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16. Abstract

This report presents an evaluation of the 4-cycle magnesium sulfate soundness test to control quality of coarse aggregates for use in hot mix asphaltic concrete and seal coats. A total of 41 aggregates were tested for the purpose of this study in the laboratory and the behavior of eight of the aggregates was evaluated in the field by examining roadway performance. The soundness test was found to be the best method for predicting performance among specific gravity, absorption, aggregate durability index, freeze-thaw, Los Angeles abrasion, and a modified Texas wet ball mill (called Texas degradation) tests. Specific recommendations have been suggested to improve the soundness procedure. Also specification limits for hot mix and seal coat projects have been included.

The repeatability of the soundness test was approximately equal to that of durability index and lower than the repeatability of Texas degradation. Statistical analysis showed high correlation between soundness and other tests at soundness losses less than 20 percent, and low correlation at higher values. Texas degradation showed the best correlation with the soundness test. The model that describes their relationship has $R^2 = 0.72$.

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EVALUATION OF THE 4-CYCLE MAGNESIUM SULFATE SOUNDNESS TEST

by
C. G. Papaleontiou
A. H. Meyer
D. W. Fowler

Research Report 438-1F

Evaluation of the 4-Cycle Magnesium Sulfate Soundness Test to Control Quality of Aggregates for HMAC and Surface Treatments

Research Project 3-9-85-438

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the

U. S. Department of Transportation
Federal Highway Administration

by the

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The University of Texas at Austin

November 1987

PREFACE

The authors would like to express their appreciation to district laboratory and maintenance engineers for their invaluable assistance and cooperation in providing information on their experience with the 4-cycle soundness test. In addition, a great deal of gratitude is due Mr. Harold Albers of the Materials and Tests Division (D-9) of the Texas State Department of Highways and Public Transportation for his valuable advice and assistance on the study as a whole. Appreciation is also extended to George Frantzi and Peter Chen for performing all the laboratory work at the Center for Transportation Research.

Finally the authors would like to express their appreciation to Don Dombroski, Fred Barth, David Whitney, Lyn Gabbert, Georgia Alford, and the entire staff of the Center for Transportation Research for their assistance in the preparation of this report.

LIST OF REPORTS

Report No. 438-1F, "Evaluation of the 4-Cycle Magnesium Sulfate Soundness Test," by C. G. Papaleontiou, A. H. Meyer, and D. W. Fowler, presents results of laboratory and field evaluation of the 4-cycle soundness test; results of other material tests and statistical analyses of the relationship between tests and soundness; and results of a district wide survey on their use and experience with the soundness test.

ABSTRACT

This report presents an evaluation of the 4-cycle magnesium sulfate soundness test to control quality of coarse aggregates for use in hot mix asphaltic concrete and seal coats. A total of 41 aggregates were tested for the purpose of this study in the laboratory and the behavior of eight of the aggregates was evaluated in the field by examining roadway performance. The soundness test was found to be the best method for predicting performance among specific gravity, absorption, aggregate durability index, freeze-thaw, Los Angeles abrasion, and a modified Texas wet ball mill (called Texas degradation) tests. Specific recommendations have been suggested to improve the soundness procedure. Also specification limits for hot mix and seal coat projects have been included.

The repeatability of the soundness test was approximately equal to that of durability index and lower than the repeatability of Texas degradation. Statistical analysis showed high correlation between soundness and other tests at soundness losses less than 20 percent, and low correlation at higher values. Texas degradation showed the best correlation with the soundness test. The model that describes their relationship has $R^2 = 0.72$.

SUMMARY

The 4-cycle magnesium sulfate soundness test is a laboratory method to control quality of coarse aggregates for hot mix asphaltic concrete (HMAC) and seal coats. The test which appears to measure an aggregate's ability to withstand degradation from traffic and climate effects, is specified by several Texas districts. However, acceptable values vary between districts and while this may be appropriate, there are no hard data to justify the differences.

The objectives of this study were to investigate if the soundness test is a valid measure of durability, and determine the most appropriate parameters for the test considering aggregate and pavement type, region, and traffic. Additionally, the objective was to determine the relationship of the soundness test to other material tests for the purpose of identifying a more appropriate or nondiscriminating test, or a simpler test to perform with less variability that provides equal information on performance. A total of 41 aggregates representing the most common or problem aggregates used by districts were tested in the laboratory. Tests included specific gravity, absorption, freeze-thaw, Los Angeles abrasion, aggregate durability index, a modified Texas wet ball mill (called Texas degradation), and 4-cycle magnesium sulfate soundness.

The performance of eight aggregates similar to those tested in the laboratory was evaluated in the field by examining surface disintegration of HMAC and seal coats constructed with the materials. The selected aggregates exhibited all the ranges of soundness values or were predicted with varying quality under the different tests. Results indicated that the soundness test is the best among the methods considered for predicting performance. The other tests have discriminated in favor of using two or more unacceptable aggregates. Specific recommendations have been made for the most appropriate specification soundness limits and for improving the soundness procedure.

A state wide survey has revealed that specification limits in districts are governed by material availability or prices. Districts that specify the soundness test have experienced increased performance with its use.

Extensive statistical analysis has been performed on the laboratory results. This included scatter plots, transformations, correlation, regression, and covariance. Freeze-thaw and Los Angeles had the lowest correlation with soundness, while absorption and Texas degradation the highest. Freeze-thaw, aggregate durability index, and Texas degradation showed high correlation among each other. Bivariate and multivariate models describing the relationship of tests with soundness have been developed. The best one variable model describing soundness variation was obtained with Texas degradation ($R^2 = 0.72$). The best two variable model was obtained with Texas degradation and specific gravity.

IMPLEMENTATION STATEMENT

Comparison between laboratory results from aggregate tests and field performance of HMAC and seal coats has revealed that the 4-cycle soundness test is the most appropriate among the tests considered for predicting aggregate behavior. Suggested modifications to soundness procedure may help improve repeatability of the test. Implementation of specified soundness limits will help districts improve roadway performance.

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CHAPTER 1. INTRODUCTION

RELATIONSHIP BETWEEN LABORATORY EVALUATION AND FIELD PERFORMANCE

The question of predicting in the laboratory the service life of aggregates when used in hot mix asphaltic concrete (HMAC) or seal coat road surface applications has been a subject of investigation for over 150 years. Hundreds of reports have been published pertinent to this issue, each contributing its merit to the complex problem.

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 word "performance" as applied to aggregates, is rather a vague term which reflects factors such as degradation, splitting, abrasion, wear, polishing, skid resistance, ravelling, stripping or resistance to deformation. It is also affected by many variables which can be either controlled or uncontrolled, e.g., aggregate mineralogy, pavement type, pavement design, subgrade conditions, maintenance practices, traffic characteristics, or weather conditions. Aggregate performance has, in addition, a synergistic effect on the overall performance of the road. Undesirable aggregate quality may lead to pavement disintegration, ravelling, cracking, bleeding, instability, rutting, or deformation.

The broad definition of aggregate performance, the wide range of variables affecting service life of aggregates, and the effect of aggregate quality on the overall performance of roadways connote the difficulty of developing a material test to assess performance. Various studies have developed several tests or proposed modifications to tests for better predictions and precision, but up to this date no single test has been completely successful. The controversy behind the results and recommendations of these studies and the many tests, demonstrate the level of influence of variable conditions in road design, construction, weather, and traffic on the relationship between laboratory and field.

One material test that has been somewhat successful in predicting performance is the 4–cycle magnesium sulfate soundness test. The test takes seven days to perform and as reported has low repeatability. The purpose of this study is to examine the test in the laboratory and assess it in the field.

THE 4–CYCLE TEST

The magnesium sulfate soundness test is a laboratory method for evaluating aggregates in HMAC and seal coats. It originated more than 150 years ago and through the years it has undergone several changes. Texas is among 26 states that utilize the test for quality control of aggregates.

The test which has been developed to determine the weather resisting properties of aggregates, has also shown indications that it reflects an aggregate's ability to withstand degradation from traffic. Several research studies have indicated that test results correlate with field performance, while others, have reported that the test discriminates against certain aggregate types like carbonates, cherts, shales and rhyolites. The repeatability of the test as stated in the ASTM standard specification is very low, and an outright rejection of an aggregate without confirmation from other tests more closely related to the specific service intended, is not recommended by the specification.

Sixteen Texas districts specify the test either for hot mixes and/or seal coats. The majority use a limit of 30 percent loss for aggregate rejection, while others specify lower or higher limits. While these numbers may be appropriate, there are no hard data to justify the differences.

PROBLEMS INVESTIGATED, OBJECTIVES, AND SIGNIFICANCE

The study will focus on examining the relationship of the soundness test to aggregate performance. If such a relationship exists, an investigation will be made as to what values are acceptable, if values should be statewide or regional, or whether different values for hot mixes and seal coats are more appropriate. Other aggregate tests will be evaluated in the lab and their relationship to the soundness test and field performance will be examined.

The objective of the study is to develop the most appropriate parameters for the 4–cycle magnesium sulfate soundness test on a statewide or regional basis, or identify a better test method for evaluating the durability of aggregates. This would be implemented through a recommended specification.

When a material test can predict performance in service it has significant benefits. It precludes inferior materials from use in certain applications, and permits better pavement management in terms of predicting when remedial treatment will most likely be required.

WORK PLAN

The work necessary to accomplish the objectives of this study was divided into four tasks. Each task is presented in the following paragraphs.

Task 1 - Literature Search

A search of the published literature related to the development, mechanisms, and use of the 4–cycle magnesium sulfate soundness was carried out. Additionally, the current practice and experience of Texas districts with the test was gathered through interviews with district maintenance and laboratory engineers. A search of literature related to the use and development of other material tests was also carried out to facilitate the laboratory task.

Task 2 - Laboratory Evaluation

A total of 41 aggregates that represent the most widely used or problem sources from all regions of the state were gathered and their physical properties determined in the laboratory. Tests included specific gravity, absorption, freeze-thaw, aggregate durability index and 4–cycle soundness. A modified procedure of the Texas wet ball mill test was also used. A thorough statistical analysis was performed to determine the relationship of the soundness test with other tests.

Task 3 - Field Evaluation

Hot mix and seal coat projects that were constructed with eight of the aggregate sources tested in the laboratory were examined in five districts and their performance evaluated.

Task 4 - Specification

Laboratory and field evaluations were compared and analyzed together with the experience of districts, and specific recommendations were made for the evaluation of aggregate durability.

CHAPTER 2. LITERATURE SURVEY

INTRODUCTION

A literature survey on publications related to the development and use of the 4–cycle soundness and other material tests, and their relationship with field performance, was carried out. The survey helped with identifying available tests to be performed for the laboratory task, and with the understanding of degradation mechanisms and their prediction by laboratory tests.

FIELD DEGRADATION

The purpose of a material test is to predict the performance of an aggregate prior to its use in the field. The success of a method depends on (1) how well it simulates in the laboratory the effects of the environment and traffic in service, (2) its repeatability, and (3) the time, effort, and cost to generate results.

An understanding of the mechanics of degradation in the field helps to evaluate, use, or improve a method.

The term "degradation" as applied to road aggregates, is defined as the reduction in size through physical or chemical processes (Ref 37). Physical degradation occurs as a result of action of construction equipment, traffic, or the environment (Refs 37 and 43). Chemical degradation is the result of alteration or disintegration of the mineral constituents of a rock caused by the environment (Ref 37). There are three components of degradation (Refs 9, 18, 19, and 37):

1. fracture, breakage, or split of a particle,
2. complete disintegration of a particle to sand or plastic fines, and
3. polish or wear of the surface.

Fracture and disintegration of a particle occur during construction due to rolling, in service from the action of traffic, and due to physical or chemical weathering throughout the life of the pavement. Wear occurs due to attrition of particles with traffic. Degradation and wear reduce the frictional resistance and interlock of particles in bituminous mixtures which in turn cause a change in the bituminous properties. The result is loss of stability, shearing, ravelling, or polishing of the mat (Refs 7, 9, 18, 19, and 37). Seal coats have more pronounced effects due to the action of traffic or the weather, as aggregates are more exposed.

MATERIAL TESTS

Material tests are divided according to the mechanism of evaluating quality, into four categories.

1. ***Abrasion and Crushing.*** It includes the Los Angeles abrasion test. Aggregate is abraded in the presence of steel balls in a steel drum. Degradation takes place due to interparticle attrition and breakage from the balls. The test simulates the breakage of aggregates due to mixing operations, construction equipment, and traffic.
2. ***Wet Abrasion.*** It includes Washington degradation, Deval abrasion, California durability index, Oregon air test, sand equivalent, jar mill, detrition value, and modified Los Angeles abrasion tests. Aggregate is abraded in a drum in the presence of water or air jets and the production of plastic fines (minus No. 200) is used as a measure of durability. The tests simulate the production of fines produced by the kneading and pumping action of rollers and traffic.
3. ***Soundness.*** It includes freeze-thaw, 4–cycle soundness, accelerated soundness, and dimethyl sulfoxide tests. These are accelerated weathering tests that try to simulate the effect of physical elements on chemical decomposition.
4. ***Petrography.*** It includes textural analysis, thin sections, x-ray deffraction or insoluble residue tests. Aggregate is evaluated according to texture, grain size, mineral composition or rock classification.

A questionnaire on aggregate degradation among sixty-six states and agencies in USA and Canada in 1973 (Ref 12) revealed that the most widely used tests were the Los Angeles abrasion (65 percent used it) and soundness tests (55 percent). Thirty–six percent of the agencies that used only the Los Angeles test felt that they were protected from problem aggregates, as compared to 90 percent feeling protection when used in combination, a soundness or a wet abrasion test. Very few states and agencies reported using petrographic analysis.

The Los Angeles abrasion test has been under examination in many research studies. Interesting are the controversial conclusions of these studies as to its ability to predict performance. Several early reports (Refs 26, 38, and 41) have indicated a very good correlation with the field, while others (Refs 7 and 29) suggested very little correlation. Others reported that the Los Angeles best correlates with metamorphic rocks. Metcalf and Goetz (Ref 17) found the Los Angeles machine similar to that of the mixing and compacting operations of bituminous mixtures. Minor (Ref 18) in his study on degradation of surfacing materials suggested that steel balls should be omitted and the material allowed to break down by abrading against itself.

Much of research was devoted to developing and improving tests that relate degradation to the production of plastic fines (Refs 4, 7, 14, 18, and 20). The tests have been reported as more successful in predicting performance than the Los Angeles test.

Tests for soundness have obtained varying degrees of success. Allen (Ref 1) recommended that the magnesium sulfate test should not be used to reject materials, and that the freeze-thaw is more reliable. Taylor (Ref 29) found that the soundness test distinguished between bad and good aggregates but the fact that degradation took place in the larger sizes questions its validity because degradation in place occurs in the finer fractions. Spellman (Ref 28) reported that wet abrasion tests correlate best with soundness. Gandhi and Lytton (Ref 10) found no correlation of soundness with performance.

SUMMARY OF SELECTED STUDIES

A summary of few of the reviewed studies is given in the following paragraphs along with the authors and the title of each publication. The listing is chronological, which helps understand how tests have been devised and evolved through experience after usage and after a better interpretation of the mechanisms of field degradation and of the theory behind the development of each test.

1938

1. Wood, W. H., "Significance of the Los Angeles Abrasion Test as a Measure of the Service Value of the Coarse Aggregates." The report discusses the considerations that led to the adoption of the Los Angeles (L.A.) abrasion test by the Texas Department of Highways. Tests were made on 287 samples of limestone and 110 samples of gravel. The allowable Los Angeles abrasion loss for asphalt surface coarses was suggested to be 35 percent.

1939

2. Shelburne, T. E., "Degradation of Aggregates under Road Rollers." A comparison is made between the amount of fines produced by 5 and 10-ton rollers in compacting surface treatments and the fines produced in the L.A. test. It is reported that the abrasion losses at 500 revolutions in the abrasion test in 5 to 10 times greater.

1940

3. Shelburne, T. E., "Crushing Resistance of Surface Treatment Aggregates." The report suggested that precoating aggregates prior to construction has a small effect on the amount and rate of degradation.

1942

4. Labuin, R. J., "Road Making Properties of Certain South African Stones." Thirty-six aggregate samples were compared to pavement performance. The conclusion was that the physical tests predict to a certain extent performance, but the microscopic examination of thin sections is far more precise and safer for performance prediction.

1948

5. Knight, B. H., and Knight, R. G., "Road Aggregates, their Uses and Testing." This book emphasizes the importance of geological and petrological tests, rather than chemical tests, for the prediction of road performance. It points out that it is very easy to test an aggregate in the lab but is by no means simple to evaluate accurately the road making qualities of aggregates. For such an evaluation the experience of many workers in this field is necessary.

6. Pauls, J. T., and Carpenter, C. A., "Mineral Aggregates for Bituminous Construction." The report states that to a certain degree the strength and toughness requirements are influenced by the grading. Aggregates with low proportion of fines tend to degrade more than aggregates cushioned by a higher percentage of fines. Accordingly, aggregates with strength and toughness are more necessary for the coarser graded mixtures than for the denser gradations.

7. Shergold, F. A., "A Review of Available Information on the Significance of Roadstone Tests." The paper is a summary of work done up to 1948 on the relation of the results of mechanical tests on aggregates to the life and behavior of the roads in which they were used. The L.A. abrasion test was found to have the best reproducibility among all the other existing tests. It was also found to correlate well with the degradation behavior of aggregates in surface treatments.

1953

8. Minor, C. E., "Degradation of Surfacing Materials." The report suggests that plastic fines generated in degraded aggregates are the most detrimental to the pavement life. It states that present tests are not set up to detect aggregates that tend to degrade into fines and suggests that if the steel balls in the L.A. test are omitted and the aggregates allowed to break down by abrading against themselves then the test could serve this purpose.

1955

9. O'Harra, W. G., "Evaluation of the California Sand-Equivalent Test." After examining several thousand tests of aggregates the report concludes that the sand equivalent results and the amount of clay-like fines (minus No. 200) are the most important factors in judging the quality of aggregates.

1957

10. Curry, R. L., "Investigation of a Proposed Aggregate Degradation Test Method." A comparison of the standard L.A. test and a modified L.A. test in which the aggregates were soaked for 48 hours and tested in the presence of water of weight equal to 10 percent of the weight of the sample, showed no difference in the results of the two procedures.

1959

11. Taylor, C. A., "The Application of Various Routine Laboratory Tests to the Determination of Potential Degradation of Quarry Rock in Highway Pavements." The purpose of this research was to find a laboratory test that will produce similar degradation to the actual degradation in the roadway. The standard L.A. test was found to be of little value as it did not indicate similar conditions to the field. The sodium sulfate soundness distinguished between the good and bad aggregates but showed the same degradation in both the large and small particle sizes. This is questionable because most of the harmful degradation in the field takes place in the finer fractions. The freeze thaw test gave an indication of the aggregate quality but the time required to conduct the test would render it undesirable.

1960

12. Ekse, M., and Morris, H.C., "A Test for Production of Plastic Fines in the Process of Degradation of Mineral Aggregates." The report states that production of plastic fines in aggregates due to traffic is a major cause of instability in pavements. This type of degradation is not predicted by the standard L.A. test. The test was modified by removing the steel spheres and operating the machine for four hours. Comparison tests between the two procedures showed three aggregates to be nonplastic in the standard test but highly plastic in the modified test. These aggregates were rated excellent from the standpoint of resistance to abrasion.

1962

13. Day, H.L., "A Progress Report on Studies of Degrading Basalt Aggregate Bases." The report describes the Idaho degradation test. The test is run on a 1,100-gram sample soaked for 16 hours and abraded in a Deval machine for 1850 revolutions in the presence of water. The height of the generated minus No. 200 material is measured in a sand equivalency cylinder.

1963

14. The Oregon State Highway Department has developed a test that degrades aggregates by means of air dispersion in water. One hundred grams of 3/4-inch aggregate is placed in a 1000-ml hydrometer jar, covered with water to a depth of 1 inch and subjected to air dispersal through six jets for 20 minutes at 20 psi air pressure.

15. Moavenzadeh, F., and Goetz, W. H., "Aggregate Degradation in Bituminous Mixtures." The study indicated, after examining three kinds of aggregates, that the magnitude of degradation, as measured by the percent increase in surface area, is affected by (1) the gradation: the denser the mix the less the degradation, (2) the aggregate type: aggregates with high L.A. values resulted in high degradation, (3) the compactive effort: increased magnitude of load or number of repetitions increased the degradation. Load magnitude was found to affect degradation more than the number of repetitions.

1966

16. Breese, C. R., "Degradation Characteristics of Selected Nevada Mineral Aggregates." The study correlated four existing degradation tests: the Oregon degradation test by air dispersion in water, the jar-mill test, the Washington degradation test, and the California durability index test. All these tests use a sedimentation analysis of the minus No. 200 material produced. The Washington test was found to have the best correlation when compared with the other tests and with field evaluation.

1968

17. West, T. R., Johnson, R. B., Smith, N. M., and Aughenbaugh, N. B., "Tests for Evaluating Degradation of Base Course Aggregates." Base course aggregates from 140 sources in 12 states were studied for the purpose of developing an improved test for aggregate degradation. Tests included: L.A. abrasion (standard

and wet), sodium sulfate, freeze-thaw, specific gravity, absorption, insoluble residue, and petrographic analysis. The sodium sulfate was found to be a nonreliable test because of its great variability. In the proposed test procedure aggregates are divided into (a) carbonates, sedimentaries, and metamorphic, (b) basalts, and (c) heterogenous gravels. Separate tests are suggested for each group as follows: (a) L.A., freeze-thaw, and limited petrographic analysis, (b) L.A. (standard and wet) and complete petrographic analysis, and (c) L.A., freeze-thaw, and megascopic petrographic analysis.

1971

18. Larson, et al., "Modification of the Standard Los Angeles Abrasion Test." The study compared the L.A. standard and modified tests and the Washington degradation tests. The modified L.A. test includes 250 revolutions with the aggregate in the dry state plus 250 revolutions after a fixed amount of water has been added. A sedimentation analysis is run on the entire sample, and the percent loss minus No. 16 is determined. The standard and modified L.A. had an almost perfect correlation when percent losses were compared. The modified L.A. and Washington sediment heights had a relatively good correlation, but the modified L.A. compared better with the petrographic analysis than the Washington test did.

1972

19. Miles, D. K., "Accelerated Soundness Test for Aggregates." The study compared the L.A. and sodium sulfate soundness tests with an accelerated soundness test in order to find a test that predicts more accurately the performance of rock used as riprap. The accelerated soundness consists of determining the percent loss after submerging rock samples in solutions of ethylene glycol, potassium acetate, ammonium acetate, and dimethyl sulfoxide for 15 days. Results of the comparison indicated that no single test was satisfactory for predicting the performance of all rock types. Instead, different tests appeared to be more suitable for evaluating different types of rock. The L.A. showed the best correlation with observed field performance of metamorphic rocks. The soundness test best predicted the performance of sedimentary rocks, and the absorption test correlated well with the igneous rocks. The accelerated soundness compared with the existing tests reflected lower correlation with the field performance.

1975

20. McCall, V. D., "Investigation of Deteriorated Hot Mix Asphaltic Concrete Resulting in a Modified Soundness Test for Aggregates" (Ref 16). Deterioration of hot mix asphaltic concrete roads in Odessa District in Texas led to modification of the standard 4–cycle magnesium sulfate test used for concrete aggregates. The major changes to the test were the number of cycles (4 cycles were used instead of 5) and the use of aggregate size up to No. 50 instead of No. 4. As it is reported, after specifying the test, eight projects monitored for performance showed no indication of failure. In addition, asphalt used in hot mixes has shown a decrease of 1 1/2 to 2 percent; this has been attributed to the elimination of absorptive aggregates.

21. Spellman, D. L. Woodstone, J. H. and Bailey, S. N., "Concrete Aggregate Durability Tests." The research conducted by the California Department of Transportation aimed at developing a simpler test than the sodium soundness for measuring the ability of aggregates to resist degradation. Tests considered were (1) elastic fractionation: it is based on the theory that hard materials bounce farther than soft, (2) heavy media separation: unsound low specific gravity material is separated from sound material by floatation in heavy liquid, (3) freeze-thaw: the aggregates are subjected to rapid freezing and thawing cycles, (4) durability index: relates the quality of the aggregate to the amount of fines generated from aggregates when subjected to abrasion, (5) autoclave degradation: the aggregates are subjected to a superheated steam, (6) detrition value: the aggregates are abraded in a 5-gallon paint shaker in the presence of water and the percent loss is determined. The detrition value was found to have the best correlation among the five tests with the soundness test. There were cases, though, of low soundness losses and high detrition values. All other tests gave poor correlation with the soundness test.

CHAPTER 3. THE 4–CYCLE MAGNESIUM SULFATE SOUNDNESS TEST

INTRODUCTION

The 4-cycle magnesium sulfate soundness test is a laboratory procedure developed to determine the resistance of aggregates to disintegration, when subjected to weathering action in HMAC and seal coats. The method involves subjecting aggregates to alternate cycles of soaking into a saturated solution followed by oven drying. Reduction in aggregate size is reported as the soundness loss.

The test was included in the standard ASTM specifications in the 1930's. Several research studies have been conducted since then to understand the mechanism by which salt disrupts rock particles, improve precision of the method, and evaluate its prediction of field performance.

In the following chapters are discussed the development and theory of the test, factors affecting reproducibility, current differences between the Texas and ASTM soundness tests and comments on the laboratory tests.

THE DEVELOPMENT OF THE TEST

The literature on the soundness test dates back over 150 years to a procedure employed by Brard (Ref 11) in 1828. This early test consisted of boiling aggregates in a saturated solution of sodium sulfate for thirty minutes in order to complete saturation, followed by cooling under fresh solution for several hours and a twelve hour crystallization period in a dark room. The test technique was changed considerably before appearing in 1931 as a standard test in the ASTM annual book with designation Method C88, and title "Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate." The low reproducibility of the method brought up the first revisions in the late 1930's. Changes which were suggested by Garrity and Kriege (Ref 11) and others (Refs 36 and 42) included an increase in the amount of magnesium sulfate required to obtain a saturated solution, and a specific gravity requirement of 1.295 to 1.308 instead of 1.290. The test went through several revisions as tentative before being advanced to a standard in 1963 (Ref 3). A major problem was the multiplicity of alternative procedures allowed within the method. Either sodium or magnesium salts might be used, the number of cycles was not designated, different aggregate size distributions were permissive and equipment specifications were unclear (Refs 39, 40, and 42). The changes included elimination of alternate aggregate gradings, limitations on oven efficiency and final screening over sieves with openings five sixths as large as those used in preparing the samples.

A failed HMAC roadway section on I-10 in Pecos and Reeves counties in Texas in 1970, led to the development of a modified soundness test in 1975 (Ref 16). Up to that date the soundness test was used only for concrete aggregates which were normally subjected to 5 cycles of soaking in the salt solution. The modified test which was intended for use for aggregates in bituminous mixtures and surface treatments, subjected aggregates in 4 cycles of soaking and drying. Because both Type C and Type D hot mixes contain coarse and fine aggregate the test was modified to include sizes from minus 3/4–inch to plus No. 50. Also, only magnesium sulfate was used to prepare the solution because it gave a wider range of results and it could retain better its specific gravity.

The Texas State Department of Highways and Public Transportation (SDHPT) adopted the soundness test for use for hot mix and surface treatment aggregates in the late 1970's. The method was revised several times since then.

Today, the soundness test for coarse aggregates essentially consists of immersing carefully sieved weighed fractions of the plus No. 8 portion in a saturated solution of sodium or magnesium sulfate for 18 hours at 70°F plus or minus 2°F, and drying them at constant weight at 230°F for each cycle. The weight loss is then based on the amount of material passing through the next smaller sieve over which each size was originally prepared.

THEORY

Details of the mechanism by which the sulfate test disrupts the rock particles are best described by Garrity and Kriege (Ref 11). The 18-hour immersion of the dried specimen in a saturated solution of sodium or magnesium sulfate is presumed to fill the pores of the aggregate with this liquid. During the drying portion of the cycle the moisture is removed from the solution within the pores leaving a deposit of anhydrous salt in the pore spaces and walls. The second immersion of the specimen in the solution brings fresh saturated solution in contact with the solid anhydrous salt deposited in the pore during the drying period, thereby producing crystallization of the hydrated salt. The crystals formed occupy a larger volume than the anhydrous salt does and exert pressure against the pore walls. Pressure increases as crystal growth continues with more cycles of immersion and drying. This disrupting action of the confined salt within the pores serves, as the ASTM notes, as a measure of the resistance of the mineral aggregate to natural weathering forces, particularly the expansive action of water on freezing. There has been, however, no evidence, either theoretical or experimental, to support the argument (Ref 3). According to Verbeck and Landgren (Ref 35), the growth of sulfate crystals in pores is not analogous to the development of pressure by freezing water. The validity of this argument will be examined in the laboratory investigation of this study.

Losses approximately equal to those generated by a sulfate solution have been found to occur when the test was run with distilled water (Ref 11). This points out the contribution of simple wetting and drying to disruption of particles. Wuerpel (Ref 42) found loss to be approximately proportional to the number of cycles. Finally, it has been shown that extended heating beyond that needed for dehydration of crystals adds a destructive action to the particles (Ref 11).

REPRODUCIBILITY OF THE SOUNDNESS TEST

The significance and use paragraphs of Test Method C88 states that "since the precision of this method is poor, it may not be suitable for outright rejection of aggregates without confirmation from other tests more closely related to the specific service intended." The precision statement calls for a single operator coefficient of variation for magnesium sulfate of 11 percent. Therefore two tests should not differ by more than 2.82 x 11 = 31 percent in more than 5 percent of the cases (Ref 2). The multilaboratory respective numbers are 25 and 71 percent. Sodium sulfate has almost twice as high precision indexes indicating its very low accuracy.

The statements of low precision and limited significance, and the lack of inflexible limits have been the subject of speculation over the years. Several researchers who investigated the variables and problems associated with the test, have shown that the following influence the magnitude of loss measured (Ref 3):

(1) amount of salt in solution,
(2) specific gravity of the solution,
(3) method of preparation of solution,
(4) type of salt,
(5) temperature of solution,
(6) length of drying time,
(7) efficiency of drying oven,
(8) type of sample container,
(9) technique of sieving in the preparation of samples, and
(10) technique of sieving in the measurement of loss.

It has been shown that salt should be in excess when solution is ready for use to ensure saturation (Ref 11). Maintaining a saturated solution is essential for the promotion of crystal growth. Mechanical stirring should be used during both the preparation of the original solution and subsequent agitation before each cycle (Ref 11). Also at least ten minutes of thorough agitation should precede the immersion of the test specimen. The type of salt seems to affect greatly the results. Magnesium sulfate subjects aggregates to a more severe disintegration than sodium sulfate. The hydrated form of the magnesium sulfate was suggested for use instead of the anhydrous form because the latter is never formed in the drying period of the test cycle (Ref 11). Using one type of salt is also recommended as it may reduce possible variations due to quality and type of salt. The technical grade salt (epsom salt) might be more appropriate as it is readily available and less expensive. The magnesium sulfate was suggested for use instead of the sodium sulfate because its solubility is less sensitive to temperature changes (Refs 11 and 21). This explains the lower precision of the sodium test and the necessity for a strict temperature control when this type of salt is used. Extended drying time has been reported to affect results as it added to the destructive action (Refs 21, 40, and 42). A series of tests on sands has shown an increase in soundness loss from 7.5 percent to 10.1-18.3 percent when drying time was extended from 4 to 48 hours (Ref 11). The efficiency of the oven, the type and number of containers and the presence of other specimens in the oven are likely to influence the time needed to dry samples to constant weight. It has been proposed to reverse the cycles, that is, soak the material for six hours and dry it for seventeen to achieve complete drying (Ref 39). This was supported by indications that coarse aggregate would absorb as much water in six hours as it would in 24 hours and that crystal growth ceased within an hour after immersion (Ref 11). Comparisons between normal and reverse cycles showed smaller losses in the reverse cycle which indicated insufficient absorption of the sulfate solution. Finally, sieving of aggregate for sample preparation or measurement of loss is critical. Caution is recommended by the fact that when sieving is done on a mechanical sieve shaker the effective opening of the sieve is reduced due to the vigorous horizontal movement, and subsequent hand sieving (procedure followed in the test) will let more particles pass through.

DIFFERENCES BETWEEN THE TEXAS AND ASTM SOUNDNESS PROCEDURES

Test Method Tex-411-A (Ref 32) and ASTM C88 tests for soundness have the following differences in procedure:

(1) Texas uses sieve No. 50 as the smallest sieve when testing hot mix or seal coat coarse aggregate. The ASTM uses the No. 4 as the smallest sieve.

(2) Texas prepares the magnesium sulfate solution by dissolving the salt at 130°F. The ASTM specifies a temperature of 77 to 86°F.

(3) The temperature of the solution can be maintained between 68 and 75°F in the Texas test. The ASTM allows a range of 68 to 72°F.

(4) Texas specifies that specific gravity measurements should be obtained prior to stirring the solution. Additionally, it requires measurements once a week.The ASTM specifies measurements for specific gravity should be obtained after agitation.

(5) After completion of the last cycle Texas soaks the material overnight in warm tap water to remove salt, while ASTM specifies washing the sample and use of barium chloride to detect presence of salt. The Texas method does not use the barium chloride because tap water at D-9 contains enough

salts to cause cloudiness of the water and mask the effect of barium chloride.

COMMENTS ON SOUNDNESS TESTS

The 4-cycle magnesium sulfate soundness test was conducted on 39 aggregates supplied by Texas districts. Several problems have been encountered at the initial stages of testing due to misinterpretations of the Texas and ASTM standards and difficulty in maintaining a specific gravity of the solution within acceptable limits.

The intent was to perform the soundness test using the same procedure followed by the Materials and Test Division (D-9) of the Texas SDHPT. This would offer the opportunity to investigate their method and also compare the results of the two laboratories. Evidently, the Texas method went through tentative revisions since its last publication in March of 1986. The revisions were discussed with engineers at D-9 and a written interpretation of the method was sent to D-9 for verification. The changes were advanced to a standard in November of 1986.

Specific Gravity and Temperature of Sulfate Solution

The inability to maintain a saturated magnesium sulfate solution caused the project an appreciable delay. The ASTM method specifies that the solution "when used shall have a specific gravity between 1.295 and 1.308." It also says to "stir the solution and then determine the specific gravity." The two clauses seem contradicting. Also, if a measurement is obtained after stirring, the number will be affected by suspended particles, and a specific gravity of 1.295 will not reflect a saturation level. Several magnesium sulfate types have been used to prepare solutions. Their specific gravities ranged between 1.289 and 1.292 after reaching a stable level. Solutions had specific gravities above 1.297 the first one or two days after manufacture. This was an indication that continual stirring was needed to maintain a specific gravity within specification limits.

After experiencing these problems, D-9 raised the required temperature of solution from between 68-72°F, to between 68-75°F. The higher temperature raised the specific gravity above 1.295 but this does not mean that the solution is at saturation because saturation point raises with temperature. Another problem may be the wider temperature range allowed. Literature indicated that solubility is greatly affected by temperature and the wider tolerance may reduce repeatability of results. The New York State Department of Transportation is using a temperature range of 72-76°F (Ref 15) and probably this is more appropriate. As it was understood the specific gravity level does not affect highly disrupting (Ref 15) action or precision of results, as long as it is kept at a steady level around 1.285 and 1.295. Trying to achieve a hundred percent saturation by daily mechanical stirring may introduce additional error as this condition is highly unstable. It may also be desirable for checking purposes to measure the specific gravity before and after stirring of the solution. Measurements after stirring should be obtained at least 3 hours after agitation to allow suspended particles to settle.

Specimen Size

Most of the aggregates tested had size distribution between the 1/2–inch and No. 4 sieves. This is also the size distribution of seal coat aggregates (Grades 3, 4, and 5) and hot mix coarse aggregates. According to the soundness test, sample preparation for these sizes is as follows (for calculation purposes the sizes are also given in mm):

Cat	Sieve Size	Weight Sample	Sieve to Determine Loss
A	3/4 in. - 1/2 in. (19-12.5 mm)	670 g	5/16 (8.0mm)
	1/2 in. - 3/8 in. (12.5-9.5 mm)	330 g	
B	3/8 in. - No. 4 (9.5-4.75 mm)	300 g	No. 5 (4.0 mm)

The sizes between 3/4 and 3/8 inch are combined to determine loss.

There has been the question of how to prepare the sample in case the size between the 3/4 and 1/2 inch sieves does not exist (the solution would be to get either 330 or 1000 g of the 1/2-3/8 inch size) and whether D-9 should revise the specification to test the 1/2-3/8 inch size separately.

Probably the answer lies between the relationship of the minimum and maximum size in each category and their relationship with the sieve used to determine loss.

In category A sieve 5/16 inch is (9.5 – 8.0) / 9.5 x 100 = 16 percent smaller than sieve 3/8 inch, and (19 – 8) / 19 x 100 = 58 percent smaller than sieve 3/4 inch. In category B sieve No. 5 is (4.75 – 4.0) / 4.75 x 100 = 16 percent smaller than sieve No. 4 and (9.5 – 4.0) / 9.5 x 100 = 58 percent smaller than sieve 3/8.

Therefore, despite the fact that category A is divided into two sizes, the relationship of the sieve to determine loss with the minimum and maximum sieve in each category is exactly the same. If then size 3/4-1/2 inch is tested separately using for example the 3/8 inch sieve to determine loss, the loss will be much higher. Probably the reason for dividing category A into two sizes is the need for having a good distribution of sizes within the category. This need not be done with the smaller sized category B because sieve 3/8 inch is only 4.75 mm greater than sieve No. 4 and presumably a good distribution of sizes is obtained when sieving the sample.

If the 3/4-1/2 inch size is absent then the test procedure should not change. Taking a 1000 g sample instead of 330 g for the 1/2-3/8 inch size, will probably increase precision because of the larger size. However, a better precision for only that size is not desirable, because it will not compare with the precision of the other losses and the procedure will not be a consistent one that can be used to compare losses from different aggregates.

Repeatability of Results

Repeat tests were performed for thirteen of the aggregates. Table 3.1 shows standard deviations and coefficients of variation in ascending order of the mean soundness values. Standard deviation increased with increased level of soundness. The average standard deviation of all soundness values was found to be 1.96. The critical soundness values are those close to specification limits (which range between 25 and 40 percent). The average standard deviation of soundness values greater than 25 percent was 3.00. The population standard deviation specified in ASTM C88 for a soundness value of 20 percent is f(11,100) x 20 = 2.20.

TABLE 3.1. ***REPEATABILITY OF THE SOUNDNESS TEST RESULTS***

Agg No.	Average Soundness (% Loss)	No. of Observations	Standard Deviation	Coefficient Variation (Percent)
30	1.9	3	0.59	31
25	2.2	3	0.72	33
18	2.9	4	1.46	50
16	8.4	3	1.51	18
15	9.1	3	0.20	2
41	10.0	3	0.69	7
26	14.4	2	1.27	9
8	17.1	2	4.10	24
7	29.3	3	3.81	13
37	36.1	4	2.45	7
40	39.0	3	4.37	11
13	46.0	2	1.63	3
5	63.5	3	2.65	4

A comparison between results of tests performed at the Center for Transportation Research and D-9 Laboratories was also made. Repeat tests on five aggregates (Nos. 37, 38, 39, 40, and 41) were found to differ by 1 to 45 percent.

Recommendations

The following observations and changes are recommended to the soundness procedure:

(1) The magnesium sulfate should be the only specified sulfate for solution manufacture. The technical grade heptahydrate magnesium sulfate is recommended for use.

(2) The temperature of the magnesium sulfate solution should be maintained at 73 ± 2° F.

(3) Based on the above temperature, D-9 should specify a specific gravity of the magnesium sulfate solution such that can be obtained and maintained constant under normal D-9 preparation and mixing practices. The specific gravity will probably be at a range between 1.293 and 1.298.

(4) When a certain aggregate size is absent the procedure should remain unchanged. Material coarser than the No. 50 sieve available in amounts of more than 5 percent should be prepared and tested at the specified weights.

(5) Four (4) cycles of immersion and drying of sample should be specified as a standard procedure for HMAC and seal coat aggregates.

(6) Because drying time has been reported to influence disrupting action and be influenced by aggregate size, container size and type, and efficiency of oven, a drying time clause should be as follows, "Dry samples to constant weight; drying time should be not less than 6 hours and not more than 8 hours."

CHAPTER 4. LABORATORY TESTS

AGGREGATE TESTS

The following tests were performed on the collected aggregates at the laboratory of the Center for Transportation Research. Test method designations are given in parentheses.

(1) Absorption and specific gravity (Tex-201-F) (Ref 30),
(2) Absorption and specific gravity of synthetic aggregates (Tex-433A) (Ref 34),
(3) Gradation (Tex-401A) (Ref 31),
(4) Freeze-thaw (Tex-432A) (Ref 33),
(5) Aggregate durability index, and
(6) Texas degradation.

The first four tests were performed according to Texas Standard Specifications. The freeze-thaw test is specifically used by SDHPT to test synthetic aggregates. To examine if its use could be extended for other materials, it was used to test all aggregates collected.

Because aggregate durability index is a test not used in Texas, and Texas degradation is a modification of a test, the two are discussed in more detail in the following chapters.

AGGREGATE DURABILITY INDEX

The "Aggregate Durability Index" is a standard ASTM procedure with designation ASTM D3744. The test was developed from Test Method No. Calif. 229-E, "Method of Test for Durability Index."

As stated in the ASTM the method was developed to permit prequalification of aggregates proposed for use in the construction of transportation facilities. The durability index calculated from the test establishes a measure of the relative resistance of an aggregate to producing detrimental clay-like fines when subjected to mechanical degradation in the presence of water.

Significance and Use of the Aggregate Durability Index Test

The test assigns an empirical value to the relative amount and character of plastic fines that may be generated in an aggregate when subjected to mechanical degradation in the presence of water. The theory behind the development of the test is that an excess of clay is detrimental to the performance of any aggregate whether for gravel base, bituminous mixture or portland cement concrete. Clay when combined with water becomes an effective lubricant which reduces the frictional resistance or stability of the base or surface course and, as a result, the load carrying capacity. Additionally, dust coating on aggregates prevents a strong bond with asphalt either in a HMAC mixture or a seal coat treatment.

The ASTM states that the method provides a rapid test for the evaluation of a new source. Research has also indicated that it may be suitable for use instead of the sodium sulfate soundness for evaluating the durability of fine aggregates in portland cement concrete. The ASTM also suggests investigating the possibility of expanding the application of this method to control the quality of aggregates for use in bituminous paving mixtures.

The precision of the method is similar to the soundness test. Standard deviations for a single operator of durability indexes in the 60's, 70's, and 80's are 3.5, 2.5, and 1.5, respectively. It is clear that precision of results from low quality aggregates is much lower than precision from good aggregates.

Summary of Method

Separate and different test procedures are used to evaluate the coarse and the fine portions of a material. Procedure A is used for the plus No. 4 portion, procedure B for the minus No. 4, and procedure C for aggregates that contain most particles between the 3/8-inch and No. 16 sieves.

In procedure A, 2500 g of the plus No. 4 portion is prepared to a specific grading and washed in a mechanical vessel for 2 minutes. The plus No. 4 portion of the material is then agitated with water in the vessel for 10 minutes. The generated minus No. 200 fines are placed in a plastic cylinder and let settle for 20 minutes. The height of the sediment column is used to calculate the durability index.

In procedure C, 500 g of the minus No. 4 portion is washed in a mechanical vessel for 2 minutes. A 3 oz. portion of the plus No. 200 material is then placed in a plastic cylinder and agitated for 30 minutes on a mechanical sand equivalent shaker. The sedimentation part is performed as in procedure A.

Comments on Laboratory Tests

The durability index test was performed on the aggregates collected for this study. The intent was to follow the ASTM procedure but the method failed to provide guidelines on how to prepare a specimen when a certain size of an aggregate is not present. In such a case the California test guidelines were used in conjunction with the ASTM procedure.

Early test results had indicated a good correlation with the soundness test, and since precision of a replacement test for soundness would be required, it was decided to perform twice procedure A and three times procedure C. Also, the possibility of eliminating one of the two procedures was examined, to reduce complexity and equipment requirement (procedure A and first wash of procedure C is performed on a modified Tyler sieve shaker, while the second wash of procedure C is performed on a mechanical sand equivalent shaker). For this purpose the sample size of aggregates that could only be tested under procedure A was changed from minus No. 4 to a size between 3/8 inch and No. 8 sieves, so that procedure C could be performed as well.

Correlation analysis (Table 5.2) and a plot of the results (Fig 4.1) showed a good relationship between the two procedures. The average standard deviation was found to be 4.00 for procedure A and 1.83 for procedure C.

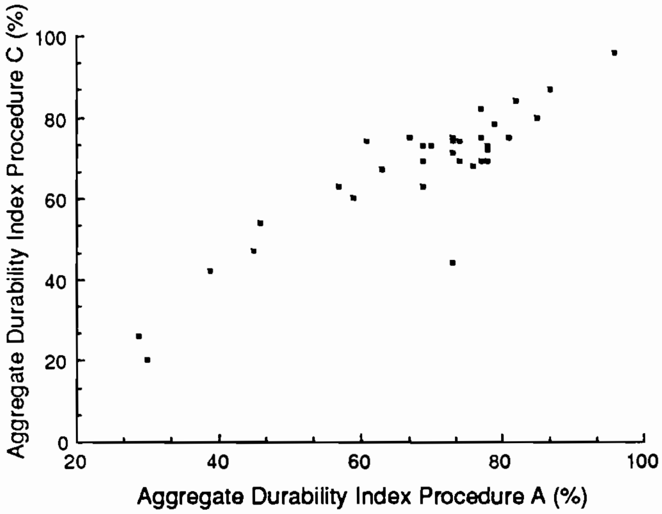

Fig 4.1. ***Aggregate durability index - procedure C vs. procedure A.***

The durability index procedure takes two days to perform. Also, in addition to having two test methods for coarse aggregates and two wash procedures for each, a correction for the weight of specimen and volume of wash water is applied, when procedure A is used. This requires additional testing for specific gravity and absorption. Procedure C is easier to perform than Procedure A because sample size is easier to handle (100g compared to 2,500g), does not require additional tests, and human error is not involved during the second wash. The simplicity and higher precision of procedure C make it preferable over procedure A. Results have also indicated that a slight change in procedure makes procedure C sufficient for the test. There was also indication that initial wash could be deleted, without any inverse effects. Elimination would shorten the run time to one day, simplify the test, and require one mechanical shaker.

TEXAS DEGRADATION TEST

Wet Ball Mill Test

Texas Test Method Tex-116-E titled "Ball Mill Method for Determination of the Disintegration of Flexible Base Material," is a laboratory procedure specifically designed to measure the ability of aggregates to withstand degradation in the road base and detect soft aggregate which is subject to weathering.

The test consists of a water-tight steel cylinder (mill) of 0.5 cubic foot of volume. An aggregate mass of 3.4 kg of the plus No. 10 portion is placed in the mill together with 6 steel spheres and water. The mill is rotated for 600 revolutions and the generated material passing No. 40 sieve is expressed as a percent of the initial charge. The material loss is called the wet ball mill value.

Development of Texas Degradation Test

The wet ball mill method as it is cannot be used for surface aggregates. Several reasons have urged us to consider a modified procedure to test aggregates under this study. The initial thrust came from two district laboratories that experienced satisfactory results with the test. The ball mill machine is available at the districts and adoption of the test would not require additional equipment. Also the literature survey indicated a widespread use of wet abrasion tests among states. It has been reported that abrasion (which includes the Los Angeles test) does not simulate correctly the field conditions and that water should be added in the mill and steel balls excluded, to allow aggregate to break down by abrading against itself. Finally, early results from durability index had shown sediment to correlate well with soundness except with two aggregates. Use of a more vigorous machine than the one used with durability index and obtaining a percent loss by weight in addition to the sediment,was expected to improve correlation with the soundness test.

A literature search of abrasion and wet abrasion tests has produced Table 4.1 which shows the parameters used in each test, including sample size and weight, number of revolutions, and volume of water. Having this table as a guideline, a testing program was carried out to determine the most appropriate parameters for a modified wet ball mill procedure.

The intent was to generate a simple procedure without sacrificing precision. It is the feeling of the researchers that simplicity should be the major characteristic of a materials test because it helps reduce time, effort, and human error. A complicated procedure does not necessarily increase precision as it may add variation from the additional variables considered.

A tentative procedure was devised which includes a sedimentation part and calculation of percent weight loss through No. 8, 10, 16, and 200 sieves in order to determine the most appropriate sieve. The method is titled "Tentative Texas Degradation Procedure" and is included in Appendix A.

The procedure eliminated first wash and correction for sample weight applied by the durability index test, and used a specimen weight of 3,000g Shaking was performed for 10 minutes in the presence of water and four spheres. Total run time was two days.

TABLE 4.1. COMPARISON OF ABRASION AND WET ABRASION TESTS

	Los Angeles Abrasion ASTM C-131	**Modified Los Angeles**	**Wet Ball Mill Tex-116-E**	**Detrition Value**	**Durability Index Procedure A ASTM D3744**	**Durability Index Procedure C ASTM D3744**
Sample Size	Proc. B 3/4-3/8 Proc. C 3/8-No.4	3/4-3/8	+ No. 4	+ No. 4	+ No. 4 1st wash + No. 200 2nd wash	- No. 4 1st wash No. 4 -No. 200 2nd wash
Sample Weight	Proc. B 5,000 g. Proc. C 5,000 g.	5,000 g	3,500 g	7,500 g	2,550 g	500-1st wash 120-2nd wash
Charge (no. of spheres)	Proc. B 4,584 g. (11) Proc. C 3,330 g. (8)	4,584 g	400 g (6)	No	No	No
Container Volume	202 lit	202 lit	19 lit	19 lit	7.8 lit	7.8 lit -1st wash 300 ml - 2nd wash
RPM or Cycles	30/min	30/min	60/min	Paint shaker Model 33	280 min	175/min
Total Cycles or Revolutions	500	250 dry 250 wet	600	--	1st wash 560 2nd wash 2,800	1st wash 350 2nd wash 5,250
Shake Time	16.5 min	16.5 min	10 min	30 min	1st wash - 2 min 2nd wash - 10 min	1st wash - 2 min 2nd wash - 30 min
Water in Container	No	1,000 nil after first 250 cycles	1,900 ml	2,250 ml	1,000 ml	1,000 ml - 1st wash 70 mil - 2nd wash
Drying Temperature	220°F	220°F	140°F	Uses the wet weight	220°F	220°F
Sieve Used to Determine Percent Loss	No. 12	No. 16	No. 40	No. 4	No. 200	No. 200
Sedimentation Test	No	Yes	No	No	Yes	Yes
Soaking of Sample	No	No	1 hr in 1/2 gal.	30 min drain for 5 min	1st wash - 1 min 2nd wash - 1 min	1st wash - 10 min 2nd wash - 10 min

Laboratory Tests

The tentative Texas degradation procedure was used to test the collected aggregates. Comparison of each weight loss and sediment with the soundness test is shown in Chapter 5 in the form of correlation analysis, scatter plots, and regression models. Results indicated that weight losses and sediment have very high correlation among them. This eliminated the usefulness of measuring both weight loss and sediment during the test. The loss minus No. 10 was found to have the best correlation with the soundness test.

Figures 4.2 and 4.3 show scatter plots of Texas degradation sediment with procedures A and C. The two plots indicate good relationship between Texas degradation and durability index. The fact that a strong relationship exists between procedures A and C (Fig 4.1) and between the two procedures and Texas degradation, indicates that Texas degradation can replace the durability index test and that the simplified method employed by Texas degradation did not affect the accuracy of the test.

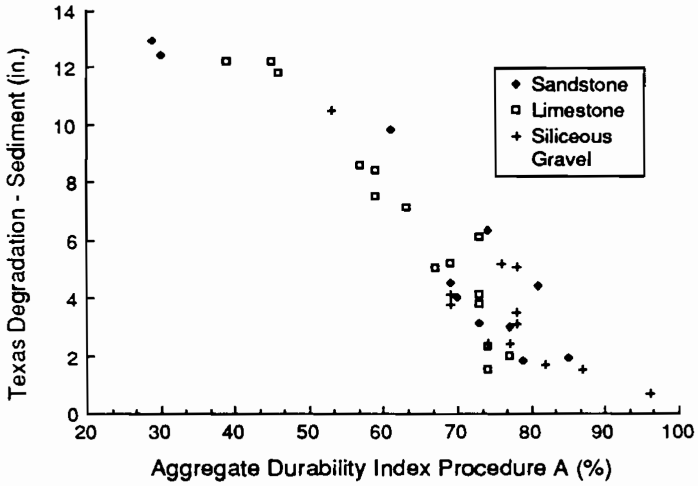

Fig 4.2. ***Texas degradation sediment vs. aggregate durability index procedure A.***

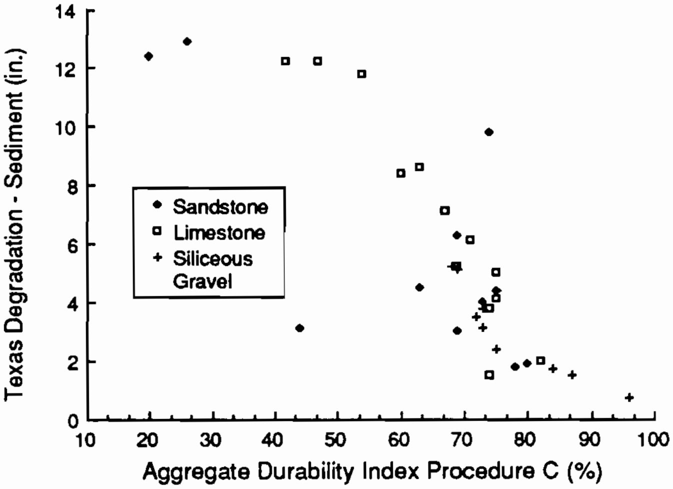

Fig 4.3. ***Texas degradation sediment vs. aggregate durability index procedure C.***

The average standard deviation of repeat tests on six aggregates was found to be for the minus No. 10 loss 0.48, and for the sediment 0.32. The average standard deviation of repeat soundness tests was found to be 1.96 and of repeat durability index tests 4.00 and 1.83 for procedures A and C, respectively. The coefficient of variation around the mean was used as a comparison among the tests. Values obtained were 8.8 percent for Texas degradation minus No. 10 loss, 5.2 percent for Texas degradation sediment, 6.0 percent for soundness, and 10.6 percent for procedure A and 4.4 for procedure C of durability index. These values show no appreciable differences among the repeatability of the three tests.

Based on the above results a final Texas degradation method is proposed in Appendix B. This method is suggested as a probable replacement for the soundness test. Texas degradation sediment and other losses should be considered if the test is going to be used for other purposes.

CHAPTER 5. STATISTICAL ANALYSIS OF THE LABORATORY TEST RESULTS

SIGNIFICANCE OF THE STATISTICAL ANALYSIS

One of the primary purposes of this study was to investigate the relationship between the 4–cycle magnesium sulfate soundness test and existing aggregate quality tests that are simpler to perform than the soundness test. If a strong relationship is found, then the soundness value of an aggregate could be estimated by performing the easier test. The benefit from this would be faster test results at a comparable cost.

The soundness test has proved to be, in many cases, an accurate method of predicting in the laboratory the performance of coarse aggregates when used in hot mix asphaltic concrete or seal coat road surface applications. The test, however, has two major disadvantages; a lengthy and tedious procedure (it takes eight days to run), and low reproducibility (repeat tests are allowed to vary as much as 31 percent). The above reduce the importance and meaning of the test. Therefore, not only a simpler test is required, but also one which is more repeatable than the soundness test.

To be able to perform a reliable analysis with sound conclusions about the relationship between tests a large number of aggregates is required that will cover all the possible ranges of soundness values. The large number of samples and tests, and the complexity of the analysis brings the need for a statistical analysis.

Using statistical inferences and modeling, equations that describe the relationships between tests can be developed, which if found strong and significant, can be used for future purposes to estimate a soundness test result from the result of another test. Additionally, if a test is found to correlate strongly with the soundness test, then inverse prediction could be used to estimate a limit for the test from the respective limit of the soundness test. The benefit would be a direct use of the new test instead of transforming results to soundness values.

LABORATORY TESTS USED IN THE ANALYSIS

The following aggregate tests were performed in the laboratory. In parentheses are given the names of the tests as labeled in the analysis:

(1) four-cycle magnesium sulfate soundness (MSS),
(2) absorption (ABS),
(3) specific gravity (SG),
(4) freeze-thaw (FT),
(5) aggregate durability index, Procedure A (ADIA),
(6) aggregate durability index, Procedure C (ADIC),
(7) Texas degradation test, minus No. 8 (TDT8),
(8) Texas degradation test, minus No. 10 (TDT10),
(9) Texas degradation test, minus No. 16 (TDT16),
(10) Texas degradation test, minus No. 200 (TDT200), and
(11) Texas degradation test, sediment (TDTSED).

In addition, Los Angeles abrasion (LA) and Polish Value (PV) results from quality monitoring (QM) tests on the aggregate sources considered in this study were furnished by D-9. QM test dates and dates of sampling of aggregates coincided to reduce the effect of probable quality variation within a source.

A total of 41 aggregate samples from 33 quarry sources were collected for testing. These were supplied by district laboratories in Texas and represented the most commonly used or problem sources in each district.

The aggregates were divided into four groups; limestones, sandstones, siliceous gravels and lightweights. Only two lightweight aggregates were collected and therefore were not included in the analysis to eliminate the bias of a small sample size.

Each aggregate was tested with the full battery of tests. Repeat tests were performed with soundness, aggregate durability index, and Texas degradation to check the reproducibility of the methods. Table 5.1 shows the laboratory results.

HARDWARE AND SOFTWARE FOR STATISTICAL ANALYSIS

Because of the large number of samples involved and the diversity of the parameters used, the necessity for computer statistical analysis was noted. An IBM Personal Computer AT was used for most of the calculations. The Statistical Analysis System (SAS) software program of SAS Institute Inc. (Refs 22, 23, and 24) was loaded into the IBM and used for the analysis of the data.

The SAS system is a software package developed specifically for

(1) information storage,
(2) data modification, and
(3) statistical analysis.

It basically consists of two tools, the SAS editor and the SAS statements. The editor is used to store data and create data files. The SAS statements comprise a program developed to read a designated SAS file and according to the needs, modify the file, create new data sets, produce tables or graphs, perform various computations including sophisticated statistical procedures, and print the results.

TABLE 5.1. *LABORATORY TEST RESULTS*

Agg No.	Aggregate Type	4-Cycle Soundness (% Loss)	Absorption (%)	Spec Grav	Freeze Thaw (% Loss)	Aggregate Durability Index	
						ADI-A	ADI-C
1	Cr. Limestone	52.2	3.3	2.47	15.4	44	47/46/49
2	Cr. Limestone	6.1	0.8	2.66	2.6	87/59	74/75/76
14	Cr. Limestone	7.6	1.9	2.54	1.7	74/71	71/73/71
17	Cr. Limestone	17.0	3.6	2.47	3.1	59	58/59/63
20	Cr. Limestone	39.0	2.2	2.56	14.9	44/34	40/39/45
26	Cr. Limestone	15.3/13.5	2.7	2.52	10.3	62/54	-
28	Cr. Limestone	1.7	0.8	2.70	1.1	77/75	82/82/82
29	Cr. Limestone	17.1	4.3	2.32	1.9	63/62	68/66/66
30	Cr. Limestone	2.3/2.1/1.2	1.4	2.52	4.3	74/74	72/76/75
37	Cr. Limest Strat #1	36.5/39.4/34.5/34.0	2.9	2.51	9.8	56/58	63/62/65
38	Cr. Limest Strat #2	40.1	8.4	2.16	1.0	68	68/68/71
39	Cr. Limest Strat #3	6.0	2.9	2.49	1.5	73/73	74/74/75
40	Cr. Limest Strat #4	43.6/34.9/38.6	3.9	2.45	21.1	46/46	53/55/54
41	Cr. Limestone	9.6/9.6/10.8	3.6	2.40	1.9	67/65	76/74
3	Cr. Sandstone	13.3	2.6	2.49	3.9	68/80/78	68/68/68
5	Cr. Sandstone	65.8/64.1/60.6	3.9	2.26	3.1	69/71/67	59/60/63
6	Cr. Sandstone	18.5	-	-	3.0	-	68 / 65
7	Cr. Sandstone	31.6/24.9/31.4	5.5	2.30	23.7	31/29	19/15/26
8	Cr. Sandstone	14.2/20.0	2.9	2.48	3.0	87/66/56	73/74/74
10	Cr. Sandstone	6.1	3.2	2.25	1.9	77/77	71/70/67
12	Cr. Sandstone	67.1	5.1	2.32	13.8	37/21	26/24/26
13	Cr. Sandstone	47.7/45.4	3.3	2.31	0.8	77/63	74/72/71
18	Cr. Sandstone	4.9/2.6/2.8/1.4	2.3	2.49	1.4	82/88	82 / 78
19	Cr. Sandstone	8.5	1.3	2.58	2.8	79	76/78/80
27	Cr. Sandstone	43.9	3.7	2.24	-	72	43/46/43
31	Cr. Sandstone	2.5	1.2	2.58	1.1	81/80	78/73/73
9	Cr. Flint Gravel	1.8	0.7	2.59	0.7	94/78	87/87/85
15	Cr. Gravel	9.1/8.9/9.3	1.0	2.57	2.1	78/78	68/76/73
16	Pea Gravel	7.3/7.7/10.1	2.1	2.59	6.7	75	65/69/71
21	Pea Gravel	5.2	1.4	2.61	4.1	80/74	72/73/73
22	Gravel	5.9	1.6	2.60	9.2	53	-
23	Gravel	2.4	1.2	2.63	5.2	73/64	-
24	Pea Gravel	6.8	2.2	2.60	6.7	80/74	70/70/68
25	Gravel	2.6/2.7/1.4	1.4	2.63	4.5	70/67	71/76/73
32	Cr. Silic Gravel	3.7	0.7	2.65	1.9	73/74	-
33	Cr. Silic Gravel	8.6	1.0	2.61	5.2	76/78	71/74/78
34	Cr. Silic Gravel	4.7	1.2	2.60	2.0	82/81	82/85/85
35	Cr. Silic Gravel	1.3	0.8	2.57	0.7	96/96	96/96/96
36	Cr. Silic Gravel	2.9	0.5	2.67	1.4	74/72	-
4	Lightweight	-	4.8	1.55	3.4	90	-
11	Lightweight	-	10.1	1.39	2.4	96	90/85/80

(Continued)

TABLE 5.1. (Continued)

Agg No	Aggregate Type	Texas Degradation - No 8 (% Loss)	- No 10 (% Loss)	- No 16 (% Loss)	- No 200 (% Loss)	Sed (in.)	Los Angeles (% Loss)	PV
1	Cr. Limestone	12.7	11.2	9	6.5	12.2	30	39
2	Cr. Limestone	4.8	4.4	3.6	2.5	4.1	21	28
14	Cr. Limestone	7.3	6.2	5	3.8	6.1	27	29
17	Cr. Limestone	13.9	11.4	8.7	4.8	8.4	28	41
20	Cr. Limestone	17	13.7	9.9	5.7	12.2	30	37
26	Cr. Limestone	7.5	7.2	6.6	5.5	7.5	21	42
28	Cr. Limestone	5	4.5	3.5	2.3	2	21	27
29	Cr. Limestone	9.4	9	8.3	6.3	7.1	31	36
30	Cr. Limestone	3.4	3.1	2.6	1.6	1.5	16	33
37	Cr. Limest Strat #1	7.1	6.8	6.3	5.3	8.6	-	-
38	Cr. Limest Strat #2	12.9	12.4	11.6	10	5.2	-	-
39	Cr. Limest Strat #3	8.3	5.4	4.9	3.9	3.8	-	-
40	Cr. Limest Strat #4	11.7	11.2	10.3	8.8	11.8	-	-
41	Cr. Limestone	8/10.3	7.6/9.5	6.7/8.3	4.9/5.9	4.6/5.4	31	36
3	Cr. Sandstone	7	6.5	5.2	3.8	6.3	26	47
5	Cr. Sandstone	9.6	8.6	7.1	3.1	4.5	28	-
6	Cr. Sandstone	-	-	-	-	-	26	47
7	Cr. Sandstone	16.2	14.1	11.1	5.7	12.4	-	-
8	Cr. Sandstone	13.2/14.2	11.9/12.8	9.9/10.5	5.8/6.1	9/10.5	26	47
10	Cr. Sandstone	13.4	10.2	7	3.9	3	26	46
12	Cr. Sandstone	16	15	13.5	8.4	12.9	29	45
13	Cr. Sandstone	7.7	6.8	5.6	2.6	4	25	43
18	Cr. Sandstone	7.1	6.2	4.6	2	1.9	27	36
19	Cr. Sandstone	13.8	12	9.3	2.7	1.8	29	39
27	Cr. Sandstone	12.4	10.9	8.7	2.7	3.1	-	-
31	Cr. Sandstone	4.1	3.9	3.6	2.1	4.4	25	41
9	Cr. Flint Gravel	5.3/5.8	4.6/5.0	3.4/3.7	1.8/2.1	1.4/1.6	20	26
15	Cr. Gravel	6.3	4.8	3.3	2	3.5	16	29
16	Pea Gravel	11.5	8.9	5.5	2.6	5.2	22	-
21	Pea Gravel	8.4	6.8	4.5	2.2	3.1	24	-
22	Gravel	7.9	7.4	6.5	4.5	10.5	25	-
23	Gravel	5.8	5.4	4.6	2.9	4.1	25	-
24	Pea Gravel	10.8	8.7	5.7	2.7	5.1	24	-
25	Gravel	6.2	5.7	4.8	2.9	3.8	22	-
32	Cr. Silic Gravel	4.7	4.4	3.8	2.7	2.3	26	33
33	Cr. Silic Gravel	8.5	7.8	6.5	2.3	2.4	31	30
34	Cr. Silic Gravel	7.9/7.2	7.1/6.6	5.7/5.4	2.0/2.1	1.7/1.6	23	34
35	Cr. Silic Gravel	2.9	2.7	2.2	1.1	0.7	19	34
36	Cr. Silic Gravel	4.5	4.2	3.7	2.5	2.4	22	27
4	Lightweight	11.4/11.7	10.3/10.3	8.1/8.1	4.1/3.9	0.9/0.9	12	43
11	Lightweight	9.9/10.4	8.2/8.6	5.8/6.1	3.1/3.2	1.1/1.2	26	48

(Continued)

TABLE 5.1. (Continued)

Agg No.	Aggregate Type	Gradation (Cumulative Percentage Retained)					
		1 in.	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8
1	Cr. Limestone	-	-	-	11.8	83.9	98.4
2	Cr. Limestone	-	-	2.3	37.8	98.9	99.5
14	Cr. Limestone	-	-	-	5.3	65.9	93.5
17	Cr. Limestone		-	-	7.1	60.5	89.5
20	Cr. Limestone	-	-	-	3.7	54.2	89.6
26	Cr. Limestone	-	-	39.2	94.9	99.3	99.6
28	Cr. Limestone	-	-	0.9	32.4	96.7	99.6
29	Cr. Limestone	-	-	23.5	76.5	94.9	98.2
30	Cr. Limestone	-	-	41.8	87.2	99.5	99.6
37	Cr. Limest Strat # 1	-	0.8	28.0	91.9	99.6	99.6
38	Cr. Limest Strat # 2	-	1.6	26.4	83.9	98.2	98.3
39	Cr. Limest Strat # 3	-	0.4	31.6	91.6	99.2	99.6
40	Cr. Limest Strat # 4	-	1.6	28.7	91.5	99.4	99.4
41	Cr. Limestone	-	-	20.6	58.7	97.8	98.3
3	Cr. Sandstone	-	-	-	5.1	82.4	96.8
5	Cr. Sandstone	-	-	-	3.6	80.9	97.7
6	Cr. Sandstone	-	-	-	4.7	78.6	97.2
7	Cr. Sandstone	-	5.7	38.1	54.1	72.6	82
8	Cr. Sandstone	-	-	1.2	20.3	96.0	98.9
10	Cr. Sandstone	-	-	0.4	10.1	64.4	95.3
12	Cr. Sandstone	-	-	0.9	23.6	93.2	96.1
13	Cr. Sandstone	-	-	-	11.3	86.5	98.0
18	Cr. Sandstone	-	-	36.7	89.9	99.5	99.6
19	Cr. Sandstone	-	-	-	7.3	73.5	94.0
27	Cr. Sandstone	-	-	30.8	50.0	72.5	81.6
31	Cr. Sandstone	-	-	44.4	90.2	99.2	99.3
9	Cr. Flint Gravel	-	-	0.5	28.6	94.8	97.9
15	Cr. Gravel	-	-	0.9	18.2	66.0	85.0
16	Pea Gravel	-	-	-	1.3	59.4	98.2
21	Pea Gravel	-	-	-	0.8	84.7	99.8
22	Gravel	9.2	24.6	65	90.0	99.2	99.7
23	Gravel	1.2	15.9	71.0	96.2	99.8	99.8
24	Pea Gravel	-	-	-	-	63.7	98.2
25	Gravel	-	4.3	50.5	86.9	99.4	99.8
32	Cr. Silic Gravel	-	-	44.0	94.9	99.6	99.7
33	Cr. Silic Gravel	-	-	0.3	34.3	98.2	99.6
34	Cr. Silic Gravel	-	-	-	33.5	98.2	99.2
35	Cr. Silic Gravel	-	-	37.7	89.7	99.7	99.7
36	Cr. Silic Gravel	-	-	34.9	93.7	99.2	99.5
4	Lightweight	-	-	1.7	38.5	97.3	97.8
11	Lightweight	-	-	13	34.5	82.8	97.1

METHODOLOGY OF STATISTICAL ANALYSIS

The purpose of the statistical analysis was to find which test or tests best correlate with the 4–cycle magnesium sulfate soundness test and develop models describing their relationship. In more statistical terms, the effort was to find the tests that best describe the variations in the soundness test.

The methodology for the analysis was carried out in the following steps:

(1) scatter plots (Ref 5),

(2) correlation analysis (Ref 6),

(3) transformations of variables (Ref 5),
(4) linear regression analysis (Refs 6 and 27),
(5) analysis of covariance (Ref 13),
(6) multivariate linear regression and covariance (Refs 6 and 13),
(7) selection of the best models (Refs 6 and 25), and
(8) comparison between actual and predicted soundness values and tests for linearity for the best models (Ref 25).

Scatter Plots

The first step of the analysis was to visualize the relationship of the independent (also called the regressor) variables with the dependent (or response) variable. Independent variables are all the tests performed to be used in correlation and prediction of the 4–cycle soundness test. The dependent variable is the test we want to predict which is the soundness test.

Scatter plots are very useful because they assist with further analysis in that they show visually the relationship between two variables, the direction of the relationship (positive or negative), and the type of relationship (linear or curvilinear). The plots can then be used to decide which variables should be included in models and what type of data transformations should be applied. Additionally, they can assist with detection of multicollinearity problems in cases where independent variables are strongly linearly interrelated. When the data are represented by a straight line then simple linear regression is used to describe their correlation. In the case of curvilinear relationship the data should be linearized by an appropriate transformation or nonlinear regression should be applied. The SAS software on the microcomputer can perform to this date only linear regression and therefore, data were transformed when necessary.

Plots of the soundness test values versus the other laboratory tests are shown in Figs 5.1 through 5.11. The different aggregate groups (sandstone, limestone and siliceous gravel) are represented with different symbols to show whether different trends exist among the groups. The following is a discussion on the plots:

Soundness vs. Absorption (Fig 5.1). Several research studies have indicated that the 4–cycle test is more a measure of absorption of an aggregate rather than an indication of durability. The general trend of the aggregates tested showed higher soundness losses with increasing absorption. All gravels had absorption less than 2.2 percent and soundness less than 10 percent. Limestones and sandstones were scattered throughout the plot. All aggregates with absorption less than 2 percent had soundness less than 10 percent. At higher absorptions soundness varied by as much as 40 percent. The plot indicates that some type of exponential transformation might be appropriate.

Soundness vs. Specific Gravity (Fig 5.2). In general the soundness loss of aggregates decreases as the specific gravity increases. This indicates a negative relationship. All aggregates with specific gravities higher than 2.55 had soundness values less than 10 percent. As the specific gravity decreases, the soundness values obtain a wider range; aggregates with 2.25 specific gravity had soundness losses ranging between 5 and 65 percent. All siliceous gravels had soundness losses less than 10 percent and specific gravities higher than 2.55. Sandstones and limestones obtained all the range of soundness and specific gravity values. Despite deviation from linearity no trends were indicated as to the necessity and type of transformation.

Soundness vs. Freeze-Thaw (Fig 5.3). The soundness test, as stated in the ASTM procedure, simulates the degradation of aggregates due to the expansion of water in pore spaces on freezing. Therefore, a freeze-thaw test would be expected to be closely related to the soundness test. The overall plot showed a very poor relationship. Soundness values varied by as much as 40 percent even at extremely low

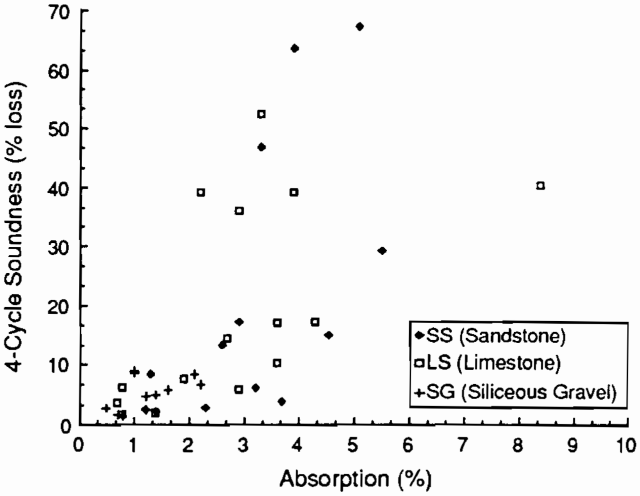

Fig 5.1. *4-cycle soundness vs. absorption.*

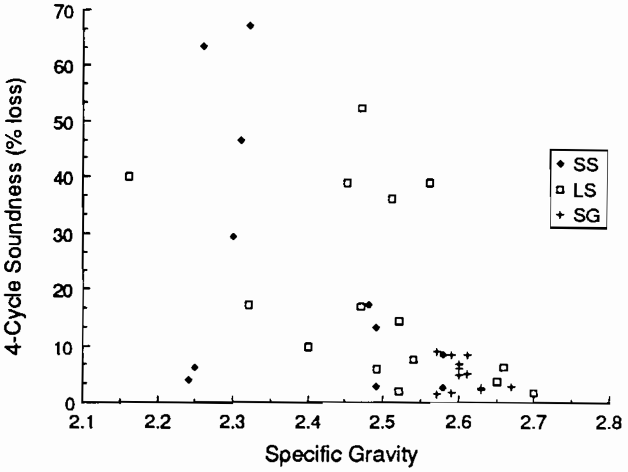

Fig 5.2. *4-cycle soundness vs. specific gravity.*

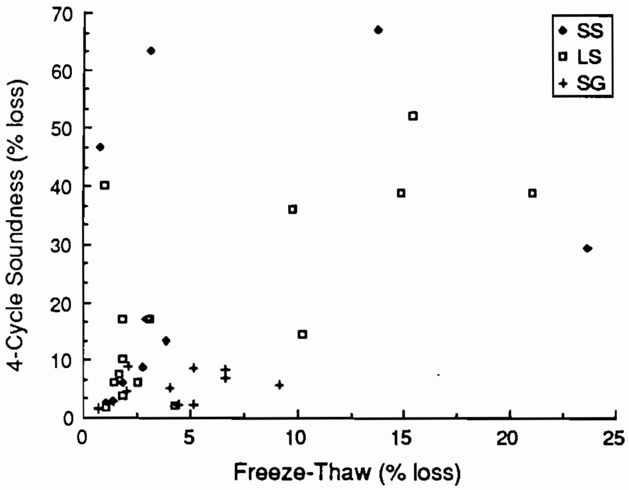

Fig 5.3. *4-cycle soundness vs. freeze-thaw.*

freeze-thaw losses. In general, soundness increased with increased freeze-thaw. All gravels had less than 10 percent soundness losses. All aggregates with more than 13 percent freeze-thaw loss had soundness values greater than 30. A high proportion of the low quality materials as determined by the soundness test, were depicted as such by the freeze-thaw test. However, other bad materials did not degrade by the freezing and thawing action and were shown as very durable under this test. Three other aggregates with less than 3 percent freeze-thaw loss had soundness values greater than 63 percent. On the contrary, there weren't any aggregates with high freeze-thaw losses that had low soundness.

Soundness vs. Los Angeles Abrasion (Fig 5.4). The scatter plot demonstrated that there is no relationship between the two tests. The 27 aggregates that had soundness less than 20 percent had abrasion loss greater than soundness which ranged between 16 and 31 percent. The five aggregates with soundness greater than 30 had abrasion ranging from 25 to 30 percent. Aggregates between 25 and 30 abrasion had as low as 3 percent and as high as 65 percent soundness. The above portray nothing in common between the tests. In terms of specification values, five aggregates failed the soundness test by far exceeding the 30 percent limit but none failed the abrasion test of 35 percent limit. If the abrasion limit is dropped to 30 then five aggregates won't pass the test, three of which have soundness less than 16.

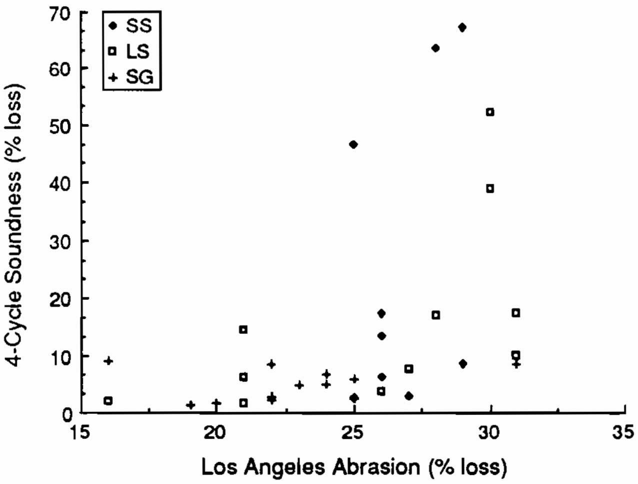

Fig 5.4. *4-cycle soundness vs. Los Angeles abrasion.*

Soundness vs. Aggregate Durability Index, Procedure A (Fig 5.5). The distribution of points in this plot indicated increasing soundness loss with decreasing durability index. The trend is more distinct than with other tests. All the aggregates that failed soundness had index less than 70. But seven aggregates with soundness less than 20 also had index less than 70. As previously, the test failed to distinguish good and bad aggregates (as set by a soundness limit of 30 percent) at low index numbers. All the low soundness aggregates had durabilities higher than 72. Into this category fell all the gravels. Limestones and sandstones were scattered in the plot.

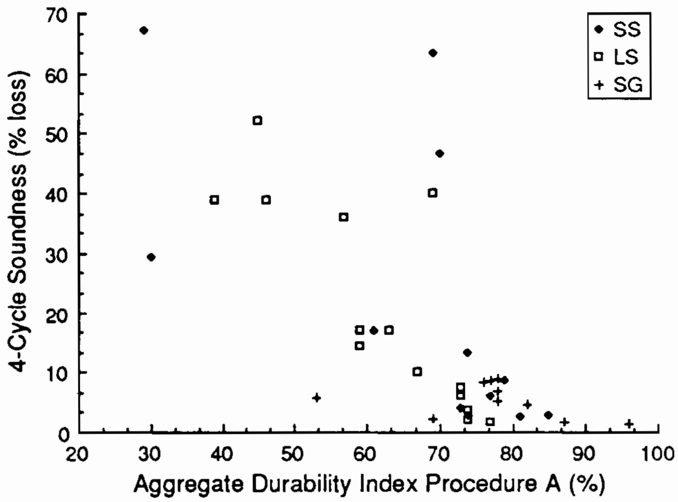

Fig 5.5. *4-cycle soundness vs. aggregate durability index procedure A.*

The two tests measure different properties of aggregates but their plot suggests that the relative amount of production of clay like fines in the durability test has some relation with breakage from the salt in the soundness test. The plot indicated that some type of exponential function could increase the linear dependency of the two tests, better than the arithmetic function.

Soundness vs. Aggregate Durability Index, Procedure C (Fig 5.6). Approximately the same relationship as with procedure A of the durability test was noted with the plot of soundness and procedure C. Procedures A and C are parts of the same test and they are used interchangeably according to the size distribution of aggregates. The problem is that they require different and expensive equipment to perform.

One scope of the laboratory study was to investigate whether one of the two procedures was adequate to perform the test, thus reducing its cost. For this purpose aggregates were tested under both procedures irrespective of the ASTM requirements. Minor changes were applied to the ASTM procedure to make testing possible.

The scatter plots of procedures A and C with soundness suggested that one procedure might be sufficient should the durability test be specified as a replacement for the soundness test.

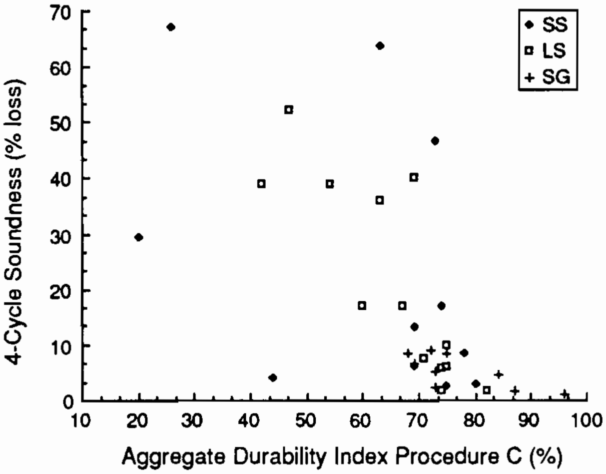

Fig 5.6. *4-cycle soundness vs. aggregate durability index procedure C.*

Soundness vs. Texas Degradation (Minus No.8 to minus No. 200) (Figs 5.7 - Fig 5.10). The figures indicated that the soundness of aggregates could be related to the reduction in size when aggregates are subjected to mechanical breaking in the ball machine. However, as with all the tests examined thus far, the test seems inadequate to predict the variation in soundness at values greater than 30.

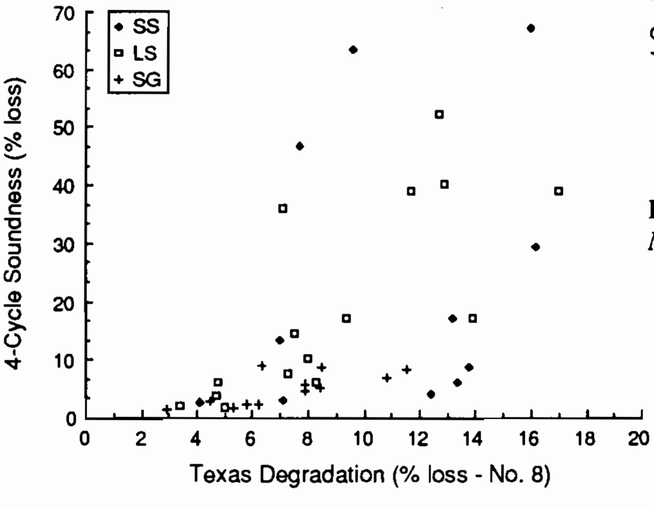

Fig 5.7. *4-cycle soundness vs. Texas degradation (minus No. 8).*

All degradation losses (minus No 8 to minus No 200) had similar distribution of points in the plots with the soundness test. Which loss best correlates with the soundness test will be determined by correlation and regression analyses. A logarithmic function seems the least appropriate for linearizing the plots.

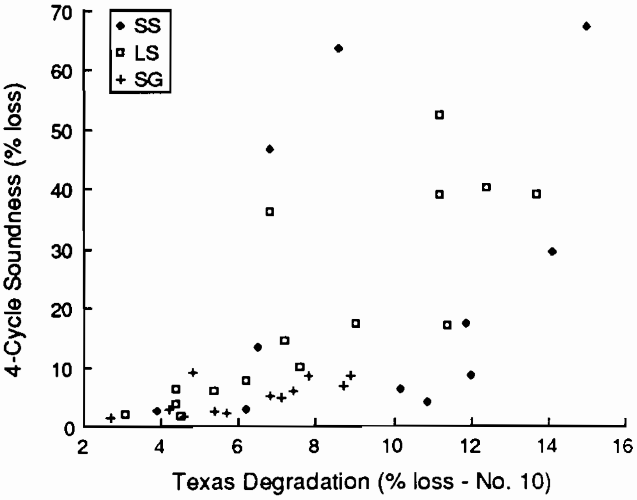

Fig 5.8. *4-cycle soundness vs. Texas degradation (minus No. 10).*

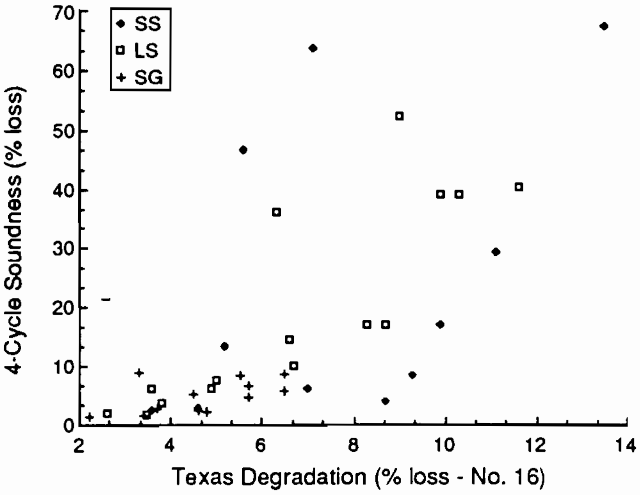

Fig 5.9. *4-cycle soundness vs. Texas degradation (minus No. 16).*

Soundness vs. Texas Degradation Sediment (Fig 5.11). The sedimentation part of the degradation test gave a scatter plot similar to the weight loss in the same test. Changes in soundness values greater than 30 were not accurately predicted with the sediment test as well.

General Comments on Scatter Plots. It is clear from the above discussion that none of the tests performed in the laboratory could accurately predict the soundness test. A major problem occurs at high soundness values where these tests have been proved to be in-

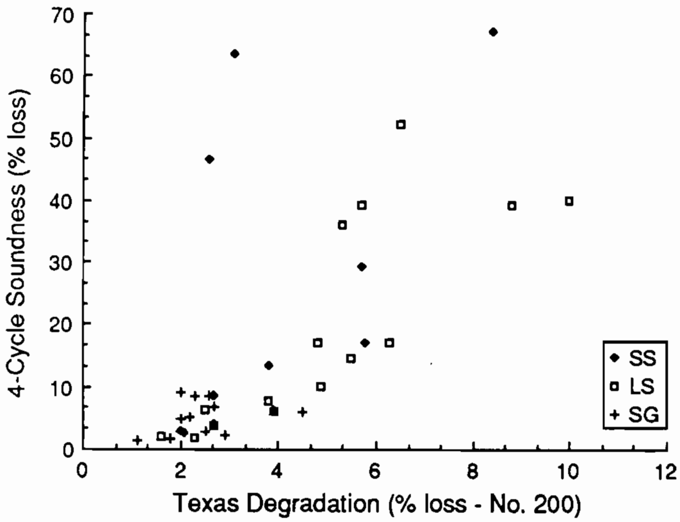

Fig 5.10. ***4-cycle soundness vs. Texas degradation (minus No. 200).***

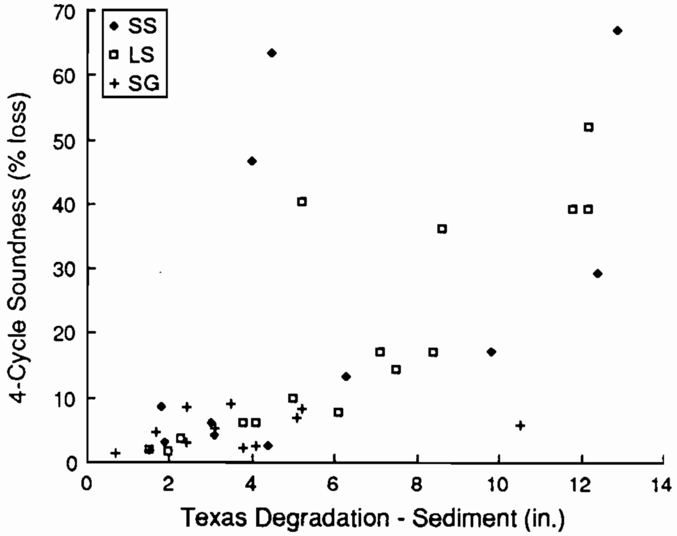

Fig 5.11. ***4-cycle soundness vs. Texas degradation (sediment).***

sensitive to changes in soundness. In all the plots the relationship was more of a nonlinear type, especially at high soundness. At low soundness values all tests except freeze-thaw indicated some correlation with the soundness test. At high test values (low with the durability index and specific gravity) the soundness loss of aggregates varied by as much as 40 to 50 percent, indicating the inability of the tests to depict the soundness variation at high soundness values. Only with siliceous gravels did the tests have a good correlation with the soundness test. With limestones and sandstones the relationship was weaker. Nine aggregates had soundness losses exceeding 29, meaning they were inferior aggregates. Of those six were also found inferior aggregates in most of the other tests. The other three, two sandstones and one limestone, were tested as good aggregates in the other tests. The soundness test was more severe than any other test. If a specification limit was set to each test, such that it would exclude from use all agrregates with soundness higher than 30, then five to ten aggregates would also be considered inappropriate for use.

The above suggest two solutions: (1) transform the data to linearize the relationships and (2) introduce more than one independent variable in a regression model to account for the variation in soundness not accounted for by the one variable.

Correlation Analysis

In order to facilitate transformation of data and multiple regression, a correlation analysis among the tests was carried out. The correlation coefficient (r) is a measure of the way in which two tests co-vary and it yields values between +1 and -1. If two variables increase together, r is positive. If one variable increases while the other decreases, r is negative. The correlation coefficient is also an indication of linearity; values near +1 or -1 indicate strong correlation as well as strong linear relationship between variables. This means that a non-linear relationship will have a low r value, which may be misleading if a scatter plot of two variables is not drawn and the relationship examined.

The scatter plots between the tests indicated a high variance at high soundness values and low variance at low values. Equal dependent variable variances at the different independent variable levels is one of the assumptions in regression analysis. Should this analysis be attempted between tests the assumption will be clearly violated.

Table 5.2 shows the correlation matrix between the laboratory tests. The top value represents the correlation coefficient, the middle the significance of the correlation, and the bottom the number of observations in each relationship.

The highest correlation of the soundness test was with Texas degradation minus No. 16 loss (0.72) and the lowest with Los Angeles abrasion (0.46). Other interesting correlations were between procedures A and C in the durability index (0.91), between Texas degradation sediment and procedure A (0.90), between Texas degradation minus No. 8 and minus No. 10 (0.99), and minus No. 10 and minus No. 16 (0.97), and between procedure A and freeze-thaw (0.85). These correlations, which are much higher than any correlation of soundness with other tests, indicate a strong relationship among Texas degradation, durability index, and freeze-thaw tests.

The specific gravity and absorption tests are highly correlated (0.90) and therefore can not be used simultaneously in prediction models. Their use would probably cause collinearity problems.

TABLE 5.2. *CORRELATION MATRIX AMONG LABORATORY TESTS*

	MSS	ABS	SG	FT	LA	ADIA
MSS	1.00000(1)	0.69420	-0.74408	0.50510	0.46320	-0.63741
	0.0000(2)	0.0001	0.0001	0.0014	0.0076	0.0001
	38(3)	37	37	37	32	37
ABS		1.00000	-0.90023	0.36091	0.58209	-0.54275
		0.0000	0.0001	0.0306	0.0006	0.0005
		37	37	3	31	37
SG			1.00000	-0.21818	-0.46029	0.38218
			0.0000	0.2011	0.0092	0.0196
			37	36	31	37
FT				1.00000	0.29164	-0.84570
				0.0000	0.1053	0.0001
				37	32	36
LA					1.00000	-0.46621
					0.0000	0.0082
					32	31
ADIA						1.00000
						0.0000
						37

	ADIC	TDT8	TDT10	TDT16	TDT200	TDTSED
MSS	-0.69677	0.62767	0.67688	0.72056	0.61825	0.59402
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	33	37	37	37	37	37
ABS	-0.58119	0.64600	0.70365	0.78200	0.80906	0.53006
	0.0005	0.0001	0.0001	0.0001	0.0001	0.0007
	32	37	37	37	37	37
SG	0.50419	-0.52088	-0.57716	-0.65268	-0.57881	-0.34522
	0.0033	0.0010	0.0002	0.0001	0.0002	0.0364
	32	37	37	37	37	37
FT	-0.84617	0.59720	0.61842	0.60249	0.56153	0.81284
	0.0001	0.0001	0.0001	0.0001	0.0004	0.0001
	32	36	36	36	36	36
LA	-0.49179	0.62020	0.67106	0.70696	0.59008	0.48158
	0.0092	0.0002	0.0001	0.0001	0.0005	0.0061
	27	31	31	31	31	31
ADIA	0.91185	-0.65305	-0.68914	-0.72538	-0.73631	-0.89932
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	32	37	37	37	37	37

(1) Correlation Coefficient

(2) Significance of Correlation

(3) Number of Observations

(continued)

Transformation of Variables

Transformation of variables helped reduce the difference in variance between high and low soundness values and increase the correlation coefficients between the variables. The scatter plots suggested logarithmic or exponential transformations.

Based on the results from scatter plots and correlation analyses of untransformed data, several transformations were performed to strengthen linearity and correlations. Transformations included 1/x, 1/y, ln x, ln y, x^2 and y^2, $x^{1/2}$ and $y^{1/2}$, where x and y are the independent and dependent variables, respectively. The best correlations were obtained when the independent and dependent variables were transformed to their natural logarithm. For simplicity, only those results are shown. Table 5.3 shows the correlation matrix of the natural logarithm of soundness with the other tests and Table 5.4 the correlation matrix of the natural logarithm of all the tests. In some cases there was an increase in correlation by as much as 10 points. The highest correlations were obtained between the natural logarithm of soundness, and the natural logarithm of absorption and Texas degradation loss No. 16 (0.80 and 0.82, respectively). Scatter plots of the two relationships are shown in Figs 5.12 and 5.13. A comparison with plots of untransformed data shows increased linearity and approximately equal variance in the distribution of soundness values across each value of the independent variables.

Linear Regression Analysis

Linear regression analysis provides a simple technique for establishing a functional linear relationship between the dependent variable y and one or more independent variables. This relationship in expressed in an equation with the form

$$y = \alpha_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_p x_p + e$$

where

y = dependent variable,
$x_1, x_2, \ldots, x_p$ = independent variables,
$\alpha_0, \beta_1, \ldots, \beta_p$ = regression coefficients, and
e = error term.

When this equation contains one independent variable it is called a bivariate or simple linear regression equation and when more, a multiple regression equation. The advantage with simple regression as applied to this study, is that only one laboratory test is needed to estimate the corresponding soundness test value. The disadvantage is that only a part of the variation in soundness may be explained by the variation in the one single test. Should this be the case other laboratory tests will be needed in the model to account for the additional variation in soundness. The multiple regression thus offers a stronger relationship but requires additional tests which add to the time and cost of performing the tests.

Simple Linear Regression. All the laboratory tests were regressed with the soundness test and the models describing their relationship were obtained. Three important tests were performed to evaluate the models.

(1) The "F" test for the overall significance of the model. Alpha level used was 0.05.
(2) The "t" test for the significance of the independent variables. Alpha level used was 0.05.
(3) The R^2 (coefficient of determination). This takes values from 0 to 1 and it is a measure of the proportion of the total variation in y that is explained by x. The higher the R^2, the stronger the model is and the more the variation in y is explained by x.

All models presented herein had significant "F" and "t" tests. All others have not been included in this report since they have only a limited importance.

TABLE 5.2. (Continued)

	ADIC	TDT8	TDT10	TDT16	TDT200	TDTSED
ADIC	1.00000	-0.76263	-0.77020	-0.75075	-0.60360	-0.82364
	0.0000	0.0001	0.0001	0.0001	0.0003	0.0001
	33	32	32	32	32	32
TDT8		1.00000	0.98189	0.91460	0.64141	0.68150
		0.0000	0.0001	0.0001	0.0001	0.0001
		37	37	37	37	37
TDT10			1.00000	0.96784	0.72076	0.71069
			0.0000	0.0001	0.0001	0.0001
			37	37	37	37
TDT16				1.00000	0.83193	0.73108
				0.0000	0.0001	0.0001
				37	37	37
TDT200					1.00000	0.78056
					0.0000	0.0001
					37	37
TDTSED						1.00000
						0.0000

TABLE 5.3. *CORRELATION MATRIX BETWEEN TRANSFORMED SOUNDNESS RESULTS AND LABORATORY TESTS*

	ln MSS		ln MSS
ln MSS	1.00000 (1)	ADIC	-0.72316
	0.00000 (2)		0.00010
	38 (3)		33
ABS	0.74639	TDT8	0.74724
	0.00010		0.00010
	37		37
SG	-0.74183	TDT10	0.78206
	0.00010		0.00010
	37		37
FT	0.52408	TDT16	0.80283
	0.00090		0.00010
	37		37
LA	0.58412	TDT200	0.69857
	0.00050		0.00010
	32		32
ADIA	-0.66433	TDTSED	0.68345
	0.00010		0.00010
	37		37

(1) Correlation Coefficient
(2) Significance of Correlation
(3) Number of Observation

TABLE 5.4. *CORRELATION MATRIX AMONG TRANSFORMED RESULTS OF LABORATORY TESTS*

	ln MSS	ln ABS	ln SG	ln FT	ln LA	ln ADIA
ln MSS	1.00000(1)	0.79894	-0.73749	0.49762	0.56570	-0.63024
	0.00000(2)	0.00010	0.00010	0.00170	0.00070	0.00010
	38(3)	37	37	37	32	37
ln ABS		1.00000	-0.85915	0.38070	0.55413	-0.54727
		0.00000	0.00010	0.02200	0.00120	0.00050
		37	37	36	31	37
ln SG			1.00000	-0.06753	-0.42887	0.37406
			0.00000	0.69550	0.01610	0.02260
			37	36	31	37
ln FT				1.00000	0.27137	-0.76331
				0.00000	0.13300	0.00010
				37	32	36
ln LA					1.00000	-0.42743
					0.00000	0.01650
					32	31
ln ADIA						1.00000
						0.00000
						37

	ln ADIC	ln TDT8	ln TDT10	ln TDT16	ln TDT200	ln TDTSED
ln MSS	-0.62881	0.77496	0.80135	0.82498	0.73544	0.71493
	0.00010	0.00010	0.00010	0.00010	0.00010	0.00010
	33	37	37	37	37	37
ln ABS	-0.57759	0.72673	0.74693	0.78722	0.76371	0.66638
	0.00050	0.00010	0.00010	0.00010	0.00010	0.00010
	32	37	37	37	37	37
ln SG	0.47561	-0.52151	-0.55920	-0.62048	-0.53336	-0.36042
	0.00590	0.00090	0.00030	0.00010	0.00070	0.02840
	32	37	37	37	37	37
ln FT	-0.73918	0.55650	0.57882	0.56077	0.53599	0.70243
	0.00010	0.00040	0.00020	0.00040	0.00080	0.00010
	32	36	36	36	36	36
ln LA	-0.42458	0.65216	0.70829	0.76441	0.63398	0.50030
	0.02730	0.00010	0.00010	0.00010	0.00010	0.00420
	27	31	31	31	31	31
ln ADIA	0.92052	-0.60156	-0.63724	-0.67771	-0.73034	-0.77636
	0.00010	0.00010	0.00010	0.00010	0.00010	0.00010
	32	37	37	37	37	37

(1) Correlation Coefficient

(2) Significance of Correlation

(3) Number of Observations

(Continued)

The models developed from the bivariate analysis between soundness other laboratory tests are shown in Table 5.5. The R^2 varied between 0.21 (Los Angeles abrasion) and 0.55 (specific gravity). These values are relatively low meaning that no single test can explain adequately the variation in the soundness test.

Simple Linear Regression with Transformed Data. As seen from the scatter plots the low correlation was partly due to nonlinear relationships. Transformed variables were, therefore, regressed again in a bivariate analysis and the new models are shown in Tables 5.6 and 5.7. Table 5.6 shows the regression equation of the natural logarithm of soundness with the other tests. The R^2 increased considerably and varied between 0.27 and 0.64. Additional analysis was performed by transforming all the test results to their natural logarithm. Models which resulted in increased R^2 are shown in Table 5.7. Texas degradation losses minus No. 16 and minus No. 10 and absorption gave the best prediction of the soundness test with R^2 0.68, 0.64, and 0.64, respectively. These values are quite high, meaning that a large part of the variation in soundness is explained by these tests. Figures 5.14 and 5.15 show the straight lines representing the models which describe the relationship of soundness with absorptionand Texas degradation loss minus No. 16 for the transformed data.

Analysis of Covariance

The analysis of covariance is a statistical technique that allows investigation of the possibility of developing a stronger regression model if additional information is available about the data which can not be used in a pure regression analysis. It is a combination of regression analysis with an analysis of variance. Covariance is used when the response variable y in addition to being linearly related to another variable x (the covariate), is also affected by treatments. Treatments are groups of data with similar characteristics. In this case, the aggregate categories (limestone, sandstone, and siliceous gravel) can be used as treatments to evaluate if they explain additional variation in soundness. The result will be three different equations combined in one model meaning that the different aggregate groups respond differently to the same test. These equations will have different intercepts but the same slope. The model for this analysis is customarily called the additive model.

The combination of treatments and a covariate can also be used to describe the variation due to significant interaction effects. Interaction is a measure of parallelism of two or more equations. If interaction is significant then models with different slopes for the different groups could be developed.

TABLE 5.4. ***CORRELATION MATRIX AMONG TRANSFORMED RESULTS OF LABORATORY TESTS***

	ln ADIC	**ln TDT8**	**ln TDT10**	**ln TDT16**	**ln TDT200**	**ln TDTSED**
ln ADIC	1.00000 0.00000 33	-0.64034 0.00010 32	-0.65449 0.00010 32	-0.65379 0.00010 32	-0.57820 0.00050 32	-0.67483 0.00010 32
ln TDT8		1.00000 0.00000 37	0.98348 0.00010 37	0.93191 0.00010 37	0.69971 0.00010 37	0.66894 0.00010 37
ln TDT10			1.00000 0.00000 37	0.97255 0.00010 37	0.75125 0.00010 37	0.69258 0.00010 37
ln TDT16				1.00000 0.00000 37	0.83914 0.00010 37	0.72510 0.00010 37
ln TDT200					1.00000 0.00000 37	0.86058 0.00010 37
ln TDTSED						1.00000 0.00000 37

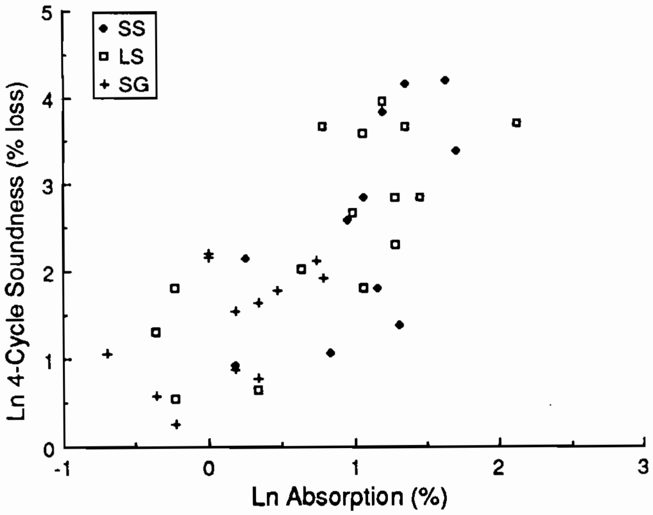

Fig 5.12. ***Ln 4-cycle soundness vs. Ln absorption.***

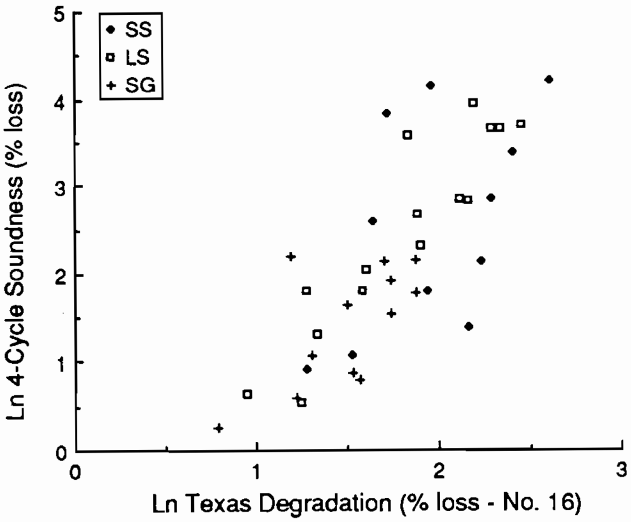

Fig 5.13. ***Ln 4-cycle soundness vs. Ln Texas degradation (minus No. 16).***

TABLE 5.5. *LINEAR REGRESSION MODELS BETWEEN SOUNDNESS AND LABORATORY TESTS*

Model	R^2
MSS = 8.1276 +1.6162 (FT)	0.255
MSS = 36.5242 + 2.0583 (LA)	0.214
MSS = 72.3672 - 0.4035 (ADIA)	0.406
MSS = 75.5042 - 0.2785 (ADIC)	0.486
MSS = -10.3351 + 3.1453 (TDT8)	0.394
MSS = -12.9587 + 3.8993 (TDT10)	0.458
MSS = -13.7645 + 4.8973 (TDT16)	0.519
MSS = 3.5964 + 5.4445 (TDT200)	0.382
MSS = 0.3954 + 3.1293 (TDTSED)	0.353
MSS = 280.97 - 105.137 (SG)	0.554
MSS = -1.9157 + 7.9333 (ABS)	0.482

TABLE 5.6. *LINEAR REGRESSION MODELS BETWEEN TRANSFORMED SOUNDNESS AND LABORATORY TESTS*

Model	R^2
ln (MSS) = 1.6655 + 0.1045 (FT)	0.274
ln (MSS) = -1.8889 + 0.1590 (LA)	0.341
ln (MSS) = 5.7819 - 0.0260 (ADIA)	0.441
ln (MSS) = 5.9294 - 0.0176 (ADIC)	0.523
ln (MSS) = 0.2042 + 0.2313 (TDT8)	0.558
ln (MSS) = 0.0822 + 0.2776 (TDT10)	0.609
ln (MSS) = 0.0991 + 0.3370 (TDT16)	0.644
ln (MSS) = 0.7784 + 0.3799 (TDT200)	0.488
ln (MSS) = 1.0352 + 0.224 (TDTSED)	0.467
ln (MSS) = 18.4728 - 6.4736 (SG)	0.550
ln (MSS) = 0.9611 + 0.5268 (ABS)	0.557

TABLE 5.7. *LINEAR REGRESSION MODELS BETWEEN TRANSFORMED SOUNDNESS AND TRANSFORMED LABORATORY TESTS*

Model	R^2
ln (MSS) = -1.9668 + 2.0206 ln (TDT8)	0.601
ln (MSS) = -1.9689 + 2.1459 ln (TDT10)	0.642
ln (MSS) = -1.5826 + 2.1770 ln (TDT16)	0.681
ln (MSS) = 0.2358 + 1.6525 ln (TDT200)	0.541
ln (MSS) = 0.5448 + 1.1608 ln (TDTSED)	0.511
ln (MSS) = 1.3169 + 1.3735 ln (ABS)	0.638

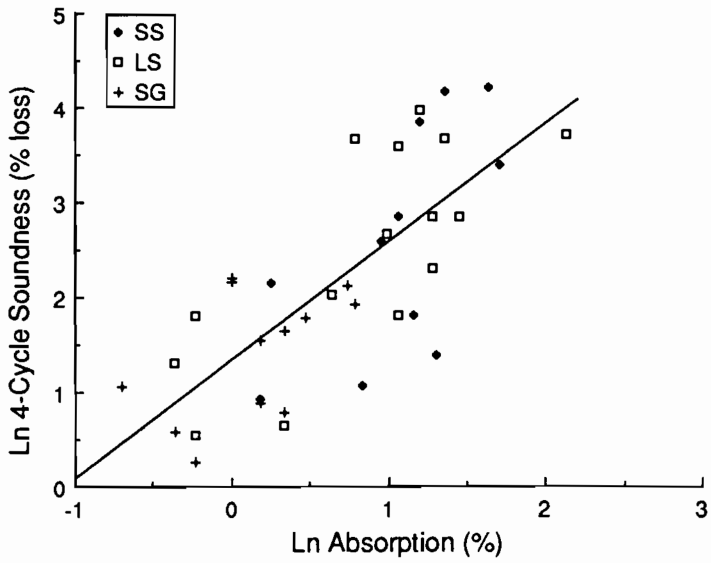

Fig 5.14. ***Linear regression relationship between soundness and absorption tests.***

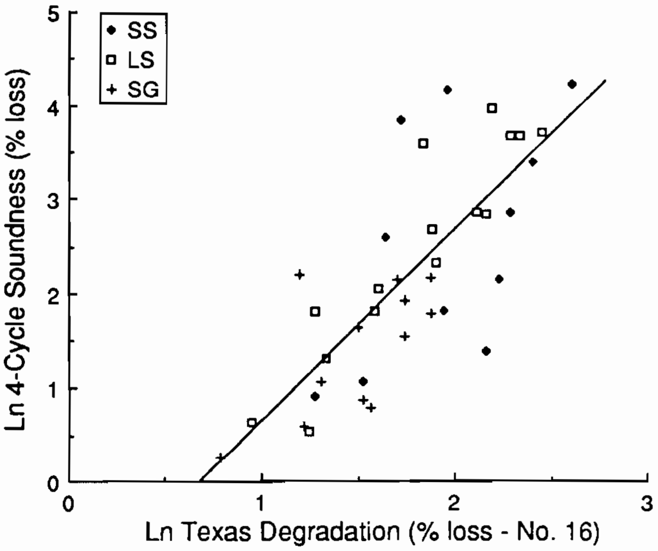

Fig 5.15. ***Linear regression relationship between soundness and Texas degradation (minus No. 16).***

The general equation due to both additive and interaction effects is

$$y = \underbrace{a + \beta X}_{(1)} + \underbrace{a_1A_1 + \dots + a_nA_n}_{(2)} + \underbrace{\beta_1A_1X + \dots + \beta_nA_nX}_{(3)}$$

where

(1) common parameters,
(2) additive effect,
(3) interaction effect,

a = common mean,
β = common slope,
X = covariate,
$a_1, \dots, a_n$ = deviation from common mean due to treatments $A_1, \dots, A_n$, and
$\beta_1, \dots, \beta_n$ = deviation from common slope due to treatments $A_1, \dots, A_n$.

The computer analysis was carried out using two SAS regression options: (1) stepwise with maximum R^2 and (2) forward selection. Stepwise regression allows introduction into the model of the independent variables one by one in a sequence that produces the highest increase in R^2. Each model then contains the combination of variables that give maximum R^2 with that number of independent variables. Forward selection introduces in the model the independent variables one by one in a sequence that produces the largest significance to the model.

The problem that arises with covariance models and in general with any models that contain more than one independent variables is multicollinearity. Multicollinearity could create misspecified models because of biased estimates of the regression parameters, R^2, and the significance of the parameters. It exists whenever independent variables are strongly interrelated. Indications of multicollinearity are: (1) correlation coefficients among independent variables more than 0.5 to 0.6, (2) opposite signs of correlation coefficient between independent and dependent variables and the parameters in regression models, (3) large changes in the parameters when a variable is added in the model, (4) instability in the significance of variables when a variable is added in the model, and (5) standardized estimates larger than one. All the models developed were checked for multicollinearity and collinear variables were removed from the models.

Covariance analysis on the available data was performed by considering the three aggregate categories as treatments and each test as the covariate. First the additive effects were examined and the resulting models are shown in Table 5.8. The models shown are only the ones that had statistically significant additive effects. The parameters SS and LS stand for sandstone and limestone, respectively. When a sandstone aggregate is tested and an equation contains the SS and/or LS parameters, one should be substituted for SS and zero for LS. For a limestone, one should be substituted for LS and zero for SS. If a gravel is tested, zero should substituted for both SS and LS. The physical meaning to this is that the different aggregates behave differently in each test and, as a result, a different model is used to

TABLE 5.8. ***LINEAR COVARIANCE MODELS WITH ONE COVARIATE***

(a) With Additive Effects

Model	R^2
ln (MSS) = 1.0611 + 1.2412 (SS) + 0.9337 (LS) + 0.0887 (FT)	0.481
ln (MSS) = 4.7407 + 1.0850 (SS) + 0.5604 (LS) -0.0220 (ADIA)	0.568
ln (MSS) = -1.8622 + 0.7717 (SS) + 0.7274 (LS) + 1.7385 ln (TDT8)	0.685
ln (MSS) = 0.0460 + 0.8153 (SS) + 1.6273 ln (TDT200)	0.640
ln (MSS) = 0.4205 + 0.7013 (SS) + 1.1163 ln (TDTSED)	0.583

(b) With Additive and Interaction Effects

Model	R^2
ln (MSS) = 0.9617 + 0.1017 (LA) + 0.0369 (LA)*(SS) + 0.0278 (LA)*(LS)	0.453
ln (MSS) = -1.5627 + 0.7628 (SS) + 1.6906 ln (TDT10) + 0.3709 ln (TDT10)*(LS)	0.718
ln (MSS) = 0.4782 + 1.1579 (SS) + 0.7917 ln (TDTSED) + 0.4442 ln (TDTSED)*(LS)	0.641

describe the relationship of the test with the soundness test.

Further analysis was carried out by considering simultaneous additive and interaction effects. The models generated are shown in Table 5.8. The best model (R^2 = 0.718) was obtained with Texas degradation minus No. 10 loss.

Transformation of variables and covariance techniques have improved the power of the models considerably. Starting with pure regression, R^2 ranged between 0.20 and 0.55. Transformations raised R^2 between 0.34 and 0.65 and covariance between 0.45 and 0.72. The soundness test was best predicted by the minus No. 10 loss in the Texas degradation test. Prediction is strong as R^2 was quite high.

TABLE 5.10. ***MULTIVARIATE LINEAR MODELS WHEN ABSORPTION IS ADDED***

(a) Regression Models

Model	R^2
ln (MSS) = 0.8198 + 0.0611 (FT) + 0.4382 (ABS)	0.633
ln (MSS) = 0.4687 + 0.0483 (LA) + 0.6429 (ABS)	0.660
ln (MSS) = 3.2602 - 0.0143 (ADIA) + 0.3860 (ABS)	0.652
ln (MSS) = 3.7726 - 0.0112 (ADIC) + 0.3216 (ABS)	0.663
ln (MSS) = -1.2028 + 1.3077 ln (TDT8) + 0.2961 (ABS)	0.702
ln (MSS) = -1.2640 + 1.4636 ln (TDT10) + 0.2604 (ABS)	0.713
ln (MSS) = -1.0698 + 1.6017 ln (TDT16) + 0.2046 (ABS)	0.717
ln (MSS) = 0.3998 + 0.8913 ln (TDT200) + 0.3128 (ABS)	0.623
ln (MSS) = 0.3493 + 0.7020 ln (TDTSED) + 0.3557 (ABS)	0.685

(b) Covariance Models

Model	R^2
ln (MSS) = 0.7983 + 0.6906 (SS) + 0.0912 (FT)*(LS) + 0.4172 (ABS)	0.704
ln (MSS) = 3.6391 - 0.0173 (ADIA) + 0.0042 (ADIA)*(SS)	0.700
ln (MSS) = 0.2014 + 0.6218 (SS) + 1.1182 ln (TDT200) + 0.2117 (ABS)	0.671
ln (MSS) = 0.3452 + 0.7601 (SS) + 0.5788 ln (TDTSED) + 0.2730 ln (TDTSED) *(LS) + 0.2730 (ABS)	0.734

Multivariate Linear Regression and Covariance

Up to this point one independent variable (bivariate analysis) and one covariate with treatments (covariance analysis) were considered to describe the best relationship of a single test with the soundness test. Previous correlation analysis has indicated that absorption and specific gravity can each be used (not simultaneously) in conjunction with other tests to predict the soundness test, without causing collinearity problems. Consequently, complete statistical analysis was performed by having this time two independent variables, the specific gravity or absorption plus another test, in a multivariate regression. Additionally, the two independent variables were used as covariates along with aggregate categories as treatments in a multivariate covariance analysis.

The models from multivariate regression when specific gravity was used are shown in Table 5.9. All the parameters in the models were significant and collinearity was not a problem. The R^2 varied between 0.609 (Los Angeles test) and 0.776 (Texas degradation sediment). The multivariate covariance analysis did not show any significant additive or interaction effects and models are not shown.

TABLE 5.9. ***MULTIVARIATE LINEAR COVARIANCE MODELS WHEN SPECIFIC GRAVITY IS ADDED***

Model	R^2
ln (MSS) = 16.3218 + 0.0786 (FT) - 5.7849 (SG)	0.677
ln (MSS) = 14.7035 + 0.0850 (LA) - 5.8276 (SG)	0.609
ln (MSS) = 17.1180 - 0.0174 (ADIA) - 4.9863 (SG)	0.720
ln (MSS) = 15.1279 - 0.0118 (ADIC) - 4.1704 (SG)	0.691
ln (MSS) = 8.6036 + 1.5045 ln (TDT10) - 3.7154 (SG)	0.766
ln (MSS) = 7.6326 + 1.5647 ln (TDT16) - 3.2469 (SG)	0.765
ln (MSS) = 11.6132 + 1.0642 ln (TDT200) - 4.2536 (SG)	0.710
ln (MSS) = 13.1365 + 0.8294 ln (TDTSED) - 4.8298 (SG)	0.776

Multivariate regression models, when absorption was used together with the other tests, are shown in Table 5.10. Again parameters were significant and there was no collinearity. The R^2 varied between 0.623 and 0.717. Multivariate covariance models with significant and noncollinear parameters are shown in Table 5.10 also. Covariance increased R^2 by approximately 0.05 to 0.08.

Selection of the Best Models

Tables 5.5 through 5.10 show all the statistically significant models with significant and noncollinear parameters, that describe the relationship of the various tests with the soundness test. Based on the number of independent variables used in the models, the type of analysis (regression or covariance), and the R^2, the models shown in Table 5.11 were selected for further analysis. The predicted 4-cycle soundness values were calculated from these models and compared to the actual values. Predicted and actual values are shown in Table 5.12.

The predicted values with asterisk represent the cases of serious descrepancies between actual and predicted values. In other words they are values that were wrongly eliminated or allowed for use when a 30 percent limit is considered. Despite improvements in

TABLE 5.11. ***SELECTED BEST MODELS BASED ON R^2, NUMBER OF VARIABLES, AND TYPE OF ANALYSIS***

Model Number	Model	R^2
1	MSS = -13.7645 + 4.8973 (TDT16)	0.519
2	ln MSS = -1.5826 + 2.1770 ln (TDT16)	0.681
3	ln MSS = 1.5627 + 0.7628(SS) + 1.6906 LN(TDT10) + 0.3709 ln(TDT10) * (LS)	0.718
4	ln MSS = 7.6326 + 1.5647 ln(TDT16) - 3.2469(SG)	0.765
5	ln MSS = 13.1305 + 0.8294 ln(TDTSED) - 4.8298(SG)	0.776
6	ln MSS = -1.0698 + 1.6017 ln(TDT16) + 0.2046(ABS)	0.734
7	ln MSS = 0.3452 + 0.7601(SS) + 0.5788 ln (TDTSED) + 0.2730(ABS) + 0.2730 ln(TDTSED) * (LS)	0.717

prediction evidenced by higher R^2, all models failed to predict quality of six to eight aggregates out of the 36. Models with higher R^2 had predicted values closer to actual values, but still failed in prediction when decision to eliminate aggregates was based on the 30 percent criterion.

Since prediction is not greatly improved when specific gravity or absorption are added to the models (models 4-7), and due to increased effort of running the additional tests, one-variable models are considered to be more preferable. Models 1-3, which use one variable, failed in seven aggregates. From those, model 3 is considered the best because of better prediction. The model requires, except from performing one test (Texas degradation minus No. 10 loss), knowledge of the type of aggregate (limestone, sandstone, or siliceous gravel).

GENERAL CONCLUSIONS FROM THE STATISTICAL ANALYSIS OF THE LABORATORY TESTS

From scatter plots and the correlation coefficients it was observed that the performed tests had a relatively low correlation with the soundness test. Most of the tests had a logarithmic or exponential relationship with soundness and in order to obtain more meaningful results from the statistical analysis several transformations were tried. The transformations raised the R^2 by approximately 0.10.

In bivariate regression the freeze-thaw and Los Angeles abrasion tests had the lowest correlation with soundness ($R^2 = 0.3$). The two aggregate durability index tests had $R^2 = 0.5$, and the various losses and sediment in the Texas degradation test a R^2 ranging between 0.5 and 0.6. The low R^2 indicated that other tests should be added to the models to account for the variation in soundness not explained by the tests used. In more engineering terms, it indicated that these tests and soundness measured different aggregate properties. Interestingly, the aggregate durability index, freeze-thaw and Texas degradation tests had better correlation among them than with the soundness test. Soundness which is supposed to simulate the freezing and thawing action of water, had the lowest correlation with freeze-thaw than with any other test. Nine of the aggregates tested failed the soundness test (30 percent limit). However, none of the aggregates tested exceeded the specification limit for the Los Angeles test (35 percent). This suggests that the specification limit for the abrasion test should be re-examined if it will be used as a substitute for the soundness test.

Among the four different measured weight losses (from minus No. 8 to minus No. 200) and the sediment in the Texas degradation test, the loss minus No. 16 had the highest correlation with soundness ($R^2 = 0.681$). Also the losses had a very high correlation with the sedimentation part of the test and therefore sediment could not be used together with the losses in prediction models.

The covariance technique was used in a bivariate regression. Additive and interaction effects between material types and test results were examined for significance. The minus No. 10 loss in the Texas degradation test was found to be the best predictor of the soundness test in this analysis. The R^2 found was quite high (0.718).

In an effort to further improve prediction, multivariate models were examined by adding specific gravity and absorption in conjunction with other tests. Such models are less preferable because in order to predict soundness, two tests (either specific gravity or absorption plus one other test) should be performed on the same aggregate. This, however, does not increase the time needed to predict a soundness value because all tests require two days to run and can be run simultaneously. The advantage of this procedure is more accurate prediction. The disadvantage is the increased effort required to perform two tests.

Models with specific gravity were found to have higher R^2 than models with absorption and therefore the first are preferable.

Finally, multiple regression was used together with covariance and improvements in prediction were examined. All models containing the specific gravity did not show significant changes while prediction of some absorption models was slightly improved.

The best one variable model based on R^2 and the comparison between actual and predicted values is the model that used the No. 10 loss from the Texas degradation test. The best two variable model uses the sediment from Texas degradation and the specific gravity. Both models failed to predict the soundness of eight of the aggregates when the soundness limit for the predicted values was set to 30 percent. When the limit was dropped to 25 percent, the first model failed in six and the second in four aggregates.

TABLE 5.12 *COMPARISON BETWEEN ACTUAL AND PREDICTED SOUNDNESS VALUES*

Aggregate		Actual	Predicted MSS from Selected Models Model Number (R^2)						
Number	Type	MSS	1 (0.519)	2 (0.681)	3 (0.718)	4 (0.765)	5 (0.776)	6 (0.734)	7 (0.717)
1	LS	52.2	30.3	24.6*	30.5	21.1*	26.1*	22.8*	29.3*
2	LS	6.1	3.9	3.3	4.4	2.7	4.3	3.1	5.8
14	LS	7.6	10.7	6.8	9.0	6.7	10.7	6.7	11.1
17	LS	17.0	28.8	22.8	31.6*	20.0	19.5	22.9	23.1
20	LS	39.0	34.7	30.2	46.2	18.3*	17.2	21.2*	21.7*
26	LS	14.4	18.6	12.5	12.3	11.1	14.0	12.2	16.4
28	LS	1.7	3.4	3.1	4.7	2.3	2.0	3.0	3.2
29	LS	17.1	26.9	20.6	19.4	30.3*	35.1*	24.5	24.3
30	LS	1.9	-1.0	1.5	2.2	2.6	3.7	2.1	2.9
37	LS	36.1	17.1*	11.3*	10.9*	10.6*	16.4	11.8*	19.5*
38	LS	40.1	43.0	42.7	37.6	86.0	58.6	97.0	57.0
39	LS	6.0	10.2	6.5	6.8	7.7	9.2	7.9	9.7
40	LS	39.0	36.7	32.9	30.5	27.9*	28.5*	31.9	33.5
41	LS	9.6	19.0	12.9	13.7	16.7	16.6	15.1	13.8
3	SS	13.3	11.7	7.4	10.6	8.4	14.0	8.2	17.8
5	SS	63.5	21.0*	14.7*	17.1*	28.8*	32.1	17.6*	20.9*
7	SS	29.3	40.6*	38.8*	39.4*	51.0*	61.3*	49.9*	58.2*
8	SS	17.1	34.7*	30.2*	29.6	23.8	19.7	24.4	23.8
12	SS	67.1	52.3	59.4	43.7	64.9	57.5	62.9	53.4
13	SS	46.6	13.7*	8.7*	11.5*	16.9*	22.9*	10.6*	16.6*
18	SS	2.9	8.8	5.7	9.8	6.9	5.2	6.3	8.2
19	SS	8.5	31.8*	26.4*	30.0*	15.6	3.2	15.9	6.1
27	SS	43.9	28.8*	22.8	25.5*	42.3	25.9	23.4	16.0
31	SS	2.5	3.9	3.3	4.5	3.5	6.7	3.4	9.9
9	SL	1.8	2.9	2.9	2.8	3.1	2.5	2.8	2.1
15	SL	9.1	2.4	2.8	3.0	3.2	5.8	2.8	3.8
16	SL	8.4	13.2	8.4	8.4	6.6	7.4	8.1	6.5
21	SL	5.2	8.3	5.4	5.4	4.5	4.3	5.1	4.0
22	SL	5.9	18.1	12.1	6.2	8.3	12.5	9.5	8.5
23	SL	2.4	8.8	5.7	3.6	4.4	4.9	5.1	4.4
24	SL	6.8	14.2	9.1	8.1	6.8	6.8	8.7	6.6
25	SL	2.2	9.7	6.2	4.0	4.7	4.6	5.6	4.5
32	SL	3.7	4.8	3.8	2.6	3.1	2.7	3.4	2.8
33	SL	8.6	18.1	12.1	6.8	8.1	3.5	8.4	3.1
34	SL	4.7	14.2	9.1	5.8	6.8	2.7	7.1	2.7
35	SL	1.3	-3.0	1.1	1.1	1.7	1.5	1.4	1.4
36	SL	2.9	4.4	3.5	2.4	2.7	2.6	3.1	2.7

*indicates failed prediction

It is essential to point out that the purpose of the statistical analysis was to investigate the relationship between the soundness test and other laboratory tests, and develop models describing this relationship. A high or a low correlation does not necessarily mean that a particular test predicts better the performance of aggregates in the roadway. Results should be examined together with field data to be able to conclude which test is more reliable. It has been observed that the major problem in the correlation analysis was the inability of tests to detect aggregates with high soundness values. Specifically the problem comes from three aggregates, two sandstones (No. 5 and 13) and one limestone (No. 37). All tests predicted that they were good aggregates while soundness rejected them from use. These aggregates will be examined closely in the field.

CHAPTER 6. EXPERIENCE OF TEXAS DISTRICTS WITH THE USE OF THE 4-CYCLE MAGNESIUM SULFATE SOUNDNESS TEST

INTRODUCTION

The 4-cycle magnesium sulfate soundness test to evaluate aggregates for HMAC and seal coats was first adopted by the SDHPT in the late 1970's. The test has not been included in the Texas Standard Specifications but is currently specified in the Construction Specifications. Several districts have utilized the test since its adoption by the SDHPT and some later on. Today 16 out of the 24 districts require the test as a means of controlling the quality of their aggregates.

At the early stages of this study the districts were contacted and their experience and evaluation of the soundness test requested. The responses of the districts are presented in this chapter.

DISTRICT EXPERIENCE WITH THE TEST

The following paragraphs include the salient points of a district wide survey concerning the experience, the program, and the practices of districts that relate to the adoption and use of the soundness test as a means to control quality of road aggregates. The survey included mail correspondence with the districts, visits with maintenance and laboratory engineers, and telephone interviews. Each district is presented separately. Aggregates stated with a number refer to Table 5.1.

District 1 - Paris

The 4-cycle soundness test was adopted by the district in 1984 in an effort to reduce plant control problems associated with variable absorptive rates of certain argillaceous limestone aggregates used in HMAC. These limestones which contain large amounts of clay and chalk of the Cretacious system have indicated variations in soundness losses ranging from 22 to 48 percent within same aggregate source. Studies in the laboratory noted that many of the particles could be easily crushed into fines while many would remain intact. Likewise, crushing of particles was observed in field cores obtained from a hot mix roadway. The district feels that the soundness test helped reduce the amount of asphalt required in a hot mix.

District 2 - Ft. Worth

The district has been requiring the test for HMAC and surface treatments for the past five to ten years. The test is used in connection with the polish value requirements. Aggregates in North Texas have indicated that skid tests do not correlate with the polish value if the material has a high 4-cycle loss. Skids on these aggregates run very low. Most of this material has been covered by seal coats, overlays, or removed in reconstruction. On the other hand, aggregates with acceptable soundness have skids close to their polish value. The test has helped the district eliminate terrible aggregates such as aggregate number 1.

District 3 - Wichita Falls

District 3 has never used this test for job control requirements.

District 5 - Lubbock

The district has difficulty in getting aggregates which can pass both soundness and polish value tests. There is only one pit from which they get crushed aggregate to pass soundness and PV of 32. Most of their aggregates which have good PV do not perform well in the soundness test. The test has helped keep high quality aggregates with good performance.

District 6 - Odessa

Severe cracking and deterioration of the road surface soon after application of HMAC on Interstate Highway 10 in 1966, led to the investigation of the aggregates on these projects as well as 16 other sources used in the district. The test results determined by the Los Angeles Abrasion Test (Tex-410-A) and Wet Ball Mill Test (Tex-116-E) proved to be inconclusive in the elimination of inferior quality materials. This resulted in the implementation of Test Method Tex-411-A, modified from ASTM C88 "Soundness of Aggregates by Use of Sodium or Magnesium Sulfate." After investigation of the 16 sources a maximum value of 25 percent was recommended. This value was increased to 30 percent in 1983. Satisfactory road performance has been observed since the implementation of the test on all hot mix aggregates in 1971.

District 7 - San Angelo

The district does not use the soundness test for quality assurance or control of aggregates used for HMAC. However, their major source is on the Quality Monitoring program of the SDHPT.

District 10 - Tyler

The district has no experience with the soundness test.

District 11 - Lufkin

They experience some problems with aggregate numbers 29 and 41 used in plant mix seals on US69 in Angelina county and US59 in Polk county. The aggregate seemed to wear exceptionally fast and lower than desirable skids were recorded. The 4-cycle soundness loss of this aggregate was 7.3 percent.

District 12 - Houston

Until 1985 the district did not require the soundness test. Beginning that year they started specifying a 30 percent soundness loss for hot mixes and seal coats. The test has eliminated one problem sandstone source used in seal coats and hot mixes and one used only in hot mixes.

District 13 - Yoakum

The district incorporated the soundness test in their specifications in 1986. In 1985 a total of 262 miles of seal coats and 8.7 miles of Type D HMAC overlays were constructed with material similar to aggregate number 12. Even though the soundness test was not a requirement at the time, soundness tests were run with the following results: 56.9, 38.0, and 43.2 for seal coat, and 67.8 and 68.3 percent for HMAC aggregates. The district allows blends of aggregates but each aggregate has to have less than 30 percent loss. Blends are used so that the polish value requirement is met.

District 16 - Corpus Christi

The sandstone geological formation of southeast Texas is the major source of supply of aggregates for HMAC and seal coats. The sandstones are quarried from many different pits but essentially have the same characteristics. They are white, grey, or reddish brown in color and comprised of two types of material; one hard with fine and densely packed grains, and one very soft with coarse and loosely cemented grains. The district has been experiencing several problems with the use of these sandstones. The soft particles absorb asphalt in a hot mix and dry it out, causing brittleness and eventual cracking of the mat. The precoat material used for seal coats due to the absorptive nature of the aggregate does not dry readily and quickly wears off under traffic permitting water to enter the aggregate. This loosens the bond with the asphalt and causes stripping of the aggregate. Additionally, soft sandstone breaks easily under traffic and soon dissolves to sand, leaving small pits on the surface of the road which can cause further deterioration.

Having encountered several problems with the sandstones, the district specified in 1984 the 4-cycle soundness test. The attempt was to exclude the soft, highly absorptive particles, a task not fulfilled by the already specified Los Angeles abrasion and decantation tests. The soundness limits used were 30 percent for seal coats and 40 percent for blends in HMAC. By setting those limits aggregate producers were compelled to change manufacturing processes to stay competitive and the district had to cut in half the amount of sandstone used in hot mixes. The above meant additional production costs at the plants and increased hauling costs of the more durable but not locally produced materials.

The district before specifying a 40 percent limit for HMAC blends had used for some time a 30 percent limit for individual stockpiles. Their experience, though, had shown that this limit prevented them from using their sandstones that improved the polish value of harder and more durable aggregates. Based on this, and after testing blends of aggregates to determine what a realistic percentage loss should be, they established the 40 percent loss. As reported, comparison between roadways constructed with the two limits has shown that performance of roads with a 30 percent maximum loss is better than those with a 40 percent loss.

District 18 - Dallas

They began using this test in 1981 to eliminate soft, porous, highly absorptive limestones which were causing several problems. The test proved to be very successful and the district has required it in all of its projects. It is the belief of the district that they were paying a premium price and receiving an inferior aggregate when only the polish value was a requirement.

District 23 - Brownwood

The district does not require the test for accepting aggregates for HMAC and surface treatments.

District 24 - El Paso

Back in 1973 the district had an interesting case with a reconstruction and resurfacing project in which a rhyolite aggregate was the specified material for the HMAC. In an effort to eliminate soft particles included in this source, which would still pass the Los Angeles abrasion test, the 5-cycle magnesium sulfate test was specified with a maximum loss of 18 percent. All preliminary soundness tests from samples taken from the quarry indicated that the hard portion of the material would pass the test. Nevertheless, when the project was under construction it was found that virtually none of the aggregate being produced would meet the specification limits after being processed through a rock crusher. Since the plans specified the material source, and the material after crushing would not meet the soundness test a dilemma existed. After a request, D-9 made a detailed geological study of this rhyolite and other rhyolite deposits and based on the results the allowable loss was recommended to increase from 18 to 30 percent. The study included laboratory evaluation of rhyolite sources in conjunction with field observations of roads constructed with these aggregates. Examination of thin sections under the microscope indicated evidence of chemical degradation in that the feldspar matrix was decomposed to secondary clay minerals. Visually, the varying degrees of decomposition were recognized by a color change. The colors varied from dark olive green to pale green to chalky cream. Lighter color was associated with more pronounced weathering. Magnesium soundness losses of these three samples were approximately 20, 80, and 100 percent, respectively. For the dark green sample the plus 3/8 in. material had a loss up to 15 percent, while the minus 3/8 in. a loss up to 25 percent. Examination of newly constructed roadways with material that failed the 18 percent limit indicated good performance of this aggregate. One other rhyolite source with a very poor service behavior had soundness losses ranging from 14 to 45 percent. However, a third source with soundness losses which ranged from 23 to 65 percent showed a very good field performance. The first source is very similar to this source and therefore it seemed highly probable that it would perform just as well in the field. The study concluded that the magnesium sulfate test provides only partial information about the potential engineering behavior of rhyolites. It was evident that with only the slightest amount of weathering the rhyolite becomes highly susceptible to the mechanical disruption of magnesium sulfate. This is supported by the fact that two different rhyolite sources showed very different field performance despite the fact that both had approximately the same soundness losses.

District 25 - Childress

The district has been using the test on all seal coat projects for the past eight to nine years. They use the test mainly to eliminate soft limestone aggregates on which there is a surface coating of dust sufficient to prevent sticking when applied to the asphalt in a surface treatment. The district was successful in eliminating the problem aggregates with the use of the test. Before this test was specified they had experienced projects with an excessive loss of aggregates, sometimes almost 100 percent. These same aggregates have not created a major problem in HMAC and therefore the test was not specified for this material.

The soundness test does not apply to precoated aggregates as the asphalt coating eliminates the dust which prevents a strong bond with the asphalt. This means that an aggregate with a soundness loss exceeding the 30 percent limit could be used in seal coats if precoated.

The district had also some problems with aggregate breaking especially during construction. To reduce the problem, pneumatic rollers are being used to compact seal coats.

CONCLUSIONS

Most of the districts reported that the 4-cycle magnesium sulfate soundness test has helped them improve the performance of HMAC and seal coat roadways. The test eliminated from use certain limestones and sandstones that are soft, very porous, highly absorptive, or coated with dust. These aggregates crush, split, shell, abrade or polish heavily under the wheel, require more asphalt to coat, or when used in hot mixes absorb large amounts of asphalt and cause cracking of the mat. Other tests, including the Los Angeles abrasion, wet ball mill, and decantantion have been proved inadequate to prevent the use of such inferior aggregates.

Several districts have associated the polish value test with soundness. A polish value requirement has allowed the use of unsound aggregates at a premium cost, while it prevented the use of aggregates with satisfactory service life. One district has reported that pavement friction does not correlate with the PV when soundness loss is more than 30 percent. In such cases, skids run very low.

Districts have also experienced negative effects after implementing the soundness test. In several cases it increased haul and costs of aggregates by preventing the use of local material or due to decreased competition. In one case the test discriminated against the use of a rhyolite material that had shown good field performance. Soundness loss on this aggregate ranged between 23 and 65 percent. The conclusion was that a very slight amount of weathering makes rhyolites highly succeptible to the mechanical disruption of magnesium sulfate. Finally, the test had failed to predict an exceptionally fast polishing and wear of one aggregate. As a result very low skids were recorded with this aggregate soon after construction of several hot mix projects in east Texas.

CHAPTER 7. FIELD PERFORMANCE OF SELECTED AGGREGATES

SELECTION OF AGGREGATES FOR FIELD EVALUATION

One of the major tasks of this study was to evaluate projects that were constructed with aggregates tested by the 4-cycle magnesium sulfate soundness test. Field evaluation would assess in service performance of aggregates and comparison of laboratory and field results would reveal which test or tests, if any, predict accurately the service life of aggregates. Laboratory results and interviews with districts helped set criteria for the selection of aggregates for on site evaluation.

Four limestone and four sandstone sources were examined in the field. These exhibited all the ranges of soundness loss, or were aggregates that caused discrepancies between the results from soundness and other tests. The statistical comparison between tests had indicated a good relationship between material tests and soundness at low soundness values. The relationship was not as good at soundness values greater than 30 percent. Two aggregates (Nos. 5 and 13) with soundness losses ranging between 30 and 65 (indicating inferior quality) have been depicted good aggregates by the other tests. Projects constructed with the two aggregates were examined in Corpus Christi. Aggregate Nos. 1 and 12 were tested inferior aggregates by all tests. These were examined in projects in Corpus Christi, Yoakum, and San Angelo. Three other aggregates (Nos. 3, 26, and 29) that tested to average soundness losses (7 to 26 percent) were examined in Austin, Lufkin and San Angelo districts. Finally, the performance of aggregate No. 14 (soundness loss less than 10 percent) was examined in San Antonio and Yoakum districts.

Field evaluation included examination of hot mix and seal coat roadway surfaces for disintegration signs (cracking of the mat, and splitting, crushing, dissolving, or shelling of aggregates) and interviews with district laboratory engineers for their experience with the aggregates under question. Results of field evaluation are presented in the following chapters. Performance of inspected HMAC and seal coat projects is summarized in Tables 7.1 and 7.2, respectively.

DISTRICT 16 - CORPUS CHRISTI

The Corpus Christi district has been involved in quality control of seal coats and HMAC road surface applications since 1961. The district is located in the south and the only aggregates available within economical distances are the locally produced sandstones. These materials come from different sources but essentially have the same characteristics. The 4-cycle magnesium sulfate soundness loss ranges between 35 and 75 percent, the Los Angeles abrasion between 28 and 35 percent, and the polish value between 40 and 50. The aggregates fail to meet the soundness requirements, but do not normally have problems meeting the

TABLE 7.1. *PERFORMANCE OF HMAC ROADWAYS*

Aggregate Number	District	County	Highway Number	ADT	Total Traffic	Construction Date	Roadway Condition
29, 41	11	Angelina	US69	11,400	14,364,000	11/83	extensive agg. wear, few popouts
29, 41	11	Angelina	SH147	640	844,800	9/83	extensive agg. wear, few popouts
29, 41	11	Angelina	US59	16,000	9,600,000	9/85	extensive agg. wear, few popouts
29, 41	14	Travis	US290	60,700	40,608,300	7/85	no surface deterioration
29, 41	15	Bexar	SH16	14,400	—	—	no surface deterioration
29, 41	14	Williamson	US183	28,800	21,880,000	4/85	good condition, few popouts
3, 6, 8	15	Bexar	IH37	15,000	—	—	no signs of deterioration
3, 6, 8	15	Bexar	IH37	8,900	—	—	no signs of deterioration
3, 6, 8	14	Travis	Loop 360	18,000	29,034,000	12/82	good condition, few popouts
3, 6, 8	15	Bexar	Loop 410	14,500	—	—	no signs of deterioration
13	16	Nueces	IH37	35,000	48,300,000	6/83	cracking, many popouts, agg. breaking
13	16	Neuces	US277	10,000	5,400,000	9/85	surface deter., agg. breaking, popouts
13	16	Neuces	SH44	9,500	6,555,000	4/85	some popouts, fairly good condition
13	16	Neuces	SH358	34,000	58,140,000	6/82	cracking, many popouts, agg. breaking
26	7	Tom Green	US67	3,000	990,000	6/86	no signs of deter. except few popouts
26	7	Tom Green	US67	3,000	6,300,000	7/81	no signs of deter. except few popouts

TABLE 7.2. ***PERFORMANCE OF SEAL COAT ROADWAYS***

Aggregate Number	District	County	Highway Number	ADT	Total Traffic	Construction Date	Roadway Condition
29, 41	11	Angelina	Loop 36	1,100	1,573,000	6/83	severe agg. wear, crushing, 90% embedment
29, 41	11	Angelina	SH7	1,400	1,932,000	6/83	severe agg. wear, crushing, shelling
29, 41	14	Williamson	US79	9,320	6,235,080	7/85	agg. wear, many particles, crushed
3, 6, 8	14	Williamson	US79	9,810	20,895,300	7/81	very good condition, few breaks
12	13	DeWitt	SH72	1,300	858,000	6/85	some shelling, few breaks and popouts
12	13	Fayette	SH95	820	541,200	6/85	severe agg. loss, many popouts and breaks
12	13	Lavaca	SH111	1,400	924,000	6/85	severe agg. loss, popouts, agg. breaking, 20% patching
12	13	Lavaca	US90-A	2,100	1,386,000	6/85	many agg. broken, agg. wear, 90% embedment
5, 27	16	Nueces	FM666	700	1,197,000	6/82	very few broken particles
5, 27	16	Nueces	IH37	—	—	7/84	severe surface deter. 40% agg. loss
14	13	DeWitt	SH72	1,225	1,212,750	6/84	good condition, some agg. breaks
14	13	DeWitt	US87	1,850	1,831,500	6/84	good condition, some agg. breaks
14	13	Gonzalez	US80	880	580,000	6/85	good condition, some breaks
14	15	Bexar	FM1303	770	—	—	good condition, some breaks
14	15	Bexar	FM2537	740	—	—	good condition, some breaks
26	7	Tom Green	US87	5,000	75,000	5/87	severe surface deter, crushing, dissolving agg.
26	7	Tom Green	US87	5,000	1,750,000	6/86	some agg. splitting and crushing
26	7	Tom Green	FM2288	1,900	570,000	7/86	asphalt bubbling, few breaks, good condition
1	7	Tom Green	US277	2,100	1,449,000	6/85	some agg. crushing and loss, good condition

abrasion limit of 35 percent. On the contrary, their polish value far exceeds the highest required limit of 32. Due to the peculiar behavior of these sandstones the district has experienced several problems with their use. When they started specifying the soundness test in 1984, the performance of roadway surfaces increased substantially.

The district did not experience any problems in HMAC or seal coats between 1960 and 1970. Hot mix applications did not require sealing for several years and the mat remained dense with no noticeable deterioration. In 1968 the aggregates that were used for overlays in three counties were crushed to meet the Navy's requirement for soundness.

In the 1970's at least four different sources of sandstones were used for overlay and seal coat programs. All hot mixes cracked badly even though designs used the maximum amount of asphalt permitted. Cracking occurred because of drying of the mix due to high absorption of the aggregates. Overlays experienced also severe deterioration problems. The sandstones contained plenty of soft particles which literally dissolved to sand under vehicles and rain. The result was a cluster of small pits on the surface ("popouts") which eventually progressed to a more severe disintegration. Soft particles, which are reddish-brown caliche, were characteristically called "blossoms" that open up like a flower in winter. Placing operations also had problems with the mix pulling under the screed due to tackiness of the mix caused by high amounts of asphalt.

Seal coats experienced much the same problems. The soft particles crushed both during placement under rollers and soon in service under traffic causing deterioration of the surface. Precoated aggregate was found to be a definite improvement over dry aggregate but was not a total solution to the problem. Precoating reduced the asphalt requirement and subsequent cracking of the mat due to decreased absorption of the material. It also strengthened soft particles which were not as readily dissolved.

The district, after experiencing these problems, had decided in 1984 to establish the 4-cycle soundness test in order to eliminate the soft absorptive sandstone particles. Until that time it required the Los Angeles abrasion test (35 percent maximum for seal coats and 40 percent for HMAC) which the sandstones easily passed. The soundness requirement was set to 30 percent for seal coats and 40 percent for hot mixes. Blends of aggregates are allowed in hot mixes with a combined loss of 40 percent.

At a visit to the district the performance of three of the problem sources used in hot mix overlays and seal coats was examined. Aggregates from the three sources were tested in this study with numbers 5, 27, 12, and 13. Aggregates Nos. 5 and 27 came from the same source at different times.

Two overlay projects on IH 37 and SH 358 that were constructed between 1982 and 1983 used aggregate No. 13. The material had a soundness value of 50-60 percent. The surface of both roads has dried out and cracked, and some soft aggregates have ground or crushed to sand leaving many small pits on the surface.

The 1984 seal coat program was the first to be constructed with the soundness requirement. A new source was selected to supply the material (aggregate Nos. 5 and 27) which at the beginning could not meet the 30 percent limit. Eventually the producer managed to meet the limit through a vertical impact crusher that crushed and eliminated the soft particles.

Several sections had been sealed with this material one of which is FM 666 in Nueces county. The seal coat is still uncovered and doesn't show any signs of deterioration. The road has some signs of bleeding and few particles were observed broken but not completely dissolved.

Material from the same source but without the soundness requirement was placed in 1984 as an underseal of the overlay project on IH 37. Due to excessive amounts of soft particles, the surface deteriorated badly. It was estimated that the job suffered a 40-50 percent aggregate loss.

In 1985 US 277 was overlayed with a Type D HMAC blend of sandstone aggregate No. 12 and a siliceous gravel. The blend met the 40 percent soundness requirement but the individual sandstone loss was much higher. Two years after construction the road suffered surface deterioration due to dissolved soft particles.

In April of 1985 SH 44 was overlayed with a Type D HMAC of the sandstone aggregate No. 12. It was the only time that District 16 had used this material in a hot mix not blended with another aggregate. The job had the 40 percent soundness requirement and the producer used a vertical impact crusher to remove soft material and meet the limit. Two years after construction and after 7 millions of accumulated traffic, the pavement was in a fairly good condition with some particles dissolving and leaving small holes on the pavement.

It is clear that the district has experienced a considerable improvement of its roadways after specifying the soundness test. The 30 percent limit for seal coats appeared adequate for the seal coat examined, as very few soft particles were present. Seal coats constructed with the same aggregate but without the soundness limit had extensive signs of deterioration. The 40 percent limit for HMAC blends seemed still inadequate. The problem is that when the soundness limit does not apply to each individual aggregate but to a blend, it allows the use of any kind of aggregate (even of a soundness loss of 60 or 70 percent) by adjusting the weight of each aggregate. Such a blend will contain very soft particles which can easily break under traffic or result in pavement cracking. That was the case with the overlay on US 277. The performance of SH 44 which used one aggregate of soundness 40 percent was better than that of US 277 even though the latter still had some signs of surface disintegration. All the roads examined had, despite any surface deterioration, adequate friction numbers.

DISTRICT 15 - SAN ANTONIO

The San Antonio district specifies a 30 percent maximum loss on aggregates for HMAC and seal coats. Most of their aggregates have losses not exceeding this limit. Only local sandstone sources in the southern part of the district show a soundness loss in excess of 40 percent.

The district has not experienced any serious degradation problems with their aggregates. They had only two cases of degrading roadway before specifying the soundness test. One was on IH 37 in Tascosa county where a local sandstone was used. The aggregate had passed the Los Angeles test requirement. The material was tested after construction of the road and had a soundness loss of 40 percent. The other project was on IH 35. The aggregate again passed the abrasion test but the soundness loss was around 50 percent. The use of the soundness test has eliminated these two problem sources.

Several hot mixes and seal coats were examined, under this study, in Bexar county. The roads were constructed with a sandstone (aggregate Nos. 3, 6, and 8) and a limestone (aggregate No. 14). The two materials have soundness losses ranging between 9-24 and 5-13 percent, respectively. The roads examined were seal coats on FM 1303 and FM 2537 constructed with the limestone, and hot mix overlays on Loop 410 and IH 37 constructed with the sandstone. All projects had excellent performance. There was no bleeding, cracking or patching of the roadway and aggregates did not seem to polish, abrade, or break into smaller pieces under traffic, except from very few "popouts" of the sandstone aggregate.

DISTRICT 13 - YOAKUM

The Yoakum district is located near good quality aggregate sources and does not have problems getting material to pass the soundness requirement of 30 percent loss. In the 1984 seal coat program the limestone aggregate No.14 was used, and in the 1985 program the sandstone aggregate No. 12.

Visits have been made to several of these projects to assess their performance. US 87 and SH 72 in Dewitt county, and US 80 in Gonzalez county used the limestone material. Bleeding and patching were obvious on US 72. There were no signs of aggregate abrasion or breaking on any of the roads. Very few particles of soft material broke to smaller pieces. The broken pieces remained in place sticking on the underlying asphalt. There were no particles missing from the matrix.

Sandstone No. 12 was used for seal coats on SH 111 and US 90-A in Lavaca, SH 95 in Fayette and SH 72 in Dewitt counties. SH 111 suffered severe aggregate loss, mainly on the roadway between the wheel paths. Several aggregate particles were seen broken and many completely dissolved leaving gaps on the surface. There were areas of 10-20 particles missing from the same spot. Aggregates abraded to a round smooth surface, more distinctively in the wheel paths. The road had about 20 percent patches. The condition of US 90-A was somewhat better. There was no shelling of aggregates but many particles were broken. Bleeding was extensive in the wheel paths and the aggregates were highly abraded and embedded as much as 100 percent in the asphalt. SH 72 had some shelling of aggregates. Fewer particles than before were broken or completely deteriorated. The condition of SH 95 was very much like SH 111, except that there were no patches.

The conclusion is that the limestone aggregate No. 14 used in projects in the San Antonio and Yoakum districts has performed very well. On the other hand, aggregate No. 12 is of inferior quality, as was also evidenced by projects in Corpus Christi. The soundness test has therefore evaluated correctly the performance of the two aggregates.

DISTRICT 11 - LUFKIN

The Lufkin district does not require the 4-cycle magnesium sulfate soundness test to control aggregates for HMAC and surface treatments. There is an abundance of aggregate sources in the area and they have to haul aggregates from distant locations.

A limestone source (aggregate Nos. 29 and 41) is extensively used at the district for hot mix and seal coat applications. It has soundness values ranging from 7 to 26 percent. The material basically consists of a natural blend of two limestones; one is hard and dense, and the other is soft and absorptive. The soundness loss varies depending on the amount of soft material present.

Several hot mix and seal coat surfaces that used this aggregate have been examined. Hot mixes included projects on US 69, SH 147, and US 59 in Angelina county. A characteristic obvious on all the roads is the extensive abrasion of the surface of the aggregate due to attrition with traffic. The wear was evidenced by the brownish color of particles exposed on the surface. Also few soft particles broke off the matrix or dissolved to powder leaving small pits on the mat.

The seal coats examined were located on Loop 36 and SH 7 in Angelina county. Again the aggregate seemed to abrade fast and most particles had rounded surfaces. On Loop 36 the aggregate was level with the surface, whereas on SH 7 most of the aggregate was exposed. In contrast with hot mixes, both roads had exceptionally large number of aggregates crushed to small pieces; other pieces stripped from the mat and other were still held together in the matrix by the asphalt. Less crushed particles were seen on Loop 36 and that was probably due to the high embedment which also caused severe bleeding on this road. SH 7 had distinct signs of stripping, especially in the areas between the wheel paths.

DISTRICT 14 - AUSTIN

The Austin district does not specify the soundness test to control aggregate quality. It is located near major aggregate sources and two of the materials used extensively in hot mixes and seal coats are a limestone (aggregate Nos. 29 and 41) and a sandstone (aggregate Nos. 3, 6, and 8).

The sandstone aggregate was used for seal coat sections on US 79 in the summer of 1981, and the limestone in the summer of 1985 and 1986. The sandstone seal coats despite being much older outperformed the limestone sections in that the particles are still exposed by as much as 30 percent and are not as worn or polished. Most of the limestone particles on the wheel paths had their surface polished from the asphalt coating which suggests a continual abrasion by traffic. Also many particles were crushed. Most of the sandstone particles throughout the road were coated with asphalt, a sign of resistance to abrasion. Fewer than 10 particles in a square foot were polished from the asphalt coating and a few of these were broken to small particles.

Samples of aggregate particles were extracted from the surface of both roads and cleaned from the asphalt using trichloroethylene solvent. The exposed face of the limestone particles was highly abraded and smoother than the unexposed faces. The exposed face of the sandstone particles was flatter than the other faces but not as polished and sleek as the limestone face.

Hot mix sections with the sandstone material on US 183 and Loop 360, and with the limestone material on US 290 were also examined. US 183 and Loop 360 had few small pits on their surface due to dissolved particles. US 290 did not have any broken particles.

Both limestone and sandstone aggregates have approximately the same range of soundness loss. The sandstone consists mainly of hard particles and a very small percentage of soft particles. These are the particles that dissolve completely in the soundness test. The harder particles only contribute to some soundness loss. In the field, the hard particles do not deteriorate but the soft ones crush and dissolve, leaving pits on the surface. The limestone consists of soft and hard particles. The soft material, which is about

40 percent, breaks and abrades substantially in seal coats. Only abrasion effects were seen in hot mixes as the soft particles are not weak enough to dissolve under traffic. Probably, the surrounding sand-asphalt matrix absorbs most of the load and prevents complete deterioration to take place as in seal coats.

The sandstone source (aggregate Nos. 3, 6, and 8) has been examined in several seal coat and hot mix projects in the San Antonio and Austin districts. The material has shown exceptional performance despite the fact that several times has tested to high soundness losses (up to 24 percent). The few soft particles which deteriorate in both hot mix and seal coats did not seem to affect performance.

The limestone source (aggregate Nos. 29 and 41), as examined in Austin and Lufkin has not performed satisfactorily. The soft part of the material crushed to small particles or abraded heavily when used in seal coats. Only abrasion effects were distinct in hot mixes.

A 30 percent limit for the limestone in HMAC is likely to be adequate but the limit ought to be dropped probably to 25 or even 20 percent for seal coats to remove some of the soft, highly abrasive material. A 30 percent limit for the sandstone in hot mixes and seal coats is more appropriate as a lower limit would sometimes prevent its use.

DISTRICT 7 - SAN ANGELO

The San Angelo district is located in the Edwards formation which is their major source of road aggregates. The soundness test is not currently required to monitor the quality of their aggregates. Beginning with the 1988 seal coat program the district will start specifying the test.

The most extensively used aggregate in the area is the limestone aggregate No. 26. It has a soundness loss ranging between 12 and 25 percent. The material is a blend of four geological strata. To examine the quality of each stratum separately, material was quarried from each one and tested in the laboratory. The four strata are represented by aggregate Nos. 37-40.

The performance of two overlay projects on US 67, one placed in the summer of 1981 and the other in the summer of 1986, was examined. The projects used the aggregate No. 26. The overlay placed in 1981 has a few longitudinal cracks. There are no signs of aggregate deterioration except from a very small number of particles that broke off the matrix leaving small pits. The overlay placed in 1986 is in a very good condition but again, a few particles are missing from the matrix. The problem with the "popouts" seemed insignificant in both cases. A few particles on the 1986 overlay are polished from the asphalt. About 30 percent of the particles on the 1981 overlay are polished. In general, the aggregate in spite of six years of use did not seem to wear exceptionally.

The seal coat on FM 2288 was placed in the summer of 1986 using precoated aggregate. Small, round spots of asphalt were noted on the surface of the roadway, which is the result of squeezing of aggregates in the mat. This effect, which is called bubbling, if excessive can cause bleeding. Only a few particles were seen crushed, and the roadway in general was in good condition. The seal coat on US 87 was also placed in the summer 1986. Here, the shearing (breaking into two pieces) of the aggregates is obvious. Particles did not seem to abrade. This road carries heavier traffic than FM 2288 and this is probably the cause of aggregate splitting.

The seal coat on US 87 frontage road was placed in May of 1987. A heavy rain 48 hours after construction shelled aggregates which did not seed adequately into the matrix. The loose rock was then pressed upon the underneath rock still held in the mat, which resulted in a severe disintegration of the aggregate in the mat. Many particles crushed severely to small pieces (did not just shear to two pieces) and others dissolved to powder. Examination of the laboratory results showed that particles that break to pieces possibly come from strata Nos. 1 and 4 (aggregate Nos. 37 and 40, respectively) and particles that dissolve, from stratum No. 2. Stratum No. 2 is a very soft, brownish dolomite while strata Nos. 1 and 4 are a soft white limestone.

In conclusion, aggregate No. 26 performed better in hot mixes than in seal coats. In hot mixes the asphalt matrix prevents the breaking of the soft white colored limestone. The soft dolomite, though, is too weak to withstand any traffic loads and crumbles leaving small pits on the surface. The lateral confinement present in hot mixes does not exist in seal coats and soft particles, either brown or white, break under the loads. There has been some evidence that deterioration is higher on roads carrying heavier traffic.

Since the aggregate performs adequately in hot mixes, a soundness loss of 30 percent seems sufficient. A 25 or less percent loss for seal coats is probably more appropriate for removal of soft material. It is important to note, however, that even at such a limit, soft material will still be present due to the natural blending of the four strata, which can disintegrate due to construction or traffic variables. Rain soon after construction, for example, could shell particles which when pressed on other particles could smash the bottom ones. This cracking does not normally take place when the rubber wheel hits the aggregate. Likewise, heavy aggregate rate application could cause a similar situation. Additionally, heavy traffic could break particles that are not normally broken from light traffic.

One other aggregate used by the district but not as extensively as the previous one, is the limestone aggregate No. 1. The material is also quarried from the Edwards formation but it consists only of soft white limestone. Its soundness value ranges between 40 and 60 percent. The aggregate was examined on a seal coat project on US 277, constructed in the summer of 1985. The overall condition of the road is good. There is some aggregate loss on the center line but on the rest of the roadway there are no gaps of missing aggregates. The embedment is approximately 50 percent, and the particles do not seem to wear exceptionally to rounded faces. There are some crushed and some sheared particles, however. Despite the fact that the road now looks in a fairly good condition, the district lab engineer noted that during construction a very large amount of particle was crushed loose from the mat. Breaking continued for two to three weeks and the road was broomed several times during that period to prevent further crushing.

FRICTIONAL PERFORMANCE OF AGGREGATES

The frictional performance of four of the aggregates evaluated in the field for degradation problems was also determined. The aggregates examined were Nos. 1, 3, 14, and 29. Figure 7.1 shows the change in friction number with accumulated traffic of hot mix asphalt roads. Each curve represents the average friction number of ten to fifteen roadways constructed with the same aggregate in three districts. Roads constructed with aggregate No. 1 showed the lowest friction in spite of the high PV of the aggregate. This is probably a result of low soundness contributing to fast wear. The rate of polish of this aggregate was exceptionally high. Aggregate No. 29 also showed a high polishing rate, and then friction values leveled out to 25 after 2 million vehicle passes. This material is relatively soft, as indicated by a soundness loss ranging between 7 and 26 percent, but its polish value is quite high (36). Aggregate No. 14 wears at a lower rate than aggregate No. 29 but in contrast with that material it continues to wear to lower friction values after 2 million passes. The polish value of this material is 29 and its soundness loss ranges between 6 and 10 percent. Aggregate No. 3 exhibited the best skid performance among the four aggregates. It has an average durability (soundness varies between 9-20 percent), but a very high frictional resistance (polish value is 47).

Despite the limited number of aggregates examined, the graphs have indicated some interesting trends. Skid performance of aggregates used in hot mixes was shown to be closely related to frictional and durability characteristics, as measured by the polish value and soundness tests. High skid numbers were asociated with both high polish value and low soundness loss. Good skid performance could not be maintained with only good polish values or with only good durability characteristics. Very low friction values were recorded with one aggregate with high polish value and high soundness loss, and with one aggregate with low polish value and low soundness loss. Two other aggregates with approximately the same soundness loss exhibited different skid performance. The higher friction values were obtained with the aggregate with the higher polish value. The above indicate that the polish value, the soundness loss, and also the interaction of the two values contribute highly to changes in skid numbers.

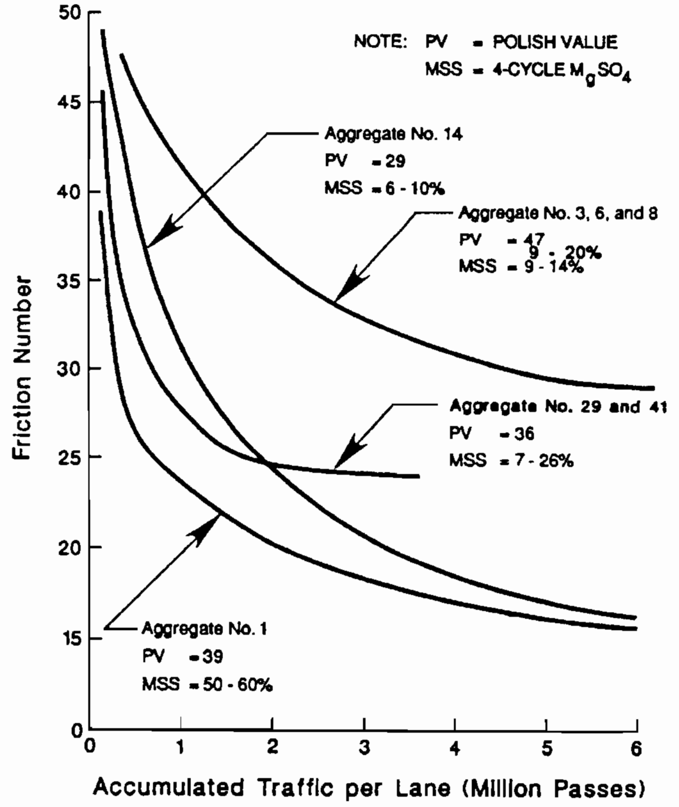

Fig 7.1. ***Frictional resistance of HMAC roadways constructed with four aggregates.***

CONCLUSIONS

Field evaluation of eight aggregates used in several hot mix and seal coat projects has revealed that the 4-cycle magnesium sulfate soundness is the best among the tests evaluated, for predicting aggregate quality. The soundness test correctly assessed the inferior performance of aggregate Nos. 5 and 13, while freeze-thaw, aggregate durability index, and Texas degradation failed to predict correctly the performance of these aggregates. All tests correctly predicted the inferior performance of aggregate Nos. 1 and 12, and the good performance of aggregate Nos. 3 and 14. The performance of aggregate No. 29 (which crumbles and wears in seal coats) was more precisely predicted by Texas degradation. Soundness and durability index tests discriminated somewhat in favor of using the material, while freeze-thaw failed the most. The quality of aggregate No. 26, which showed an average performance, was more precisely predicted by the freeze-thaw test; the results from other tests were approximately the same.

Soundness was the most successful among the material tests in predicting disintegration of aggregates. Its correlation with the freeze-thaw test was very low but this did not affect its ability to predict degradation due to weathering action. In fact, freeze-thaw failed in this aspect in few of the aggregates, despite better simulation of field conditions. Soundness failed to predict some breakage and splitting of two aggregates, but this was probably due to the varying quality of these materials (contained very soft and very hard particles). Also it failed to predict excessive wear of one of the two aggregates. This type of disintegration seemed to be more related to attrition action which is better simulated in abrasion tests. Texas degradation and durability index tests were more successful in predicting the quality of this aggregate, than the Los Angeles abrasion. These tests detect aggregates that break into plastic fines that cause reduction in road stability and prevent aggregates from adhering strongly to the asphalt. The Los Angeles test failed to pinpoint any of the inferior aggregates (either soft or prone to wear) and its usefulness becomes questionable.

As it was evidenced, a major problem exists when testing an aggregate that is a natural blend of material of highly varying quality. A blend for example, of a very hard and very soft material will probably give an acceptable combined loss, but the soft material will disintegrate when used on the road. Aggregate No. 26 is a blend of four strata, three of which showed a soundness loss exceeding 35, and one a loss of 6 percent. The soundness loss of a blend of this material varies according to the amounts of each strata present. When on the road, the soft particles of the blend will crumble.

A similar situation occurs when blends of sound and unsound material are used by districts for the purpose of improving frictional properties. The unsound material if too soft will disintegrate fast in the road.

CHAPTER 8. ANALYSIS OF A QUESTIONNAIRE TO DISTRICTS CONCERNING SPECIFICATION LIMITS FOR THE SOUNDNESS TEST

SPECIFICATION LIMITS

The final investigation of this study included a survey of Texas districts concerning what effect a soundness loss specification of 25 for seal coats and 30 percent for HMAC would have to each district .

The above limits were decided upon a thorough investigation of the performance of several HMAC and seal coat projects constructed with four limestone and four sandstone aggregates in six districts. Evaluation of the results of the investigation has revealed that aggregates are under higher stresses in seal coats than in hot mixes, as they receive direct loads from traffic, and are more exposed to weather. Also seal coat aggregates are greatly influenced by design and construction variables (rate of application of asphalt and aggregate, asphalt temperature, type of roller, brooming, and traffic control), and the weather during construction (rain, temperature, humidity) that are in most cases difficult or beyond any human control. Specifically, the San Angelo district has recently faced a complete disintegration of a roadway surface constructed with an aggregate that normally splits to a much lesser degree, because of rain soon after construction. In order to cope for unexpected and undesired conditions there is a need for stricter control of seal coat aggregates. It is believed that similar conditions affect hot mix aggregates to a lesser degree. To withstand higher stresses and unexpected conditions seal coat aggregates should be stronger and more durable and this can be achieved by specifying stricter test limits to the aggregates.

It has been substantiated that aggregate performance problems become noticeable when the soundness loss is in the 20's. Problems in general increased with increased soundness losses. Most districts currently specify a 30 percent loss for both hot mixes and seal coats. Two limestone aggregates examined thoroughly in the field have demonstrated a very good performance in hot mixes, while degradation problems have been observed in seal coats. The two materials had soundness losses ranging between 10 and 25. Cracking, crumbling, splitting, abrasion, and shelling problems were noted on several seal coat projects while only abrasion and crumbling to a lesser degree on hot mixes. One sandstone material with soundness loss values between 10 and 25, has exhibited excellent performance despite some crumbling of soft particles. One other sandstone, which was crushed to produce a soundness below 30, has also produced satisfactory results in a seal coat project.

A value of 30 for hot mixes is therefore likely to be adequate, while a 25 seems more appropriate for seal coats. Caution should be exercised, however, to avoid excluding by this limit material with good past performance like the two sandstones. Using a 25 limit for limestones and 30 for sandstones may be the solution.

QUESTIONNAIRE

A questionnaire (Appendix C) was prepared and sent out to district offices requesting how it would affect the district a specification limit of 30 for hot mixes and 25 percent for seal coats, in terms of material availability and road performance. Specific questions asked were whether these limits would eliminate usual sources, restrict the use of local sources, cause excessive haul distances or change maintenance practices. Additionally, the experience of districts using these limits was asked.

All 24 districts replied to the questionnaire. The summarized results of the survey are shown in Table 8.1. The table shows district specification limits and whether a specification of 25 for seal coats and 30 for hot mixes, would affect their program.

The following replies were obtained. Eight districts do not specify the soundness test, while eleven others specify it for both seal coats and hot mixes. Two districts specify the test for hot mixes only, and three for seal coats only. Out of the 14 districts which use the test for seal coats, eleven specify a 30 percent limit, one 25 (Lubbock), one 20 (Paris), and one 32 (Abilene). Out of the 13 districts which use it for hot mixes, 10 specify a 30 percent loss, one 25 (Lubbock), one 32 (Abilene), and one 40 (for blends) (Corpus Christi).

Specifying a 25 percent limit on seal coats would affect a total of five districts. These districts are located in two geographical areas. These are in central-west Texas and include Brownwood, San Angelo, Abilene, and Odessa. The other is south Texas and includes Corpus Christi and Pharr.

Districts in central-west Texas have a very limited number of suppliers most of which produce soft limestones with high soundness losses. Brownwood, which specifies a loss of 30 percent, acquires its aggregate mainly from three suppliers. A 25 percent limit would probably eliminate one of those. San Angelo will start specifying a loss of 30 for seal coats only, in 1988. A loss of 25 would sometimes eliminate their major local source. Abilene currently requires a 32 limit for seal coats but they will probably reduce it to 30. A lower loss would eliminate sources that have historically used and require excessive haul. A loss of 25 percent was used in the past by the district but after allowing 30 percent limit, aggregate prices went down by 30-40 percent due to increased number of suppliers and competition.

One other area that might be affected from a 25 limit on seal coats is south Texas. Pharr has reported that some not local sources will be excluded from usage. The Corpus Christi district has reported that it would not affect availability because local sandstones cannot meet this value nor have they been able to meet 30 which they now require. Therefore, lowering the limit would cause no problems, only because locally produced sandstones have already been excluded from usage.

TABLE 8.1 *SUMMARY OF THE RESULTS OF QUESTIONNAIRE TO DISTRICTS*

	Soundness Test Spec. Limit		Effect (Yes/No) of Spec. Limit	
District	Seal Coat	HMAC	Seal Coat 25 Percent	HMAC 30 Percent
1 - Paris	20	30	No	Yes
2 - Ft. Worth	30	30	No	No
3 - Wichita Falls	-	-	No	No
4 - Amarillo	-	-	No	No
5 - Lubbock	25	25(1)	No	Yes
6 - Odessa	30	30	Yes	No
7 - San Angelo	30	-	Yes	No
8 - Abilene	32	32	Yes	Yes
9 - Waco	-	30	No	No
10 - Tyler	-	-	No	No
11 - Lufkin	-	-	No	No
12 - Houston	30	30	No	No
13 - Yoakum	30	30	No	No
14 - Austin	-	-	No	No
15 - San Antonio	30	30	No	No
16 - Corpus Christi	30	40(2)	No	Yes
17 - Bryan	-	-	No	No
18 - Dallas	30	30	No	No
19 - Atlanta	-	-	No	No
20 - Beaumont	-	30	No	No
21 - Pharr	30	30	Yes	No
23 - Brownwood	30	-	Yes	Yes
24 - El Paso	-	-	No	No
25 - Childress	30	-	No	No

(1) 30 percent for screenings (+ No. 10)
(2) total loss of a blend

A total of five districts will be affected if the soundness limit for hot mixes is specified at 30 percent. Two are in the central-west area (Brownwood and Abilene), one north-west (Lubbock), one north-east (Paris), and one south (Corpus Christi). Brownwood, which does not specify any limit for HMAC, has reported that a soundness limit of 30 percent coupled with the polish value requirement would cause an unacceptable increase in material prices. Abilene, which currently specifies 32, has reported that it might be affected by a 30 even though they believe that the district will eventually require that limit. Lubbock currently uses a 25 limit on coarse aggregate and 30 on screenings (plus No. 10 portion). If raised to 30 it would open less desirable material sources that under past experience lead to roadway shelling, stripping and bad performance. Paris also feels that this loss would permit the use of two sources that are borderline (their loss ranges between 26 and 48). Finally, Corpus Christi, which uses a combined loss of 40 on blends, has noted that imposing a 30 percent loss to individual aggregates, would practically eliminate all their local sandstones. In such a case, all acceptable sound and polish value aggregates would have to be imported.

In terms of district experience with the test ten districts (Nos. 1, 2, 5, 9, 12, 13, 14, 15, 16, and 18) reported that after implementing the test, the performance of their roads have improved in that it has eliminated soft and absorptive material. District 6 has increased the limit from 25 to 30 on hot mixes. District 20 has not noticed any change in performance as a result of a 30 percent requirement on hot mixes, and district 21 has found out that the reliability of the test is low. Six other districts use aggregates with very low soundness values and a soundness test would not affect their program.

A 25 limit on seal coats would not affect eighteen districts mainly because the aggregates they use test to a lower percent. Four districts opposed the limit because it will cause material shortage and increased prices (central-west Texas), one reported that it will just prevent the use of non-local sources, and one stated that local sources cannot meet this value nor have been able to meet 30 which they now require.

For hot mixes, nineteen districts believe that a 30 percent loss would not affect their program, three reported that it will eliminate local sources, cause excessive haul, and raise prices, and two feel that it will affect performance negatively by permitting the use of unacceptable material.

CHAPTER 9. SUMMARY AND CONCLUSIONS

SUMMARY

The objectives of the study were to

(1) investigate the 4-cycle magnesium sulfate soundness test in the laboratory,

(2) evaluate the 4-cycle soundness 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 soundness 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 4-cycle soundness or a better method for evaluating aggregate behavior in the field.

A total of 41 aggregates (14 limestones, 12 sandstones, 13 siliceous gravels, and 2 synthetic lightweight) from 33 quarries in Texas, Oklahoma, and Arkansas representing the most common or problem materials used by Texas districts, were tested in the laboratory. Tests included specific gravity, absorption, freeze-thaw, Los Angeles abrasion, aggregate durability index, a modified procedure for the Texas wet ball mill (called Texas degradation) and the 4-cycle soundness. Statistical analysis was used to determine repeatability of methods and develop models describing the relationship between soundness and the other tests.

The behavior of 8 aggregate sources evaluated in the lab, was assessed in several Texas districts by examining their performance in selected HMAC and seal coat projects. District experience in using the 4-cycle soundness test to qualify aggregates was gathered by visits to district offices, mail correspondence, and telephone interviews.

Based on the relationship between laboratory and field results and the experience of districts, specific recommendations are suggested for quality control of hot mix and seal coat aggregates.

CONCLUSIONS

1. The 4-cycle soundness test was the best among seven laboratory methods in predicting performance of aggregates in HMAC and surface treatments.
2. The soundness 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 losses.
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 is more affected by the magnitude of load rather than repetition of load. Repetition affects primarily wear of aggregates.
6. Most districts after implementing the soundness test 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 has been 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 4-cycle soundness test does not guarantee a high frictional performance if an aggregate has a low PV.
9. Specifying only the PV test 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 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 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 state that it would allow the use of unacceptable material.
14. Roads constructed with a soundness limit greater than 30 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. The model describing the relationship of the two tests is given in Table 5.11. The R^2 for the model is 0.718.
19. The combination of Texas degradation sediment and specific gravity tests gave the best two variable relationship with the soundness test. The model describing this relationship has $R^2 = 0.776$ and is given in Table 5.11.
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

1. The 4-cycle magnesium sulfate soundness test should be used to evaluate quality of aggregates for use in HMAC and surface treatments.
2. Specific observations and recommendations to improve the soundness test are included in Chapter 3 under "Recommendations."
3. A 30 percent soundness limit should be applied to HMAC and a 25 limit to seal coats.
4. Siliceous gravels should not be tested for soundness.
5. Research should be focused toward reducing run time and simplifying the 4-cycle soundness procedure.
6. When blends of aggregates are used, the soundness test should be performed on each individual aggregate.
7. District laboratories with tap water that does not contain enough salt to mask the effect of barium chloride when performing the soundness test, should use the barium chloride as a means of detecting presence of salt, as it may reduce the run time of the test.
8. Specification of the Los Angeles abrasion test should be discontinued.
9. The Texas degradation test (Appendices A and B) should be used as a replacement to Los Angeles abrasion. A testing program is required to determine which loss and/or sediment should be evaluated during the test.
10. Appendix B contains the test procedure that correlated best with the 4-cycle magnesium sulfate soundness test. 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.

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APPENDIX A. TENTATIVE TEXAS DEGRADATION TEST PROCEDURE

1. Split a 3,000 g. dried sample of aggregate and sieve over the 3/4-inch x No. 8 sieves. Discard material retained on the 3/4-inch sieve and passing the No. 8 sieve and replace with 3/4 - No. 8 material. Final sample should weigh 3,000 ± 25 g.

2. Place the sample in a mill and add a volume of water equal to b(f(A,100) x 3000) + 1000 ml, where A is the one hour absorption. After a period of 10 minutes has elapsed, add four spheres and agitate for 10 minutes.

3. Pour the contents of the mill into the nested No. 8 and No. 200 sieves placed in a pan provided to collect the wash water.

4. Allow the wash water to stand undisturbed in the collection pan and pour the upper portion of the water back through the sieves until all the minus No. 200 material has been washed through the sieve.

5. Pour the wash water from the collection pan into a plastic bottle and add water to 1,200 ml. Cap the bottle, agitate for 20 seconds, and pour in a graduated cylinder, containing 7 ml of stock calcium solution, up to the 15 inch mark.

6. Stopper the cylinder and invert for 20 times in 35 seconds.

7. Allow the cylinder to stand for 25 minutes and record the sediment height.

8. Dry to constant weight the material retained on No. 200 sieve and record the weight. Sieve the sample over the Nos. 8, 10, and 16 sieves and calculate the percent loss through each sieve based on the weight of sample from Step 1.

APPENDIX B. TEXAS DEGRADATION TEST

SCOPE

The method describes a procedure for determining the resistance of aggregate in HMAC and Surface Treatments to disintegration in the presence of water. The Texas degradation value is calculated as the percent loss minus No. 16 and represents degradation resulting from a combination of attrition, impact, and grinding. Research has indicated that the test has high correlation with the durability index test which represents a measure of the relative resistance of an aggregate to producing clay-like fines.

APPARATUS AND MATERIALS

1. Wet Ball Mill (similar to Test Method Tex-116-E),
2. Metallic Spheres. The abrasive charge consists of four (4) steel spheres approximately 1-7/8 inches in diameter, weighing between 390 and 445 grams.
3. A balance with a minimum capacity of 10,000 g, accurate to ± 1 g.
4. A set of standard U.S. sieves containing the 3/4 inch, 1/2 inch, 3/8 inch, No. 8, and No. 16 sizes.
5. Oven, air dryer with temperature set to 230 ±9°F.
6. Miscellaneous equipment includes large pans, wash bottles, etc.

PROCEDURE

1. Split a 3,000 g dried sample of aggregate and sieve over the 3/4-inch x No. 8 sieves. Discard material retained on the 3/4-inch sieve and passing the No. 8 sieve, and replace with 3/4 to No. 8 material. Final sample should weigh 3,000 ± 25 g. Record the weight (W_1).
2. Place the sample in a mill and add 1,100 ml of water. After a period of 10 minutes has elapsed, add four spheres and rotate 600 revolutions at the uniform speef of 58-62 rpm..
3. Pour the contents of the mill into sieve No. 16 and wash until wash water is clear.
4. Dry the aggregate portion retained on sieve to constant weight and sieve over the No. 16 sieve. Record the weight retained on the sieve (W_2).
5. Calculate the percent loss using the formula

$$\text{Percent Loss minus No. 16} = \frac{W_1 - W_2}{W_1} \times 100$$

APPENDIX C. QUESTIONNAIRE TO DISTRICTS ON THE 4-CYCLE MAGNESIUM SULFATE SOUNDNESS TEST

1. Does your District currently require the 4-Cycle $MgSO_4$ Soundness test to evaluate the quality of aggregates used for:

   Seal Coats? Yes No

   HMAC? Yes No

2. If yes, what is the maximum allowable loss used by the District for:

   Seal Coats? ________________

   HMAC? ________________

3. If a maximum loss of 25% were specified for Seal Coats how would this affect your program in terms of material availability and road performance? (i.e., would it eliminate your usual aggregate sources, would it restrict you to use local sources, would it cause excessive haul distances, would it change your maintenance practices, etc.)

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4. If a maximum loss of 30% were specified for HMAC how would this affect your program in terms of material availability and road performance? (i.e., would it eliminate your usual aggregate sources, would it restrict you to use local sources, would it cause excessive haul distances, would it change your maintenance practices, etc.)

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5. If your district currently uses a loss of 25% for Seal Coats and/or 30% loss for HMAC, please describe your experience with these values.

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