatments.

2. A 30 percent soundness limit should be applied to HMAC, and a 25 percent soundness limit should be applied to seal coats.
3. Siliceous gravel should not be tested for soundness.
4. Research should be focused toward reducing run time and simplifying the four-cycle soundness procedure.
5. When blends of aggregates are used, the soundness test should be performed on each individual aggregate.
6. District laboratories using tap water containing insufficient salt to mask the effect of barium chloride when performing the soundness test should use the barium chloride as a means of detecting the presence of salt, as it may reduce the run time of the test.
7. Specification of the Los Angeles abrasion test should be discontinued.
8. The Texas degradation test should be used as a replacement of the LA abrasion test. A testing program is required to determine which loss and/or sediment should be evaluated during the test.
9. A tentative allowable weight loss limit of 9 percent passing the No. 16 sieve is recommended for use if the Texas degradation test is used as a replacement for the soundness test. Adjustment to this limit is probable as more laboratory and field data are generated.

RESEARCH STUDY: 0-1771

Report Title: Comparative Analysis of the Micro-Deval and Magnesium Sulfate Soundness Tests

Report Date: October 2000

Sponsoring Agency: Texas Department of Transportation

INTRODUCTION

This research was initiated to study the feasibility of using the micro-deval test (MDT) as a production test for bituminous mixes in comparison to the five-cycle MSS test that is currently used by TxDOT. Recent research studies have concluded that the MDT provides better correlation with durability performance of bituminous aggregate than any other test method currently in use. The MDT also has the advantage that the test procedure has much better repeatability and can be completed in a fraction of the time compared to the MSS test. This research also involved a comparative analysis between the MSS test and the MDT on selected Texas aggregates.

This research also investigated the possible correlations between the results of the MDT and the West Texas wet ball mill (TWBM) test for flexible base materials.

OBJECTIVES OF THE STUDY

This research carried out a comparative analysis between the MDT and the MSS tests with these two test methods being compared for:

repeatability and reproducibility based on single and multiple laboratory precision,

testing time, and

ability to identify poor quality aggregate that causes durability problems in pavements.

Appropriate specification limits for the MDT will be determined through the correlations established between MDT and MSS test values.

Also, the MDT was compared with the TWBM test for flexible base materials. Recommendations, based on the findings, were to be made to determine whether MDT should replace the current MSS test procedure.

A total of 52 aggregate sources were selected for this research. All but four are on the department's quality monitoring (QM) program and are currently used on TxDOT projects.

SCOPE OF THE STUDY

From the total of 52 aggregate sources included for testing, 12 were selected for the multiple laboratory precision study. All sources were tested at Texas Tech University. The 12 sources selected for the multiple laboratory precision study were tested at six TxDOT district laboratories in Abilene, Amarillo, Lubbock, Odessa, San Angelo, Wichita Falls, as well as at the Materials and Test Section in Austin and at Texas Tech University. At least four laboratories tested each source. Table 2 shows the dominant mineral classification for all the HMAC sources in the QM catalog and the number within each category that were included in this study.

Table 2 Aggregate Source Classification

Aggregate Category	HMAC Sources in Catalogue	Number of Sources Included in Research
Lightweight	1	-
Sandstone	2	2
Limestone	39	27
Gravel	35	12
Igneous	9	7
Limestone – Non-QM	-	4
TOTAL	86	52

FINDINGS/RECOMMENDATIONS

There are several significant findings from this research. Following are the conclusions drawn from the study:

The micro-deval test (MDT) is a more repeatable and reproducible test than the magnesium sulfate soundness test. The within-lab standard deviation and between-lab standard deviation for the MDT were found to be 0.35 and 0.92, respectively, compared with 1.55 and 3.35 for the MSS test. Accordingly, the variability in the MDT data is about one-fourth of that in MSS test data.

The MDT is a faster test than the MSS test. MDT takes only one day compared with at least five days for the MSS test.

A precision statement was developed for both the MSS test and MDT from an inter-laboratory test program. For example, two tests run on a specific aggregate at two different labs can have a maximum difference of 2.6 and 9.5 for MDT and MSS, respectively. Although statistically this is the allowable difference, the value of 9.5 for the MSS test is considered to be very high from a practical point of view.

The absorption of the aggregate has a significant influence on the results of both MDT and the MSS test. But soundness results are more sensitive to variation in absorption than MDT results.

The data did not establish a clear correlation between the MDT and MSS test results and aggregate mineralogy. However, a number of general trends were evident. In general, the carbonate aggregates performed more poorly in both tests than the non-carbonate aggregates. Among the non-carbonates, chert-rich aggregates performed best in the MDT. Aggregates of igneous origin with high percentages of ferro-magnesium minerals also performed well. Siliceous aggregates rich in quartz did not perform as well as those with high percentages of chert. In terms of aggregate categories found in the TxDOT QM catalog, limestones and sandstones yielded higher MDT and MSS loss than gravel or igneous rock.

There is a fair correlation ($R^2 = 0.78$) between micro-deval and soundness values. The best-fit regression is a second order polynomial curve. This indicates a possibility of having a bilinear relationship, i.e., one linear relationship for aggregates with lower MSS loss values (for example, < 30 percent) and another for aggregates with higher MSS loss values. Since most of the aggregates (except for two) in this study have MSS loss values less than 30 percent, it was only possible to develop a linear relationship for lower MSS loss values, with an $R^2 = 0.7$. From this regression, a limit of 18 percent and 25 percent micro-deval loss would ensure less than 20 percent and 28 percent MSS loss, respectively, at a 95 percent confidence level. Although this model did not consider the effect of absorption, most of the aggregates in this region have less than 2 percent absorption.

The MSS prediction model incorporating absorption also has a good correlation ($R^2 = 0.84$). Considering this model, an aggregate with less than 1.7 percent absorption would ensure less than 20 percent MSS loss if its measured MDT loss is less than 18 percent. Similarly, a MSS loss value of less than 30 percent could be ensured for an aggregate with less than 2.1 percent absorption if its micro-deval loss is less than 25 percent.

The MDT could be an excellent job quality control tool for the aggregate sources that are currently in the TxDOT quality monitoring program.

For flexible base aggregate, the wet ball mill test is a more consistent and repeatable test than the MDT.

The wet-ball mill and micro-deval tests showed a very good correlation ($R^2 = 0.9$). Since they both have the same abrasion mechanism, it was an expected trend.

The following are recommendations made by the researchers of this study:

If the MDT is to be considered a substitute for the MSS test, it will be necessary to expand the current database to include high soundness sources and, hence, evaluate the potential impact from the adoption of a specification limit based on the MDT.

The shorter testing time and good repeatability and reproducibility of the MDT make it a very attractive tool for aggregate quality monitoring. However, with the present state of knowledge, there are two reasons it is not feasible for this test method to be used as a substitute for the MSS test. First TxDOT engineers have many years of experience with the use of the MSS tests for the evaluation of the durability of bituminous aggregates. As a result, they have developed confidence using this test method and a "feel" for what MSS test results mean in terms of pavement performance. Before the MDT can be considered as an alternative to the MSS test, TxDOT engineers must develop similar experience with the new test method. Secondly the vast majority of the aggregate sources included in this research were selected from the aggregate sources in the TxDOT's QM catalog. As a result, the database that was developed did not provide much information on aggregate sources of marginal quality (i.e., those with MSS loss over 30).

The MDT's greatest contribution could be as a job control test. This test would also provide an incentive for the producers to add the micro-deval procedure as a quality control tool to better track and react to changes in quality during production.

There is no need to replace the wet ball mill test with the MDT for flexible base aggregates.

RESEARCH STUDY: 7-3994

Report Title: Alternate Polish Value and Soundness Specifications for Bituminous Coarse Aggregates

Report Date: December 1998

Sponsoring Agency: Texas Department of Transportation

INTRODUCTION

The main focus of this study was to examine the deficiencies of, and potential improvement solutions to, the polish value specifications and test procedure. The project was initiated to resolve the following issues:

- TxDOT's Wet Weather Skid Accident Reduction Program (WWSARP) – which includes primarily a PV specification and secondarily a skid history program;
- Use of Local Materials – which is directed at the aggregates used and its specifications for PV and five-cycle $MgSO_4$ soundness; and
- Cost and Benefit Analysis – which requires the examination of the aggregate usage and its effects on pavement's structural and skid performance.

However, the project that was originally planned for three years was terminated under the directive of TxDOT in August 1998.

SCOPE OF THE STUDY

Upon termination of this study, the following objectives had been accomplished:

17. identify limitations and constraints of current TxDOT procedures pertaining to the WWSARP;
18. identify factors affecting the reliability of PV and skid testing;
19. improve the PV test procedure and quantify PV's contribution to the skid performance of pavement surfacing aggregate;
20. develop an improved correlation between aggregate PV and pavement skid performance;

21. establish comparison in PV testing between the TxDOT and American Society for Testing and Materials (ASTM) procedure; and
22. develop recommendations and available options for consideration in improving the identified deficiencies.

BACKGROUND

In carrying out the study, the following tests and research were referred to:

- WWSARP
- polish value specification
- Rated Source Polish Value Program
- polish value test
- Skid Testing and Skid History Program
- previous TxDOT studies:
    - Research Project 490 – Investigation of the Frictional Resistance of Seal-Coat Pavement Surfaces
    - Research Project 1222-1F – Establishment of Acceptable Limits for 4-Cycle MSS and Modified Wet Ball Mill Tests for Aggregates Used in Seal Coats and HMAC Surfaces
    - Research Project 0-1459 – Use of Pavement Skid History as the Basis for TxDOT Skid Reduction Program
    - Research Project 0-187-9 – Continued Monitoring of Pavement Test Sections
    - Research project 0-187-10 – Continued Monitoring of Seal Coat Sections

FINDINGS/RECOMMENDATIONS

This study presents a need to encompass design, material, and construction variables to develop an order of priority in design procedures and specifications to satisfy the engineering and economic considerations. The following are the recommendations of this study:

1. *Polish Value Testing and Specification* – The present PV test procedure and specifications are faulty. The new PV procedure should be implemented with a revision of the PV specification with lowering the threshold residual PV to 29.

2. *Material Selection and Design Strategy* – In order for the pavement surface/layer system to function properly, every project must be evaluated and engineered separately to allow the most effective use of available materials to arrive at optimal performance. The SN_{40} prediction equation is reduced with considerations given to residual PV and five-cycle MSS loss of surfacing aggregate.
3. *Aggregate Quality Monitoring Program* – A more effective Quality Control/Quality Assurance (QC/QA) program should be developed to provide adequate and timely reflection of the changing aggregate properties and therefore their effects on pavement structural integrity and skid performance.
4. *Skid History Program* – Aggregate sources currently participating in the skid history program should revert to the PV program, and the PV program should allow adequate adjustment to reflect the skid performance of these aggregate sources.
5. *Contingency Actions* – A plan identifying the risk of high traffic roadways in urban districts should be implemented to monitor limestone aggregate surfaces under a PV specification of not greater than 32 and high soundness loss.
6. *Public Education* – A public education program focusing on increasing the traveling public's awareness of reducing wet weather skid accidents should be developed.
7. *Test Section Construction and Monitoring* – Test sections to be constructed and monitored in differing geographical areas within the state with the performance criteria including skid and structural performance.
8. *Additional Research* – Additional study, construction, and monitoring of test sections are required to collect specific materials and performance data to validate the findings of this study.

RESEARCH STUDY: NCHRP REPORT 405 (STUDY 4-19)

Report Title: Aggregate Tests Related to Asphalt Concrete Performance in Pavements
Report Date: May 1997
Sponsoring Agency: National Cooperative Highway Research Program, Transportation Research Board and National Research Council

INTRODUCTION

Aggregates constitute about 94 percent by weight of hot-mix asphalt. Thus, the properties of both the coarse and fine aggregate are important to the performance of a pavement system. Many aggregate tests currently used for evaluating and characterizing aggregates were empirically developed and may not be related to their performance in the HMA. The National Center for Asphalt Technology conducted extensive testing on aggregates and the HMA mix to determine the performance parameters of HMA that may be affected by aggregate properties. Both the aggregate consensus and source properties were considered while evaluating the performance of HMA in a pavement. These include: (a) aggregate particle shape, angularity, and surface texture; (b) plastic fines in the fine aggregate; and (c) toughness and abrasion. Statistical analysis of the testing results establishes a correlation between the aggregate properties and the HMA performance parameters, i.e., permanent deformation, fatigue cracking, and raveling, popouts, or potholing.

OBJECTIVE OF THE STUDY

The objective of this project was to recommend a set of aggregate tests that can be used to evaluate the performance of HMA used in pavement construction and to provide a good correlation between the aggregate properties and the pavement's performance. The research also included an extensive evaluation of existing aggregate tests to assess their abilities for predicting a pavement's performance based on three HMA performance parameters: (a) permanent deformation; (b) fatigue cracking; and (c) raveling, popouts, or potholing.

SCOPE OF THE STUDY

The methodology of the study was based on the following steps:

- identification of performance parameters of HMA affected by the aggregate properties;
- identification of aggregate properties that influence the performance parameters of HMA;
- identification and evaluation of existing tests for aggregates in the U.S. and some other countries;
- identification of potential tests for measuring key aggregate properties for which no test procedure currently exists;
- laboratory tests on aggregate samples to evaluate their performance for the three performance parameters, i.e., resistance to rutting, fatigue cracking, and raveling, popouts, or potholing; and
- recommendations of new aggregate tests for evaluating a pavement's performance.

Six aggregate properties that are related to a pavement's performance were identified, and laboratory testing was completed for these aggregate properties. These aggregate properties can be summarized as:

coarse aggregate particle shape, angularity, and surface texture;
fine aggregate particle shape, angularity, and surface texture;
plastic fines in the fine aggregate;
toughness and abrasion resistance;
durability and soundness; and
characteristics of P200 material.

A variety of aggregates was selected to obtain a range of test values for the specific property to be evaluated. Specific aggregate properties were measured using both current and new aggregate tests, and these aggregates were later incorporated in HMA mixtures. The research plan did not include aggregate gradation and size because a standard sieve analysis technique already exists. Mix validation tests were carried out on these HMA mixtures using different techniques to establish a good correlation between the results and the aggregate properties. The following techniques were used to measure pertinent mix performance properties:

Superpave shear tester (evaluation of permanent deformation and fatigue cracking);

Georgia loaded wheel tester (evaluation of permanent deformation);

Hamburg wheel tracking device (evaluation for stripping); and

American Association of State Highway and Transportation Officials (AASHTO) T 283 procedures (to test stripping).

CONCLUSIONS

Based on the test results and statistical analysis on the nine aggregate evaluation tests, the following were inferred:

- The gradation and size of the aggregate can be related to the permanent deformation and fatigue cracking of the HMA. A standard sieve analysis test (AASHTO T 27) is recommended to determine the gradation and size of the aggregate.
- Micro-deval and magnesium sulfate soundness tests are related to the performance of HMA.
- In terms of raveling, popouts, and potholes, the MDT is recommended in lieu of the LA abrasion test, MSS test, and other soundness tests (freeze-thaw loss and durability index) commonly used by highway agencies to evaluate the toughness and abrasion resistance of aggregates.
- The uncompacted void content (UV) of coarse aggregate is related to permanent deformation and fatigue cracking of an HMA mix. A new test method similar to the test used for determining the UV of fine aggregates has been proposed to evaluate the UV content of coarse aggregate. The higher the UV content of coarse aggregate in a HMA mix, the greater is its resistance to permanent deformation. Thus, it is recommended that highway agencies specify a minimum percentage of UV rather than the minimum percentage of one-face or two-face fractured particles.
- The uncompacted void content of fine aggregate is also related to permanent deformation of the HMA. The higher the UV content, the greater is the resistance of HMA to rutting. It has been proposed that a minimum permissible UV of fine aggregate be specified rather than the current requirements specifying the maximum

permissible amount of natural sands in the HMA. However, if the HMA mix meets the design criteria for permanent deformation when subjected to the superpave mix analysis, the minimum UV value need not be specified.

- The methylene blue test on fine aggregate (P200 material) recommended by the International Slurry Seal Association (ISSA) has been proposed to replace the sand equivalency test and the plasticity index test. These tests determine the amount and nature of deleterious fines in the fine aggregate. The methylene blue test on P200 material is related to the stripping of HMA, which, in turn, may cause permanent deformation of the HMA pavement. The higher the methylene blue index (MBI), the more susceptible the HMA mix is to stripping. However, fine aggregate should not be rejected due to high MBI values if they meet the test criteria of stripping (AASHTO T 283 and Hamburg wheel tracking tests).
- Flat and elongated particles in coarse aggregate are related to the permanent deformation and fatigue cracking of HMA. Low percentages of flat and elongated particles are desired for a durable and workable HMA mix. It is recommended that a percentage of flat or elongated particles be used in lieu of the percentage of flat and elongated particles. A ratio of 2:1(maximum to minimum dimension of the particle) is recommended for determining the percentage of flat or elongated particles in the aggregate. This ratio would result in a maximum allowable percentage of flat or elongated particles.
- Particle size analysis (D60 and D10) represents the percentage of material (60 percent and 10 percent) passing the 200-micron sieve, respectively. D60 is related to permanent deformation of the HMA due to traffic load applications. The higher the D60 value in the mix, the lower the resistance of HMA is to permanent deformation. D10 is related to the stripping of HMA; the lower the D10 value, the higher the HMA resistance to stripping. An automated device is recommended for the gradation of P200 material instead of the AASHTO T 88 specification of using a hydrometer.

RECOMMENDATIONS

Based on the findings of project 4-19, the following tests are recommended to evaluate aggregates for HMA pavements:

- gradation and size (related to permanent deformation and fatigue cracking),
- uncompacted void content of coarse aggregate (related to permanent deformation and fatigue cracking),
- flat and elongated particles (2:1 ratio) in coarse aggregate (related to permanent deformation and fatigue),
- uncompacted void content of fine aggregate (related to permanent deformation),
- methylene blue test of fine aggregate (related to permanent deformation and fatigue cracking),
- particle size analysis of P200 material for determining D60 and D10 sizes (related to permanent deformation resulting from traffic loads as well as stripping - Note: D60 and D10 are particle sizes in millimeters that have 60 percent and 10 percent passing, respectively),
- methylene blue test of P200 material (related to permanent deformation resulting from stripping),
- micro-deval test (related to raveling, popouts, or potholes), and
- magnesium sulfate soundness test (related to raveling, popouts, and potholes).

THE AGGREGATE HANDBOOK

Sponsoring Agency: National Stone Association, Washington D.C.

INTRODUCTION

In 1991, the National Stone Association copyrighted The Aggregate Handbook, which was very ably edited by Dr. Richard D. Barksdale of the Georgia Institute of Technology. Of particular interest in this proposal is a table presented in Chapter 3 of the book that summarizes the aggregate properties for specific uses to meet the functions of pavement systems. The table is reproduced here as Table 1. Later on, in Chapter 13, the book discusses aggregate tests and mixture design methods to determine the proper selection of aggregates.

Seven sets of general aggregate characteristics are given, and subjective ratings are provided for each. The subjective ratings are whether, in the opinion of the author, each aggregate characteristic is important (I), not important (N), or unknown (U).

AGGREGATE CHARACTERISTICS SETS

The first set of aggregate characteristics includes the gradation, particle size, shape, texture, strength, and stiffness. Most of these aggregate characteristics were not investigated in NCHRP 10-12, but all of these are as important now as they were then. The second set of characteristics indicates that solubility, slaking, and aggregate pore structure are important for asphalt concrete. These are the same properties that were used in NCHRP 10-12 in 1981 as measured by soundness and water absorption. The third set is resistance to degradation, which is the same as represented in NCHRP 10-12 by the LA degradation test. It must be noted, however, that the LA degradation test did not correlate well with any of the performance characteristics of asphalt concrete surface courses in the NCHRP study. This indicates the need for a better test to take its place because the ability to resist degradation under applied loads is certainly an important characteristic of aggregates used in mixes.

The fourth set of characteristics included the coefficient of thermal and moisture expansion, pore structure, and thermal conductivity. Although The Aggregate Handbook table rates these as not important and they were not studied in NCHRP 10-12, the thermal expansion and conductivity coefficients have been found in the recently completed Strategic Highway Research Program (SHRP) asphalt research program to be very sensitive primary causes of thermal cracking.

The fifth set of aggregate characteristics is the very important measure of aggregate-binder compatibility. The table from The Aggregate Handbook lists chemical compounds, reactivity, coatings, base exchanges, and surface charges as being important to asphalt concrete performance. The NCHRP 10-12 project used petrographic evaluations and moisture-dry and freeze-thaw conditioned mixture tests to measure these characteristics. In some cases, the petrographic evaluations went farther than The Aggregate Handbook table in determining films and powders coating the aggregate: chemical character of the rock, i.e., a rating of how strongly acid or basic the rock surface is hardness, and general quality, which includes resistance to weathering, deleterious substances, chemical character, and hardness.

The sixth set of aggregate characteristics has to do with the performance of the aggregate at the tire-pavement interface and includes the effects on tire-pavement friction, tire wear, rolling resistance, glare and reflection, noise, loose material due to raveling and weathering, and others. While The Aggregate Handbook emphasizes gradation, particle size, shape, and texture, the 1981 NCHRP 10-12 project found that raveling depends upon petrographic values of chemical character (pH), powders, films, as well as soundness (or water absorption) and tensile strength of the mix. It is appropriate to view these findings, which appear at first glance to be mutually exclusive, as being complementary instead. The Aggregate Handbook focused on surface friction and did not list many of the contributors to loose materials on the pavement surface.

The seventh set of aggregate characteristics is concerned with the aggregate's ability to withstand the effects of the construction process. The NCHRP 10-12 project did not consider this set of characteristics, and so the 1991 Aggregate Handbook provides an improvement by listing particle size, resistance to degradation, and integrity during heating as being important to asphalt concrete performance. It must be added, however, that the aggregate-binder compatibility during the construction process is important, and all of the tests devised to measure that compatibility should be an important product of this research project.

RESEARCH STUDY: 404011

Report Title: Evaluation of Superpave Fine Aggregate Angularity Specification

Report Date: May 2000

Sponsoring Agency: International Center for Aggregate Research

INTRODUCTION

HMA pavements experience premature rutting due to increasing magnitude of traffic and volume. Progressive movement of the material either in the asphalt layer, the base layer, or in the subgrade may result in rutting of wheelpaths. Use of poorly graded aggregates having smooth, subrounded particles and a high percentage of rounded sand result in the loss of the shearing resistance of asphalt mixtures. In HMA mixtures, aggregate particles usually comprise 90-96 percent by weight of the total mix. Normally 40 percent by weight of HMA is fine aggregate. The major fine aggregate properties that influence the rutting potential of the HMA are: (a) particle shape and angularity, (b) particle surface texture, and (c) particle porosity.

Angular, slightly porous, rough-textured particles tend to produce rut-resistant mixtures, whereas rounded, nonporous, smooth-textured aggregates tend to produce rut-susceptible HMA mixtures. The geometric irregularities of both coarse and fine aggregate have a major effect on the mechanical behavior and physical properties of HMA mixtures. This geometric irregularity can be attributed to the aggregate particle shape, angularity, and surface texture. The validity of the fine aggregate angularity (FAA) requirements as specified by the Superpave aggregate specifications is questionable. The FAA test is based on the assumption that more fractured faces in an aggregate result in higher void content in the loosely compacted sample. However, it has been found that cubical-shaped particles with 100 percent-fractured faces may not meet the FAA requirement for high-volume traffic. Thus, new techniques such as image analysis are being used for determining particle shape, angularity, and surface texture.

OBJECTIVES OF THE STUDY

The objective of this study was to evaluate the ability of the current test method (AASHTO T-304 and ASTM C-1252, Method A) to measure fine aggregate angularity and compare the results obtained from the FAA test with other measures of aggregate angularity. Thus, it was established that the current method could clearly distinguish between aggregates with good and poor performance in HMA.

SCOPE OF THE STUDY

The research involved a comprehensive testing and evaluation of 23 fine aggregates used in HMA mix using seven different angularity tests and then correlating the results from different tests. Thus, the applicability of the testing method was determined for identifying the particle shape and angularity, surface texture, and particle porosity.

RESEARCH METHODOLOGY

The research program included a detailed laboratory testing program to determine the aggregate properties that influence the rut potential of the HMA. The following tests were performed to evaluate the fine angularity of an aggregate:

- FAA test;
- compacted aggregate resistance test; and
- three image analysis techniques:
  a) Hough Transform at University of Arkansas at Little Rock,
  b) unified image analysis at Washington State University, and
  c) image analysis using VDG-40 videograder at Virginia Transportation Research Council.

FAA FLOW TEST (ASTM C-1252)

The FAA test determines the percent air voids present in the loosely compacted aggregates (smaller than 2.36 mm) after a sample of dry aggregate is allowed to fall into a calibrated cylinder. Three methods can be used for determining the fine aggregate angularity:

Method A (Superpave classification)

To determine FAA of a specific aggregate gradation

Method B

To determine FAA for three separate aggregate size fractions

3. Method C

To determine aggregate gradation passing 4.75 mm (No. 4) sieve

Direct Shear Test

This test determines the resistance to shear of a cohesionless soil or fine aggregate due to the friction between the grains and the interlocking of the grains. The resistance is expressed by the angle of internal friction. A standard direct shear apparatus for soil is used to measure the resistance. The sample used for the test is air-dried to prevent pore pressure in the sample during the test. The air-dried sample is placed in a direct shear box that is either rounded or square in shape and is split horizontally into two parts. Either the upper or lower half is held stationary while a force is applied to the other half. The shear tests are performed at three different normal stresses. The samples fail in shear in a predefined horizontal plane when the shear stresses reach the maximum for each load.

The test is an indirect measure of the measure of the aggregate particle shape and texture, as the angle of internal friction is an indication of the particle interlocking.

Compacted Aggregate Resistance Test (CAR)

The compacted aggregate resistance test is used to evaluate the shear resistance of compacted fine aggregate. Material passing the No. 8 sieve is oven dried to a constant weight. The sample is then cooled to an ambient temperature and thoroughly mixed with 1.75 percent of water by weight. The sample is then placed in a 4-inch diameter Marshall mold to prepare a compacted sample approximately 2.5 inches high. The sample is then compacted using 50 blows by a Marshall hammer on one face. The test specimen is then tested for stability by applying an unconfined compressive load using a Marshall testing machine. A load at a rate of 2 inch/min is transmitted through a 1.5 inch diameter flat-faced steel cylinder on the plane surface of the compacted sample.

Image Analysis

The image analysis techniques are versatile tools for quantifying object geometry. These techniques are used for quantifying shape, texture, size, and distribution of different aggregate types and sizes of particles. In digital image processing, pictures of aggregate particles are digitized. Different mathematical techniques are then applied to these digital forms to quantify shape, size, and texture of particles.

Three image analysis techniques were used for the analysis:

- Hough Transform method,
- unified image analysis, and
- image analysis using VDG-40 videograder.

Image Analysis Using Hough Transform Method

This method, developed at the Applied Science Department at University of Arkansas in Little Rock, is an automated method for measuring fine aggregate shape, angularity, and texture. This technique uses "Hough Transform" along with other mathematical techniques such as fast fourier transform and neural network in the analysis. The procedure can be divided into three steps:

a) automated data acquisition,
b) image analysis, and
c) classification using neural network.

Automated Data Acquisition

Fine aggregate particles are spread over a transport X-Y glass table. Aggregates passing No. 4 sieve and retained on the No. 16 sieve are used for the analysis. A camera with a resolution of 682 X 402 pixels is used to capture images of individual particles as the X-Y table moves in both the X and Y direction. The table moves 0.00025 inch (0.00635 mm) per step for a total of 6 inches (152.4 mm). For each type of aggregate, images of approximately 500 particles are captured. A data translation DT2871 video frame grabber installed in a PC is used to capture the video signals from the camera for image analysis. The data acquisition system operates with DAGPIC software.

Image Analysis

A particle outline coordinate data file is created by DAGPIC and is analyzed using software called DAGGAER for shape characterization. The particle outline is stored in a rectangular coordinate (x, y) system during the data acquisition process. The length and width of each particle image are measured using a "virtual" caliper. The aspect ratio (maximum image dimension/minimum image dimension) of each particle is then calculated. The centroid of each particle is then calculated by averaging all x and y coordinates of each particle outline. All the rectangular coordinates are then transferred into polar (r, θ) coordinates without changing the centroid of the particle. All the values of r are then divided by the largest distance from the centroid to the edge, r_{max}, and fitted into a circle of unit radius and stored for future analysis.

T-index: A convex hull is formed using the $X_{max,}$ $X_{min,}$ $Y_{max,}$ and Y_{min} of the particle outline. The T-index provides a quantitative estimate about the particle texture. The maximum value of the index is 0.25. The T-index approaches zero for a smooth-sided particle and increases as the image becomes more irregular, i.e., the surface texture becomes rough.

E-index: The E-index is the reciprocal of the aspect ratio of the particle outline. This index provides information about the shape of the particle image, i.e., whether it is elongated or cubical.

S-index: Mathematical techniques of data processing and refining are used to change the particle outline in the form of a Hough parameter space array. The Hough transformation algorithm is then applied to the Hough parameter space array.
The S-index of an angular particle is usually greater than 0.6. The index measures the length of the straight lines and the angle between them.

R- index: This index measures the roundness of the particle. The R-index describes how straight line segments are distributed as a function of the distance from the centroid of the object. The R-index represents the radial distance to the highest density of points from the centroid of the image outline. The R-index of a circular object is 1, and the R-index of a square is 0.707.

Harmonic Component of S (θ) Function

The S (θ) function when entered into a fast fourier transform (FFT) function gives a series of harmonic components that help in providing improved shape discrimination. Second through 16th harmonic components are used as inputs for the neural network classifier.

Neural Network Classifier

The neural network helps to combine the four indices and the harmonic components into a single index that describes the angularity of each particle. A non-linear transform of all the inputs results in a single linear estimate. The computed output is compared with the desired results, and if there is a difference in the results, weighing factors within the network are adjusted to change the output towards the desired one.

Image Analysis Using Washington State University Method

This technique, developed by Dr. Eyad Masad, is an automated method of fine aggregate shape analysis. An optical microscope is used to capture particles that are painted black to obtain high-quality images. Both high- and low-resolution images are captured for the analysis of texture and shape, respectively. An image analyzer connected to the microscope converts the particle images to binary images. These binary images are subjected to different mathematical techniques to quantify shapes:

a) surface erosion-dilation,
b) fractal behavior, and
c) form factor.

Surface Erosion-Dilation Technique

Each particle image is subjected to a number of erosions and dilations. During the erosion process, pixels are removed from the binary image based on the number of neighboring pixels with different color. This simplifies the object image by removing pixels from the boundary and moving toward the center. On the contrary, the dilation process involves the addition of pixels to the object to construct a simplified image. Erosion and subsequent dilation may result in area loss; however, it is considered that the area lost after a certain number of erosions and dilations is proportional to the percent of objects smaller than a certain size and angularity. The surface parameter value increases with the increase in the surface irregularity.

Fractal Behavior Technique

Fractural behavior is defined as self-similarity exhibited by an irregular boundary when captured using different magnifications. The smooth boundaries erode and dilate at a constant rate, whereas irregular boundaries do not erode and dilate at a constant rate. Using the logic operator, images after several erosions and dilations are superimposed and the overlapping layers removed. The remaining pixels form the boundary whose width is proportional to the surface irregularities. The increase in the effective width after several erosion and dilation cycles is measured. The slope of the line that plots the effective width versus the number of erosion-dilation cycles on a log-log scale is the fractal length. Smooth boundaries have very flat slopes as compared to the steep slopes of irregular boundaries.

Form Factor Technique

The form factor (FF) is used to define surface irregularity. The area and the perimeter of the object are measured. The area is measured as the total pixels of the image, and the perimeter is the number of pixels that touch the background. The measurement varies with the resolution and is then used to determine the surface angularity. The form factor for a circular object is 1. The FF decreases with an increase in surface irregularity.

Image Analysis Using VDG-40 Videograder

The VDG-40 is an optoelectronic device developed by the French Laboratoire Central des Ponts et Chaussées (LCPC). Virginia Transportation Research Center (VRTC) has used this technique for determining the shape of the aggregate particles. The aggregates are first fed into a hopper where the vibrating separator deposits the particle into one layer to prevent overlapping of particles. The particles fall between a linear light source and a charged-couple camera. The camera catches the image of the falling particle through its horizontal strip. The coordinates of the aggregate contours and the projected surface are stored in memory and are then processed using a software algorithm to determine the shape of the aggregate particles.

CONCLUSIONS

Based on the results and the statistical analysis of the data, the following can be inferred:

- The FAA test method does not consistently identify angular, cubical aggregates as high-quality materials. Some high-quality fine aggregates with good field performance history did not meet the Superpave specification criteria for FAA.
- There was a good correlation between the CAR and the angle of internal friction (AIF) from the direct shear test.
- No correlation was found between the FAA test and the CAR test or between FAA and AIF.
- There was good correlation between the FAA and the K-index from the Hough transform image method.
- The three image analysis techniques together were found to be promising for directly quantifying fine aggregate particle shape, texture, and flat and elongated character of the particles.
- There was a fair to strong correlation between the image analysis and FAA results.

RECOMMENDATIONS

The following recommendations were made:

- ASTM C-1252 and AASHTO T 304 would provide most accurate results if specific gravity of the fine aggregate were used in computing the uncompacted voids in fine aggregates.
- Image analysis is the most promising technique for measuring the fine aggregate angularity. However, a three-dimensional technique would further offer many advantages.

LITERATURE REVIEWED

1. Abdul Malak, M.A.U., Papaleontiou, C.G., Fowler, D.W., and Meyer, A.H., "Investigation of the Frictional Resistance of Seal Cat Pavement Surfaces", Research Report FHWA/TX-89-490-1, The University of Texas at Austin, submitted to Texas State Department of Highways and Public Transportation, Transportation Planning Division, June 1988.
2. "Implication of Aggregates in the Construction and Performance of Seal Coat Pavement Overlays," Research Project 490-2, The University of Texas at Austin, submitted to the Texas Department of Transportation, August 1992.
3. Papaleontiou, C.G., Meyer, A.H., and Fowler, D.W., "Evaluation of the 4-Cycle Magnesium Sulfate Tests," Research Report FHWA/TX-88–438-1F, The University of Texas at Austin, submitted to Texas State Department of Highways and Public Transportation, Transportation Planning Division, November 1987.
4. Chien, N. F., and Chen, H., "Alternate Polish Value and Soundness Specifications for Bituminous Coarse Aggregates," Research Report 7-3994, Texas Department of Transportation, December 1998.
5. "A Comprehensive Methodology for Predicting Field Skid Resistance of Bituminous Aggregates Based on Laboratory Test Data as well as their Past Skid Performance," Research Report 0-1459, Texas Department of Transportation, September 1998.
6. Phillips, F., Jayawickrama, P.W., Hossain, M.S., and Lehman, T.M., "Comparative Analysis of Micro-Deval and Magnesium Sulfate Soundness Tests," Final Report TX99/1771-1R, Texas Tech University, Texas, October 2000.
7. Kandhal, P.S., and Parker, F., Jr., "Aggregate Tests Related to Asphalt Concrete Performance in Pavements," National Cooperative Highway Research Program, Report 405, 1998.
8. Barksdale, R.D., "The Aggregate Handbook," National Stone Association, April 1993.
9. Button, J.W., Chowdhury, A., and Kohale, V., "Evaluation of Superpave Fine Aggregate Angularity Specification," International Center for Aggregates Research, Report No. 404011-1, May 2000.