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16. Abstract

Aggregates, through internal friction, must transmit the wheel loads to the underlying layers and also be resistant to abrasion and polishing due to traffic. Aggregates are subject to crushing and abrasive wear during manufacturing, placing, and compacting hot mix asphalt concrete (HMAC), and, therefore, must be hard and tough to resist degradation and disintegration at different stages. A series of different tests are used to ensure that aggregates carry required characteristics for use in HMAC.

Within the last few years, the Texas Department of Transportation (TxDOT) has been using the Hamburg Wheel Tracking Device (HWTD) to evaluate the moisture susceptibility of HMAC. During these tests, it was noticed that softer aggregate underwent severe abrasion under the wheels of the HWTD. Therefore, a research study was sponsored by TxDOT for a period of one year to evaluate the relationship between aggregate properties and the results from the HWTD.

Three limestone, four gravel, one sandstone, and three igneous rocks were considered in the study. These eleven aggregates provided a relatively good coverage of different aggregate types used in Texas.

A series of tests were performed on the aggregates. The tests included magnesium sulfate soundness, Micro-Deval loss, L.A. abrasion, British Pendulum polish value, and acid insoluble residue. Asphalt-aggregate mixtures were prepared according to specific mix designs received from various districts. The mixtures were compacted with a Superpave gyratory compactor. The prepared specimens were tested with the HWTD. The HWTD tested specimens were evaluated by the British Pendulum equipment to quantify the aggregate polishing caused by HWTD. The final step included performing gradation analysis on the extracted aggregates to evaluate the changes from the original gradation caused by the damage and degradation produced by HWTD.

In general, based on the results of the HWTD, limestone aggregates exhibited the highest level of degradation and gravel aggregates demonstrated the toughest resistance to degradation. At the same time, in general, limestone aggregates exhibited better resistance against moisture damage compared to gravel aggregates.

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RELATIONSHIP BETWEEN AGGREGATE PROPERTIES AND HAMBURG WHEEL TRACKING RESULTS: RESEARCH REPORT

by

Mansour Solaimanian
Ginamarco Renato Pendola
Thomas W. Kennedy

Research Report 7-4977-1

Research Project 7-4977
Relationship Between Aggregate Properties and Hamburg Wheel Tracking Results

conducted for the
Texas Department of Transportation
in cooperation with the
U.S. Department of Transportation, Federal Highway Administration
by
THE CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
The University of Texas at Austin

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Implementation Statement

The results of this research project can be used to improve specifications for utilizing aggregates in HMAC, and to provide better means of controlling the quality of the aggregates to be utilized. A set of criteria can be developed for selection of aggregates based on the results from the HWTD. It is perceived that TxDOT investigates the possibility of including such criteria into specifications.

This report was prepared in cooperation with the Texas Department of Transportation, the U.S. Department of Transportation, and the Federal Highway Administration.

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Thomas W. Kennedy, P.E. (Texas No. 29596)
Research Supervisor

Summary

Aggregates, through internal friction, must transmit the wheel loads to the underlying layers and also be resistant to abrasion and polishing due to traffic. Aggregates are subject to crushing and abrasive wear during manufacturing, placing, and compacting hot mix asphalt concrete (HMAC), and, therefore, must be hard and tough to resist degradation and disintegration at different stages. A series of different tests are used to ensure that aggregates carry required characteristics for use in HMAC.

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Chapter 1
Introduction

1.1 Background

The Texas Department of Transportation (TxDOT) has been using a series of laboratory tests to determine the aggregate properties and assess their quality for use as a base material, or for use in portland cement or hot mix asphalt concrete. Los Angeles abrasion (L.A. abrasion), magnesium sulfate soundness, British pendulum polish, and acid insoluble residue are among such tests. A test called Micro-Deval has been among the most recent additions to the aggregate tests conducted by TxDOT. This test is still subject to evaluation at TxDOT.

TxDOT has been investigating two new pieces of test equipment and procedures for evaluation of the moisture damage potential of hot mix asphalt concrete (HMAC). These two include the environmental conditioning system (ECS) and the Hamburg wheel tracking device (HWTD).

Recent work in bituminous laboratory of TxDOT Construction Division has indicated that the HWTD can be used to predict moisture damage susceptibility of HMAC effectively. In addition, visual observations of wheel-tracked specimens at the TxDOT bituminous laboratory has indicated that mixtures containing soft limestone undergo severe abrasion and aggregate degradation when tested in the HWTD but mixes with tough gravel aggregates exhibit little abrasion.

Because the HWTD could distinguish between different aggregate behaviors, research was sponsored by TxDOT and undertaken by the University of Texas at Austin to find a method to quantify or categorize the extent of aggregate degradation caused by the HWTD and determine if there are any relationships between aggregate properties such as soundness loss, L.A. abrasion loss or Micro-Deval loss and the aggregate degradation in the HWTD.

1.2 Objective and Methodology

The main objective of this project was to determine the relationship between the test results from the HWTD and the aggregate properties obtained from tests such as Micro-Deval and L.A. abrasion. Once such a relationship is established, the aggregate behavior in the Hamburg test could assist in deciding whether a specific aggregate will bear enough strength to be used in the field and whether it will provide good performance. For this purpose, aggregates with known performance and available historical data were obtained from a series of different sources. Aggregate tests were performed on the procured materials. HMAC specimens for testing and comparison were prepared using these aggregates. The properties of the polished and distressed aggregates after wheel tracking were evaluated and compared with their original condition, as a minimum, through extraction and gradation analysis. The results from the HWTD test were evaluated through correlation with aggregate tests such as soundness loss, Micro-Deval loss, L.A. abrasion and polish value.

1.3 Hamburg Wheel Tracking Device

The HWTD was developed by Esso A.G. in the 1970's in Hamburg, Germany (Romero et al., 1998). This device measures the combined effects of rutting and moisture damage by rolling a steel wheel across an asphalt concrete surface that is immersed in hot water. In the Texas procedure, typically, a pair of two cylindrical samples, are attached and tested under water simultaneously with two steel wheels moving concurrently. Each steel wheel makes 20,000 passes or until 20 mm of deformation is reached. The measurements are customarily reported versus wheel passes.

The results from the HWTD are the post compaction consolidation, creep slope, stripping slope and stripping inflection point. The post compaction consolidation is the deformation measured at 1,000 passes. The creep slope is the number of repetitions or wheel passes to create a 1 mm rut depth due to viscous flow. The stripping slope is represented by the inverse of the rate of deformation in the linear region of the deformation curve, after stripping begins and until the end of the test. The stripping slope can be quantified as the number of passes required to create a 1 mm impression from stripping. The stripping inflection point is the number of passes at the intersection of the creep slope and the stripping slope, and represents the moisture damage resistance of the HMA and is assumed to be the initiation of stripping (Aschenbrener and Currier, 1993).

The Federal Highway Administration (FHWA) has been involved in several research projects using the HWTD. Researchers Stuart and Izzo (1995) worked on finding a correlation between binder stiffness and rutting susceptibility using the HWTD. They found that a stiffer binder would provide a mixture with lower rutting susceptibility. A study by Mogawer and Stuart (1995) using different binders concluded that the creep slopes should be used for evaluating rutting susceptibility. The researchers also demonstrated that decreasing the coarse aggregate content from 80 to 60 percent had no significant effect on the rutting performance of the mixtures.

Stuart and Mogawer (1997) also performed a study to evaluate the validity of laboratory tracking devices based on pavement performance results. They concluded that the increase in nominal maximum size from 19 mm to 37.5 mm, and an associated 0.85 percent decrease in optimum binder content, decreased rutting susceptibility on actual pavements. However, none of the wheel tracking devices tested, including the HWTD, adequately predicted a decrease in rutting susceptibility with increased nominal maximum aggregate size.

The Colorado Department of Transportation (CDOT) has performed extensive amounts of research evaluating HMA with the HWTD. Aschenbrener (1995) did an evaluation of factors that influence the results from the Hamburg Wheel-Tracking Device. He found that there was an excellent correlation between the stripping observed in the laboratory tests and the moisture damage of pavements with known field performance. There was also an excellent correlation between the stripping inflection point and the known stripping performance. It was found that for good pavements the stripping inflection point was higher than 10,000 passes, and for pavements that lasted one year the stripping inflection point was less than 3,000 passes. It was also found that the results from the HWTD were sensitive to aggregate properties such as dust coating on the aggregates, clay content and high dust to asphalt ratios. One other finding was that as the short-term aging time increases, samples become more resistant to moisture damage. Based on the study, Aschenbrener recommended that testing temperatures for the Hamburg Device should be selected based on the high temperature environment the pavement will experience as shown in Table 1.1.

Table 1.1 Recommended Testing Temperatures forMonday, June 10, 2002
The Hamburg Wheel Tracking Device
(After Aschenbrener, 1995)

Approximate Highest Average 7-Day Air Temperature °C	High Temperature for Performance Grade (PG) °C	Viscosity Grade Meeting the High Temperature PG	Recommended Test Temperature for the HWTD, °C
<27	46		35
27 to 31	52	AC-5	40
32 to 36	58	AC-10	45
>36	64	AC-20	50
Not specified	70	AC-20P	55

Aschenbrener, McGennis, and Terrel (1995) did a study involving several comparisons between moisture susceptibility tests and pavements of known field performance. They found that the City of Hamburg specification, a rut depth of 4 mm after 20,000 passes, is overly strict for many pavements in Colorado. Accordingly, it was necessary to revise the specification and the test temperature. The modified specification, a rut depth of less than 10 mm after 20,000 passes, compares favorably with the pavements of known field performance in Colorado.

Aschenbrener and Currier (1993) found that air void is not an important factor in regard to the results from stripping inflection point. The air voids for this particular study ranged from 4 to 10 percent. However, past testing in the CDOT laboratory using the HWTD has indicated that air voids greater than 10 percent produce significantly lower stripping inflection points than samples compacted between 6 and 7 percent air voids. They also found that the temperature should be increased as the asphalt cement stiffness increases to result in the same stripping inflection point. The temperature should increase 5 °C for every one grade increase in binder stiffness. They also found that adding 1 percent lime to aggregate improved the anti stripping performance of HMAC.

1.4 Aggregate Degradation

Degradation is the inability of the aggregate to resist breaking, and therefore, disintegration into smaller pieces when subject to forces such as compaction, wheel loads, and mixer blades. *The Aggregate Handbook* (1993) states the difference between aggregate degradation and aggregate wear. When wear occurs, the small pieces of aggregate are lost due to abrasion and are brushed aside by the wearing action of the wheel tires. This means that the worn aggregate, i.e., the part that is brushed away, no longer contributes to the aggregate structure behavior. When degradation occurs, the broken pieces, usually larger than those produced by wearing action, remain and contribute to the performance. The L.A. abrasion test is the most widely specified test for evaluation of the resistance of coarse aggregate to degradation by abrasion and impact. *The Aggregate Handbook* (1993) remarks that the L.A. abrasion test results should be used only to indicate the relative quality of aggregates from sources having a similar mineral composition. Test results do not automatically permit valid comparisons between sources distinctly different in origin, composition, or structure. Brown and Haddock (1997) tested granite, limestone, gravel, and traprock and found that the L.A. abrasion test appears to predict trends in aggregate quality but may not be an accurate measure of the breakdown potential for aggregates. The NCHRP Study 10-12 (1981) found that the L.A. abrasion test did not correlate well with any of the performance characteristics on asphalt concrete surface courses. It is evident there is a need to develop a test to measure degradation in a more precise way.

The Micro-Deval test was introduced as a provisional standard by AASHTO. Senior and Rogers (1991) indicated that the percent loss obtained from Micro-Deval is similar to the one from the soundness test. The Micro-Deval apparatus showed more precision than soundness when comparing the same aggregates. Senior and Rogers measured the performance of coarse aggregate and stated that Micro-Deval gave the best results on granular bases, portland cement concrete and asphalt concrete. The sulfate soundness test is basically used as an indication of the quality of aggregates. The purpose of this test is to be able to estimate the ability of an aggregate to resist the weathering action. From previous research studies the ASTM Standard C88 states that: *"Since the precision of this test 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."* This statement means that it is necessary to perform other tests in order to verify the aggregate properties measured by the sulfate soundness test. Sodium sulfate soundness tests were run on both coarse and fine aggregate fractions for NCHRP Study 10-12 (1981). The results using fine aggregate were not considered due to the high variability experienced. The soundness loss using the coarse fraction showed that the 12 percent limit generally specified by various states seems to be reasonable. The test gave high values when testing carbonate rocks caused by the reaction between the rock and the sulfate. The Water Absorption Test was recommended as a more reliable test instead of the soundness test when using carbonate rocks. NCHRP Study 10-12 (1981) also found that raveling of the asphalt mix could be predicted based on several tests that include soundness.

The British Pendulum Tester (BPT) is the most commonly used equipment to measure aggregate polishing in the laboratory. In a research study by Abdul-Malak et al. (1988), it was found that the aggregate soundness is an important characteristic affecting the frictional resistance of highway surfaces. The findings indicated that aggregates that had high polish values but were inadequate in soundness did not have good frictional performance. From a continuation study by Abdul-Malak et al. (1992), it was concluded that there were no good correlations between the polish value and results from tests such as the soundness, L.A. abrasion and acid insoluble. However, good correlations were found between the polish value and each of the soundness and L.A. abrasion tests for the limestone aggregate group tested.

1.5 Implementation and Contribution to the Industry

Aggregate characteristics play a major role in the performance of HMAC. Investigating aggregate behavior under the rolling wheels in the laboratory provides valuable information regarding the aggregate toughness and how it may behave once placed in the HMAC in the field. Including aggregates of different sources in this study provided a valuable database of such information. The results of this research project can be used to improve specifications for utilizing aggregates in HMAC, and to provide better means of controlling the quality of the aggregates to be utilized. The results can be used to develop a set of criteria for selection of aggregates based on the results from the HWTD. It is perceived that TxDOT investigates the possibility of including such criteria into specifications.

1.6 Description of the Report Contents

The background information and the scope of the research program are provided in this chapter. The experimental program, material selection, and the performed tests are covered in Chapter Two. The results of the study and the corresponding analysis are presented in Chapter Three. Finally, Chapter Four includes a summary along with conclusions and recommendations regarding this study.

Chapter 2
Experimental Program

2.1 General Approach

The objective of this study was finding a method to quantify or categorize the extent of aggregate degradation caused by the HWTD, and determine if there were any relationships between the HWTD test results and the aggregate properties such as soundness loss, Micro-Deval Loss, L.A. abrasion and polish value.

To achieve this goal, it was decided to approach the laboratory work in several steps. The first step was selecting and gathering aggregates from different sources. Attempts were made to include aggregates of various types. Limestone, gravel, sandstone, and granite were all included. This was followed by procurement of asphalt binders for preparing asphalt-aggregate mixtures corresponding to specific mix designs. The binders were from different sources and different PG grades. Specimens were compacted using the Superpave Gyratory Compactor (SGC), and then tested by the Hamburg Wheel Tracking. The HWTD-tested specimens were evaluated by the British pendulum device to quantify the aggregate polishing caused by the HWTD. The final step included performing gradation analysis on the extracted aggregates to evaluate the changes from the original gradation caused by the damage produced by the HWTD.

Parallel to the work described above, a second set of aggregates for performing tests on aggregate were prepared. Some of the equipment required for aggregate tests were not available at the University of Texas asphalt laboratory. Therefore, aggregate tests were conducted by the materials sections of the TxDOT Construction Division. After the aggregates were washed and sieved, they were properly bagged and shipped to the TxDOT materials section. The bags were properly labeled including necessary information on test type, aggregate type and size, etc.

A series of tests including L.A. abrasion, soundness loss, polish value and Micro-Deval loss were conducted on the aggregates. The high quality and intensive testing for the aggregates was conducted by TxDOT personnel.

2.2 Equipment and Tests Used

Preparation and testing HMAC specimens required the use of a series of test procedures and several pieces of equipment. The following provides a list of equipment for this project:

- Three large capacity ovens capable of maintaining high temperatures,
- Two totally-enclosed counterbalanced sieving machines,
- A mechanical mixer, bowl and hot plate
- A Superpave gyratory compactor,
- A Hamburg Wheel Tracking Device,
- A British Pendulum Tester,
- A Vacuum Extractor, and
- A pycnometer for measuring maximum theoretical specific gravity

The test procedures followed for the project included the following:

- Sieve analysis of fine and coarse aggregate (Test Method Tex-200-F)
- Laboratory method of mixing bituminous mixtures (Test Method Tex-205-F)
- Maximum theoretical specific gravity of bituminous mixtures, (Test Method Tex-227-F, ASTM D2041)
- Determination of density of compacted bituminous mixtures (Test Method Tex-207-F)
- Method for preparing and determining the density of hot mix asphalt (HMA) Specimens by means of the SHRP gyratory compactor (Test Method AASHTO TP4)
- Hamburg wheel tracking test (Test Method Tex-242-F)
- Determination of asphalt content of bituminous mixtures by extraction, Part II, Vacuum extraction method using chlorinated solvent (Texas Test Method Tex-210-F)
- Abrasion of coarse aggregate using the Los Angeles machine (Tex-410-A, ASTM C131)
- Soundness of aggregate by use of sodium sulfate or magnesium sulfate (Tex-411-A, ASTM C88)
- Accelerated polish test for coarse aggregate (Tex-438-A)
- Resistance of coarse aggregate to degradation by abrasion in the Micro-Deval apparatus (AASHTO Provisional Standard – Spring 1999)
- Acid insoluble residue for fine aggregates (Tex-612-J)

All the Texas test procedures are provided in the *Texas Manual of Testing Procedures* (Texas Department of Transportation, 1995-1997)

2.3 The Experiment Design

Table 2.1 presents the original testing matrix for this study. The work included procurement of eleven different aggregates as shown in the table.

Table 2.1 Testing Matrix for Aggregate Degradation Study

Agg. Code	Agg. Type	HW TD at 40 or 50°C	Extrac-tion	Grad. Anal.	L.A. Abr.	Micro Deval	Polish Value	Sulfate Sound-ness	Acid Insol-uble
BR	Limest.	√	√	√	√	√	√	√	√
VU	Limest.	√	√	√	√	√	√	√	√
CO	Limest.	√	√	√	√	√	√	√	√
HB	Rhyol.	√	√	√	√	√	√	√	√
HN	Gravel	√	√	√	√	√	√	√	√
WR	Gravel	√	√	√	√	√	√	√	√
MI	Gravel	√	√	√	√	√	√	√	√
FD	Gravel	√	√	√	√	√	√	√	√
VM	Granite	√	√	√	√	√	√	√	√
PD	Basalt/ Granite	√	√	√	√	√	√	√	√
MR	Sandst.	√	√	√	√	√	√	√	√

The number of specimens and the temperatures used for testing with HWTD are presented in Table 2.2.

Table 2.2 Number of Specimens and Temperature Used in HWTD

Agg. Code	Agg. Type	No. of Batches	SGC Specimens	HWTD Test Temp. C	Binder Source	PG Grade
BR	Limestone	12	4	40	D.Shamrock	64-22
VU	Limestone	10	4	50	Coastal	64-22
CO	Limestone	10	4	50	Coastal	64-22
HB	Rhyolite	12	6	50	Coastal	64-22
HN76*	Gravel	4	4	50	Lion Oil	76-22
HN	Gravel	2	2	50	Coastal	64-22
WR	Gravel	12	4	50	TF&A	76-22
MI	Gravel	10	4	50	Coastal	64-22
FD	Gravel	12	4	50	Coastal	64-22
VM	Granite	10	4	50	Coastal	64-22
PD	Basalt/ Granite	5	4	40	Fina	64-28
PD50*	Basalt/ Granite	5	4	50	Coastal	64-22
MR	Sandstone	10	4	50	Coastal	64-22

HN76* : 76 is stated to differentiate between use of Lion Oil (Agg. Code HN76) vs Coastal (Agg. Code HN).
PD50* : 50 is stated to differentiate between HWTD testing at 50° C vs. 40° C for Agg. Code PD

2.4 Material Selection and Procurement

An important step of this research project was selection and procurement of the materials required for the program. Aggregates and binders from specific TxDOT approved mix designs were received from different districts. The PG binders were initially from different suppliers. Some of the binders were polymer modified. In general, all eleven aggregate structures had different binders based on the original mix design.

2.4.1 Aggregates

Through coordination with TxDOT, eleven different aggregate sources were considered for this project. These aggregates provide a good representative of different aggregates used in Texas. The aggregates were of different types. Four were siliceous gravel, three were limestone, one was sandstone, and the remaining three were igneous (granite, basalt/granite, and rhyolite). Aggregates from different sources and designs had different gradations and included course, medium, and fine gradation. The amount of aggregate needed for preparation of each SGC specimen was based on two constant parameters: 63 mm height and 7 % air voids. Based on these two requirements, the amount of aggregate varied from one source to the other. Table 2.3 is presented as an example for aggregate gradation.

Table 2.3 Aggregate Gradation from Vulcan

	Percent Passing			
Sieve Size mm	Vulcan 0.38 in. 30%	Vulcan 0.25 in. 30%	Vulcan Man. Sand 30%	D. Hale Field Sand 10%
12.50	100.0	100.0	100.0	100.0
9.50	93.8	100.0	100.0	100.0
4.75	3.5	72.1	100.0	99.9
2.00	0.3	5.1	85.7	99.8
0.425	0.3	1.1	26.2	99.5
0.180	0.3	1.0	10.7	54.1
0.075	0.2	0.9	4.2	8.8

For this specific example, it was determined that approximately 2,400 gr. of aggregates were needed for obtaining one specimen with 63 mm and 7 percent air voids. The sieves with a small quantity of retained aggregate were eliminated in order to make the sieving process simple and practical. A sufficient amount of aggregate was processed and prepared to deliver four specimens per source for testing in the HWTD. The same aggregate sources were also used for preparing required batches to perform the aggregate tests at TxDOT Construction Division Soil Section (Table 2.4). These tests included L.A. abrasion, soundness, polish value, Micro-Deval, and acid insoluble residue.

Table 2.4 List of Aggregates Delivered to TxDOT for Performing Aggregate Tests

Sample ID	Test	Grade	Sieve Passing (in.)	Sieve Retained (in.)	Weight (gr.)	Date Delivered
BR4977A1	L.A. Abrasion	Vulcan 3/8"	3/8	¼	2500	03/13/00
BR4977A2	L.A. Abrasion	Vulcan 3/8"	¼	#4	2500	03/13/00
BR4977M1	Micro-Deval	Vulcan 3/8"	½	3/8	750	03/13/00
BR4977M2	Micro-Deval	Vulcan 3/8"	3/8	¼	375	03/13/00
BR4977M3	Micro-Deval	Vulcan 3/8"	¼	#4	375	03/13/00
BR4977P1	Polish Value	Vulcan 3/8"	3/8	¼	2000	03/13/00
BR4977S1	Soundness	Vulcan 3/8"	½	3/8	1000	03/13/00
BR4977S2	Soundness	Vulcan 3/8"	3/8	¼	180	03/13/00
BR4977S3	Soundness	Vulcan 3/8"	¼	#4	120	03/13/00
BR4977S4	Soundness	Vulcan 3/8"	#4	#8	100	03/13/00

2.4.2 Binders

At the beginning of this research study all eleven binders corresponding to the eleven sources were considered. Most of these binders were based on Superpave performance grading (PG grading). The binders procured are presented in Table 2.5.

Table 2.5 Original Binders Procured for Different Mixes

District	Aggregate Type	Aggregate Source	PG Binder	Binder Source	% AC
Wichita Falls	Limestone	Bridgeport	64-22	D.Shamr.	4.8
Brownwood	Limestone	Brownwood	76-22	Koch	5.2
Austin	Limestone	Hunter	64-22	Coastal	5.0
Odessa	Rhyolite	Hoban	70-22	Fina	7.3
Atlanta	Gravel	Delight, AR	76-22	Lion Oil	4.9
Corpus Christi	Gravel	Realitos	76-22	TF&A	4.6
Laredo	Gravel	Price	70-16	TFA	5.0
Pharr	Gravel	Showers	64-22	Coastal	5.5
El Paso	Granite	Vado/Mack	AC-20		5.5
Lubbock	Basalt / Granite	Pedernal	64-28	Fina	4.1
Paris	Sandstone	Sawyer	64-22	Lion	5.9

To make the comparison more meaningful, to reduce the number of variables affecting the results, and to be able to quantify the aggregate behavior, it was decided to use the same binder for all the aggregates. Coastal PG 64-22 was the binder used for this purpose. A PG 64 binder instead of a PG 70 was selected so that the aggregate interaction with the wheels becomes more severe due to the use of a softer asphalt. Therefore, rather than using the original binders used in mix designs, Coastal PG 64-22 was used with all the aggregates. The exception to this is the limestone aggregate from Bridgeport, Tx and the gravel aggregate from Realitos, Tx. For these two, the original binders (Diamnond Shamrock PG 64-22 for the former, and TFA PG 76-22 for the latter) were used. The reason for this exception was to keep at least two of the designs as the original design for the sake of possible future field comparisons. For the gravel aggregate of Delight, Arkansas and the granite aggregate of Pedernal, Tx, the specimens were made both with the original binders (i.e. Lion Oil PG 76-22 for the former and Fina PG 64-28 for the latter) and with the Coastal PG 64-22.

In regard to the test temperature, TxDOT recommends saturating and testing the HMAC specimens at 40°C. However, for the scope of this project, it was considered beneficial to increase the temperature to 50°C in order to evaluate the aggregate degradation more easily. Aggregates from the four of sources were tested using their original binders used in the mix design. Two of these four were also tested using the Coastal PG 64-22 binder. For all the remaining seven sources, Coastal PG 64-22 was used. Aggregates and binders used for this study are presented in Table 2.5.

Table 2.6 Aggregates and Binders Used in this Research Study.

No.	Aggr. Code	Aggregate Type	Aggregate Source	Aggr. Producer	PG Binder	Binder Source	% Binder	HWTD Temp., C
1	BR	Limestone	Bridgeport	TXI	64-22	D. Shamr.	4.8	40
2	VU	Limestone	Brownwoo d	Vulcan	64-22	Coastal	5.2	50
3	CO	Limestone	Hunter	Colorado	64-22	Coastal	5.0	50
4	HB	Rhyolite	Hoban	Jones Br.	64-22	Coastal	7.3	50
5	HN76	Gravel	Delight, AR	Hanson	76-22	Lion Oil	4.9	50
6	HN	Gravel	Delight, AR	Hanson	64-22	Coastal	4.9	50
7	WR	Gravel	Realitos	Wright	76-22	TF&A	4.6	50
8	MI	Gravel	Mirando	Price	64-22	Coastal	5.0	50
9	FD	Gravel	Showers	Fordyce	64-22	Coastal	5.5	50
10	VM	Granite	Vado/Mack	Jobe Conc	64-22	Coastal	5.5	50
11	PD	Basalt/ Granite	Pedernal	Western Rock Pro	64-28	Fina	4.1	40
12	PD50	Basalt/ Granite	Pedernal	Western Rock Pro	64-22	Coastal	4.1	50
13	MR	Sandstone	Sawyer	Meridian	64-22	Coastal	5.9	50

2.5 Mix Design

TxDOT District Laboratories provided the mix. All of the designs have been applied to some recent HMA overlay constructions. Some of the designs required the use of lime or liquid antistripping additives. However, for the special purpose of this project, antistripping additives and lime were not used so that the aggregates participate in a more intense interaction with the HWTD wheels. This way, degradation, if any, becomes easier to identify. However, as mentioned before, four of the aggregates were also tested using the original mix designs. The mix design information is presented in Table 2.7. In this table, for each aggregate source, the first binder in the sequence is the binder used in the original mix design, and the second binder in the sequence is the Coastal PG 64-22. Those mix design binders identified with an asterisk were not used and were replaced by Coastal PG 64-22.

Table 2.7 Mix Designs for the Asphalt and Aggregates Used in this Research Study

District	County	Highway	Contractor / Producer	Type Mix	Aggregate Type	Aggregate Source	PG Binder	Binder Source	% AC
Wichita Falls	Montague	S.H.175	Duininck Bros. Inc./ TXI	D	Limestone	Bridgeport	64-22	D.Sham r.	4.8
Brown-wood	Brown	S.H.279	Bay Maintenan ce / Vulcan	D	Limestone	Brownwd.	76-22 64-22	Koch* Coastal	5.2
Austin	Travis		Colorado Mtls.	D	Limestone	Hunter	64-22	Coastal	5.0
Odessa	Ector	F.M. 1882	Jones Bros.	CMH B-F	Rhyolite	Hoban	70-22 64-22	Fina* Coastal	7.3
Atlanta	Panola	U.S. 79	Marshall Paving Products/ Delight, Ark.	C	Gravel	Hanson	76-22 64-22	Lion Oil Coastal	4.9
Corpus Christi	Nueces	I.H. 37	Haas Anderson/ Wright	C	Gravel	Realitos	76-22	TF&A	4.6
Laredo	Webb	I.H. 35	Price	D	Gravel	Mirando	70-16 64-22	TF&A Coastal	5.0
Pharr	Cameron	F.M.324 8 E	B.C.CO./ Fordyce	D	Gravel	Showers	64-22	Coastal	5.5
El Paso	El Paso	62/180	J.D. Abrams / Jobe Concrete	19 mm	Granite	Vado/Mac k	AC-20 64-22	Coastal	5.5
Lubboc k	Lubbock	Spur 313	Williams & Peters Const. / Western Rock Pro.	C	Basalt / Granite	Pedernal	64-28 64-22	Fina Coastal	4.1
Paris	Fannin	S.H.56	Buster Paving Co / Buster-Sawyer Meridian	C	Sandstone	Sawyer	64-22 64-22	Lion* Coastal	5.9

2.6 Sieving and Batching

All aggregates were dried in the oven at 110°C for 24 hrs, followed by sieving. After sieving, the aggregates were combined to deliver the required gradation for a specific design. Batches were properly proportioned using different material sizes. A sufficient amount of the dried material was sieved to obtain twelve aggregate batches, 2,400 to 2,500 gr. for each batch.

These batches were used for preparing asphalt-aggregate specimens for the HWTD and for determining the maximum theoretical specific gravity. In addition, the sieved aggregates were combined properly to obtain the required quantities for performing aggregate tests (L.A. abrasion, soundness loss, polish value, Micro-Deval, and acid insoluble). Sieving was accomplished using the Gilson Test Master Sieving Machine™, model TM-3. A portable 8-in. Rainhart Sieve Shaker was also used for sieving when a small amount of the material was needed. This latter shaker was specifically used for checking the aggregate gradations for randomly selected batches as well as for determination of gradation for each specimen after the extraction test. For this particular project it was decided to recheck the gradations, considering the importance of them on the final analysis of the results. The original gradation per source was verified for three random batches. Later the cumulative percent passing for each aggregate was used as a parameter for comparison of gradations before and after testing with the HWTD.

2.7 Specific Gravity, Mixing, and Compacting

2.7.1 Specific Gravity

For each aggregate type, five asphalt-aggregate mixtures were prepared using the optimum asphalt content and design gradation. Of these, four specimens were compacted and used for testing with the HWTD, and one was used for determination of maximum theoretical specific gravity. For this test, most commonly known as the RICE test, between 2500 to 2600 gr. of the sample mass were used. The test was performed using a Pycnometer model H-1756 from Humboldt. The 4.5-Liter H-1756 pycnometer meets ASTM D2041. The test also uses a Residual Pressure Manometer that meets ASTM D2041. A vacuum pump is also necessary for performing the test. A vacuum pump similar to the MA-28 (115 V/60 Hz) from Gilson Company Inc. was used for performing the maximum theoretical specific gravity.

The bulk specific gravity of the compacted specimens was determined using a SG-20 Specific Gravity Bench with SGA-120 Tank, an Ohaus Balance with 0.1-gr. accuracy, and a SGA-119 Specific Gravity cradle (SGA models from Gilson Company Inc.). The specimens were left at the ambient temperature for approximately 24 hours prior to the bulk specific gravity test.

2.7.2 Mixing and Compaction

The mixing procedure was performed using the specific aggregate gradation and the optimum binder content as established based on the mix design. The mix designs for specific projects were received from districts and were not conducted at the research facility as part of this research. At the request of the research agency, different districts that had provided the research team with the aggregates also submitted some of their typical mix designs for the specific aggregates shipped to the research agency.

The temperatures for mixing and compaction were selected based on the table provided by materials section of the TxDOT construction division (Table 2.8). The binder grading presented in this table follows the Superpave performance grading. The aggregates were heated at 110 C oven overnight and the asphalt was heated in an oven for 1 ½ hours prior to mixing and for 2 hours prior to compacting.

Table 2.8 Mixing and Compacting Temperatures – TxDOT Recommendation

Binder	Compaction Temp, °F (°C)	Mixing Temp, F (°C)
PG 64-22	250 (121)	290 (143)
PG 70-22	275 (135)	300 (149)
PG 76-22	300 (149)	325 (163)
PG 64-28	275 (135)	300 (149)
PG 70-28	300 (149)	325 (163)

The equipment used for mixing consist of a heating oven, a balance readable to 0.1-g accuracy, a hot plate, a mechanical mixer and bowl, whisk, pans, spatulas, scoops and the instruments necessary for gathering all the mix stuck on the bowl and whisk.

Testing with the HWTD requires that the specimen height be 62±2 mm. In the test procedure, it is also specified that the air void should be 7±1 percent. Therefore, enough mixture had to be compacted to provide a specimen with a known height and known air void content. To determine the amount of mixture required for this purpose, some calculations were performed using the volume of the specimen (based on a diameter of 150 mm and a height of 63 mm), the maximum theoretical specific gravity, the binder specific gravity, and the binder content. This way enough material was introduced into the mold to obtain the required height and the required air void. The compaction process was started after heating the mixture and the SGC mold for two hours. Care was taken to avoid mix segregation while introducing the material into the mold. The mold containing the specimen was placed in the Superpave Gyratory Compactor (SGC) and the height control was set at 63 mm before initiating the compaction. Different specimens required a different number of gyrations to achieve the same height. After the required height was achieved, the compaction would automatically stop, and the pressure gradually released. The specimen was partially extracted from the mold and allowed to cool down with the aid of a fan.

The number and type of sources tested with the corresponding mixing and compacting temperatures are shown in Table 2.9.

Table 2.9 Mixing and Compaction Temperatures Used for the Research Study

Aggregate Source	PG Binder	Binder Source	Mixing Temp. °F (°C) *	Compact Temp. °F (°C) *
Bridgeport	64-22	D. Shamr.	250 (121)	290 (143)
Brownwood	64-22	Coastal	250 (121)	290 (143)
Hunter	64-22	Coastal	250 (121)	290 (143)
Hoban	64-22	Coastal	250 (121)	290 (143)
Delight, AR	76-22	Lion Oil	300 (149)	325 (163)
Delight, AR	64-22	Coastal	250 (121)	290 (143)
Realitos	76-22	TF&A	300 (149)	325 (163)
Mirando	64-22	Coastal	250 (121)	290 (143)
Showers	64-22	Coastal	250 (121)	290 (143)
Vado/Mack	64-22	Coastal	250 (121)	290 (143)
Pedernal	64-28	Fina	275 (135)	300 (149)
Pedernal	64-22	Coastal	250 (121)	290 (143)
Sawyer	64-22	Coastal	250 (121)	290 (143)

* Temperatures based on TxDOT Recommendation

2.8 Superpave Gyratory Compactor

The Superpave Gyratory Compactor (SGC) is believed to simulate the field compaction process more realistically compared to some other compactors. The compaction is controlled by three important parameters: the angle, number of gyrations, and vertical pressure. Past experience has shown that the SGC provides consistent results as long as the influencing parameters are calibrated properly. It also records data to provide a measure of specimen density throughout the compaction procedure. The SGC consists of four basic components:

- Mold and base plate
- Height measuring and recordation system
- Loading system, loading ram, and pressure
- Recording frame, rotating base and motor

The current Superpave procedure recommends that the mold be positioned at a compaction angle of 1.25 degrees, gyrations at a rate of 30 rpm during compaction, and a vertical pressure of 600 kPa applied to the specimen from the loading ram. A pressure gauge measures the ram loading to maintain constant pressure during compaction. The number of gyrations depends basically on the temperature and the severity of traffic. Obviously for higher temperature and traffic the number of gyrations should increase in order to get a denser specimen. Normally samples are 150 mm in diameter. For this study, the height was set at 62±1 mm, requiring sample weights of about 2,350 to 2,500 gr. As mentioned before, the test procedure with the HWTD requires a height of 62 ±2 mm and 7±1 percent air voids for the specimen. With these two restrictions, it was necessary to vary the amount of aggregate from source to source to get the proper height and air voids. The number of gyrations was variable depending on the mix configuration.

The speed of gyrations was kept as 30 rpm. The pressure was 600 kPa and the angle was set up at 1.25 degrees according to Superpave recommendations. Originally it was planned to compact forty four specimens for the eleven sources involved in this study (four specimens for each source). However, because of some changes along the course of the project the number increased to approximately sixty. The following figure shows the Troxler Model 4140 Gyratory Compactor used for this research study.

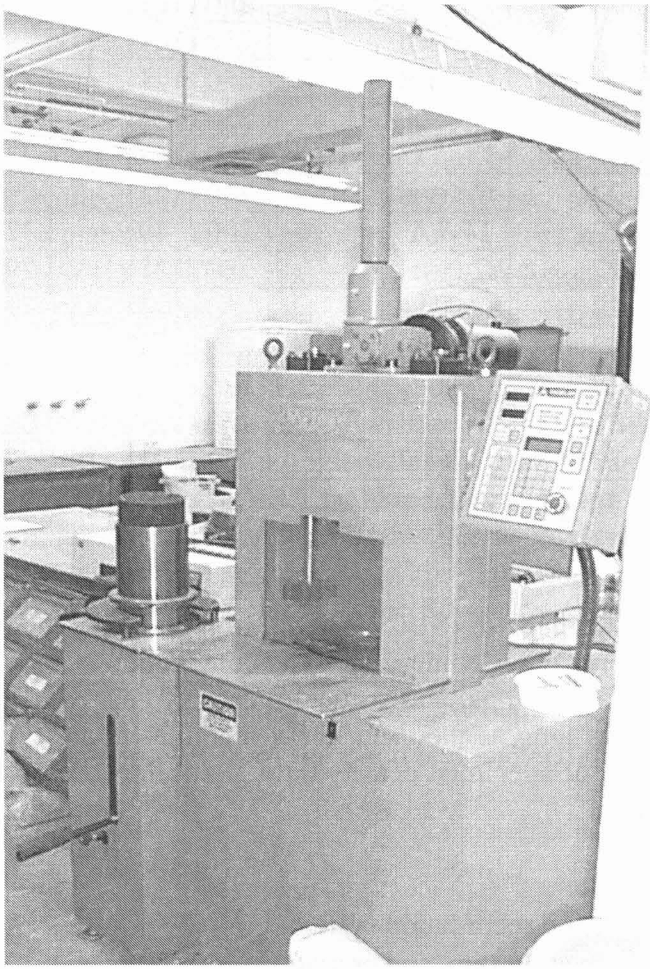


Figure 2.1 Superpave Gyratory Compactor

2.9 The Hamburg Wheel Tracking Device (HWTD)

The HWTD, shown in Figure 2.2, as developed for predicting rutting potential and moisture susceptibility of HMA specimens.

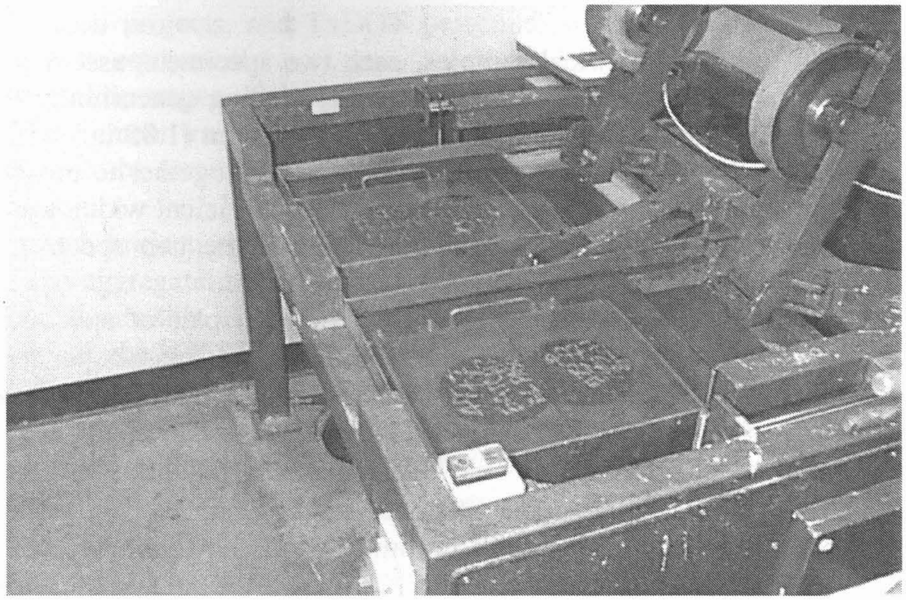


Figure 2.2 Hamburg Wheel Tracking Device

Originally, a pair of cubical or beam specimens were tested simultaneously. This type of HWTD specimen is typically 260 mm (10.2 in) wide, 320 mm (12.6 in.) long, and 40 mm (1.6 in.) deep. However, with the increasing use of the Superpave Gyratory Compactor, TxDOT has been using cylindrical specimens for testing with the HWTD. The cylindrical specimens are 150 to 300 mm in diameter and 62 mm thick, compacted to 7±1 percent air voids. The setup takes advantage of four cylindrical specimens, two per steel wheel of HWTD. Figure 2.3 shows how the two specimens are set up in the molds.

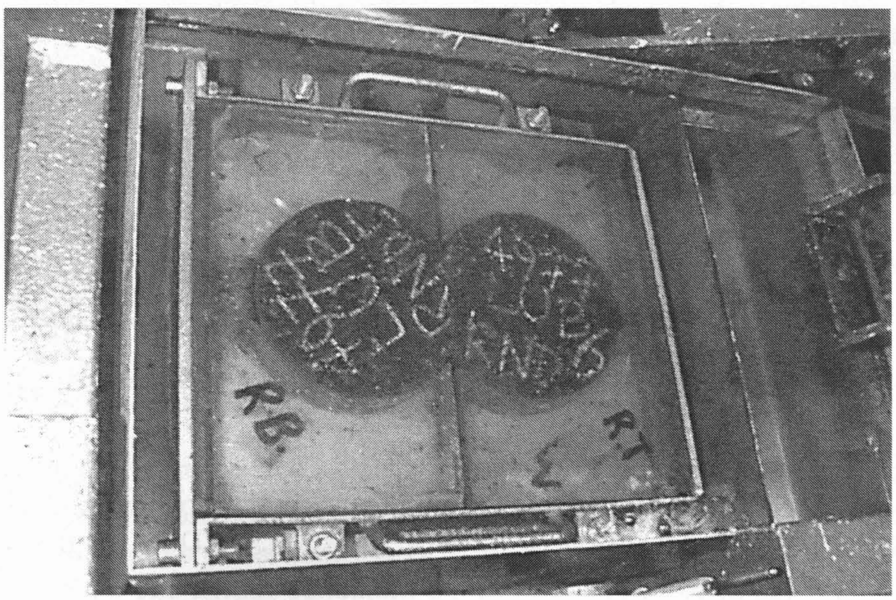


Figure 2.3 Specimens Configuration for HWTD

Typically, a pair of two cylindrical samples, each two specimens assembled together, are tested under water simultaneously with two steel wheels moving concurrently through a crank connected to a flywheel. The steel wheel is approximately 47 mm (1.85 in.) wide and loads the sample with 705 N (158 lbs). The two specimens are attached together to provide the required length for a continuous path for the wheels. In order to have sufficient width, a small segment of the specimen is removed to create a smooth surface before the two specimens are attached together.

Rut depth measurements are taken at the center of each pair of specimens by a linear variable differential transducer (LVDT). The wheel performs 53±2 passes per minute over each pair of two cylindrical samples. The test automatically stops at 20 mm of deformation or 20,000 cycles, whichever occurs first. Approximately 6 ½ hours are required for a complete 20,000 wheel pass test. The test temperature can vary between 25 to 75°C. Based on previous testing experience at TxDOT, it is recommended that the test be conducted at either 40 or 50°C, depending on the PG grade of the binder. For example, a PG64-22 binder should be tested at 40°C, and a PG 70-22 binder at 50°C. In other words, the stiffer the asphalt, the higher the test temperature will be. The following figure shows the HWTD running on one of the samples prepared for this research study.

Figure 2.4 Test being Performed by the Hamburg Wheel Tracking Device

The deformation and slope measurements are customarily reported as a function of number of wheel passes. The results from the HWTD are the post compaction consolidation, creep slope, stripping slope and stripping inflection point. However, TxDOT is not using the post compaction parameter as a criterion.

The main objective of this study was finding a method to quantify or categorize the extent of aggregate degradation caused by the HWTD. Aggregates from eleven different sources were tested using the TxDOT Hamburg device. At the time, the HWTD was heavily used by TxDOT in relation with their projects, and TxDOT personnel were very courteous in authorizing the researchers to use the equipment.

During the middle stages of the project, the HWTD suffered some failure with one of the deformation measurement transducers, leaving only one transducer available. As a result, only two specimens could be tested at one side of the equipment, causing considerable delay in the progress of the project.

In this research project, an important tool used to evaluate the aggregate degradation was comparison of the aggregate gradation before and after testing with the HWTD. Therefore, it was important to ensure that all the material was procured after completion of the HWTD test. To achieve this goal, the HWTD was vacuumed and cleaned before performing each test so that, upon completion of the test, no material from a previous test was blended with the material from the next test. The specimens were weighed before performing the test. After the test, the fine material was carefully collected from the bottom of the water tank. This collected material as well as the material cut from the side of the specimen were included in order to have a more precise measurement of final gradation. As mentioned before, a 40°C test temperature is recommended for a PG 64-22 binder. However, because this research was aimed at evaluating the aggregate degradation, the temperature was selected at 50°C to create a more severe condition. At the beginning of the project, some of the test results at 40°C indicated that the test was not severe enough to see the aggregate behavior under the wheel even though the test was severe enough to evaluate the stripping potential of the mix. At 50 °C, most of the specimens were failing within 1 ½ to 3 hours from the time the test was initiated. Failure occurred when the specimens reached 20 mm of permanent deformation. The failed specimens and the separated material were carefully stored in labeled containers until further processing.

2.10 British Pendulum Tester and Polish Value

Polishing is basically a reduction in microtexture. The process is caused by particle wear on a microscopic scale and is difficult to quantify. The British Pendulum Tester (BPT) is the piece of equipment most widely used for this purpose. This quantifies polishing using low-speed friction measurements. Such measurements are made on the wetted surface. The aggregates are washed and dried at constant mass at 110°C before performing the test. Metal molds are required to form test coupons, which should have an exposed aggregate surface area 44.5 mm (1.75 in.) wide, 16 mm (0.675 in.) deep and 89 mm (3.5 in.) long, with two outside mounting edges measuring 3.2 mm (0.125 in.) wide running the full length of the coupon and 6.4 mm (0.25 in.) deep. From past experience, it is believed that the rubber responds essentially only to microtexture because it displaces enough water so that the hydrodynamic effect, which controls the friction on coarse aggregates, is basically absent. The BPT is also used for evaluating existing pavements. The testing is performed usually on dry pavement surfaces, because 96 to 97 percent of the time pavements are dry. The BPT is used under the Texas Test Method Tex-438-A for evaluating the relative wear and polish of coarse aggregate. About 2000 gr of material passing the 9.5 mm (0.38 in.) and retained on the 6.3 mm (0.25 in.) sieve is needed. The aggregates are placed in close contact in a single layer in metal molds. A polyester resin is used as the bonding agent. Before performing the BPT it is necessary to check and adjust the length of the slider contact path. The British pendulum polish test can be performed on aggregates in two different conditions: aggregates in the original or natural stage, before they are polished, and aggregates that have been polished for nine hours using the Wessex accelerated polishing machine. These two values are known as initial polish value and polish value, respectively. A rubber air tire is used with a cross-hatching pattern tread. After checking the proper alignment and positioning of the slider, five passes are performed. The sample is superficially saturated with water before performing every pass. The first reading is disregarded, and the average of the second through the fifth readings is established as the polish value. Another type of polish value measurement is also obtained with the solid tire, known as the residual polish value. The pendulum swing is continued on the same sample until the same reading is repeated four consecutive times. This repeated number is considered the residual polish value.

For this research study, the BPT was used for two different purposes. It was first used to measure the aggregate polish value according to the Texas Test Method Tex-438-A. For this task, TxDOT soils section personnel were courteous in conducting the tests. The second use of the BPT was completely different from what is explained in Test Method Tex-438-A. The equipment was directly used on the HMAC specimens that were already tested in the HWTD. Figure 2.5 shows the configuration and leveling performed on HWTD tested specimens using the BPT.

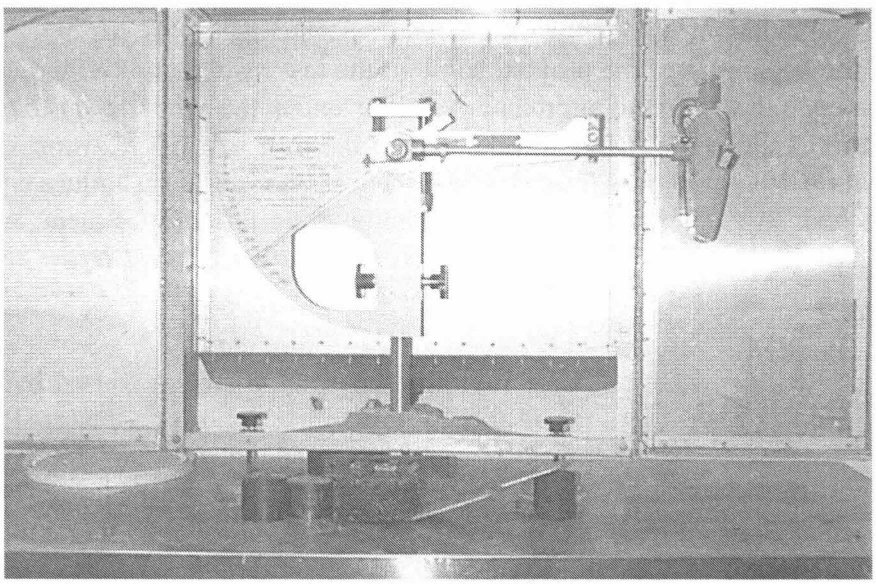


Figure 2.5 Testing with BPT Using HWTD Specimens

The objective of using the BPT in this way was to determine if it could provide valuable information on the surface roughness due to aggregate degradation caused at the surface of wheel-tracked specimens tested previously with the HWTD. This task was difficult because some surfaces had too many irregularities. In addition, the width of the rutted areas was too narrow to perform the test easily. It was decided to remove the material adjacent to the wheel-tracked surface in order to perform the test without the interference of any material with the slider. The leveling process was the critical step for obtaining representative readings. Each specimen, already tested with the HWTD, was tested by the BPT separately. The deformation from Hamburg wheel tracking was maximum at the center where the two specimens met. The deformation decreased while moving to the sides from the center of the specimen. Most of the readings were taken for surface contact lengths of 1, 2 and 3 in. Surface contact lengths between 4 and 5 in. were not considered to be representative readings because of the differences in deformation heights from one point to the other. Here, the contact length refers to the distance that the pendulum travels on the specimen. It should be noted that these BP readings are not directly comparable with the results obtained from running the BP test according to Test Method Tex-438-A.

2.11 Extraction Test

The extraction test was performed following Test Method Tex-210-F. The procedure can be performed in four different ways: the centrifuge extraction method using chlorinated solvent (part I), the vacuum extraction method using chlorinated solvent (part II), the centrifuge extraction method using non-chlorinated solvent (part III), and vacuum extraction method using non-chlorinated solvent (part IV). For this project, the vacuum extraction method using chlorinated solvent was used. The HWTD tested specimens and all the loose material recovered from the HWTD and the BPT was used for the extraction process. Sixty grams of the filtering aid, which was pure diatomaceous filter powder, was introduced in a glass beaker graduate. The filtering aid was then mixed with approximately 500 milliliter of trichloroethylene (TCE) as the solvent for the extraction for the test. A vacuum pump was used while the blend of TCE and filtering aid powder was poured uniformly through the filter surface. Meanwhile, TCE was added to the asphalt-aggregate in order to dissolve the binder and separate it from the aggregates. For this project, it was not necessary to recover the binder. The extracted aggregate was processed through sieving and its gradation was determined for comparison against its original gradation, i.e., before HWTD test. This comparison provided the basis for deciding the intensity of degradation during the HWTD test.

2.12 L.A. Abrasion Test

An important property of the aggregates is the resistance to abrasion due to traffic. The L.A. abrasion test is used primarily to evaluate the toughness and resistance to abrasion. Texas Test Method Tex-410-A (ASTM C131), "Resistance to Degradation of Small Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine," is used for evaluating abrasion resistance of coarse aggregates smaller than 38 mm (1.5 in.). This is the method normally used for hot mix asphalt (HMA) aggregates. In special cases, when aggregates are between 76 mm (3 in.) and 19mm (0.75 in.), method ASTM C535 is used. For this study, Texas Test Method Tex-410-A (ASTM C131) was selected as the proper method required for testing. The aggregate sources used for this project met the requirements for Type C and Type D grading in regard to the size. For uniform comparisons, Grade C was considered for all sources and the required gradation met the following quantities and sizes.

Table 2.10 Material Required for the L.A. Abrasion Test

Sieve Size (Square Openings) Passing	Sieve Size (Square Openings) Retained On	Mass of Indicated Sizes, gr Grade C
9.5 mm (0.38 in.)	6.3 mm (0.25 in.)	2500 ±10
6.3 mm (0.25 in.)	4.75 mm (No. 4)	2500 ±10
Total		5000 ±10

The aggregates were prepared according to the procedure, properly bagged and labeled, and transported to the soil section of the TxDOT construction division. Testing the aggregates in the L.A. abrasion machine was performed by TxDOT personnel. For each aggregate, a mass of 5,000 gr. was introduced into a heavy steel drum with eight steel balls with a total mass of 3,330±20 gr. The mix was tumbled inside the drum for 500 revolutions at a speed of 30-33 rpm. The test lasted approximately 15 minutes. The abraded aggregate was sieved through the 4.75 (No. 4), 2.36 mm (No. 8) and 1.68 mm (No. 12) sieves. The material retained on sieves 4.75 (No. 4), 2.36 mm (No. 8), and 1.68 mm (No. 12) was weighed and the percentage loss calculated as the following:

% Loss = (Original Weight – Final Weight) / Original Weight

Where,
Original Weight = weight of aggregate required to perform the test
Final Weight = gr retained on 1.68 mm (No.12) Sieve after the test

2.13 Soundness Test

The soundness loss is a measure of aggregate durability, which is a measure of how an aggregate is able to resist cycles of freezing and thawing and/or wetting and drying without disintegrating or breaking down. The detailed procedure is explained in Texas Test Method Tex-411-A (ASTM C88). First, the aggregate is washed and sieved for the test. The gradation of the washed and sieved aggregate used in the test depends on the type of pavement or material type-concrete fine aggregate, coarse aggregate for concrete, surface treatment, and HMA applications including base material and micro-surfacing. The blended aggregate is submerged in a solution of magnesium or sodium sulfate for 18 hours. The material is dried in the oven at 110°C and cooled. This process is repeated five times. Afterwards, sulfate is removed by washing the aggregates. The remaining material is sieved and compared with the initial gradation. The percent loss is calculated as the following:

Calculate individual percent loss of each size fraction,

$$c_i = [(a_i - b_i) / a_i] \times 100 \qquad (2.1)$$

Where,
a_i = initial mass of each size fraction
b_i = final mass of each size fraction

Calculate normalized percent loss of each size fraction,

$d_i = c_i$ x normalized gradation percent *(2.2)*

Calculate total percent loss,

$e = \Sigma(d_i)$ (2.3)

The magnesium or sodium sulfate is supposed to simulate the freezing and thawing action with the growing of salt crystals in the aggregate pores producing disintegration. It is assumed that these salt crystals produce effects similar to the effect of ice crystals, producing the freezing and thawing action. ASTM D692 has established limits for the percentage of the loss determined at the end of the test.

When running the test, the maximum allowable loss is 18 percent if the magnesium sulfate is used and 12 percent if the sodium sulfate is used. Procurement, washing, sieving, and preparation of aggregates were conducted by the University research team. For performing the soundness test, the same gradation was used for all eleven sources. The required gradation is showed in Table 2.11.

Table 2.11 Gradations Used for Soundness Test

Sieve Size (Square Openings) Passing	Sieve Size (Square Openings) Retained On	Mass of Indicated Sizes, gr Grade C
12.5 mm (0.5 in.)	9.5 mm (0.5 in.)	1000±10
9.5 mm (0.38 in.)	6.3 mm (0.25 in.)	180± +5
6.3 mm (0.5 in.)	4.75 mm (No. 4)	120±5
4.75 mm (No. 4)	2.36 mm (No. 8)	100±5
Total		1400±10

The results of the test were later compared with results from other tests to evaluate possible correlation.

2.14 Micro-Deval Test

The Micro-Deval Apparatus is used to test the resistance of fine/coarse aggregate to degradation by abrasion. It furnishes information helpful in judging the suitability of fine/coarse aggregates subject to abrasive action and weathering. The test also measures the durability of mineral aggregates. The procedure is described in the AASHTO Provisional Standard of spring 1999, "Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus." The test is run using water and an abrasive charge (steel balls). The purpose of the test is similar to that of the L.A. abrasion test. It varies in some aspects, like the presence of water when running the Micro-Deval Test (MDT) in comparison with L.A. abrasion test in which no water is used. The required amount of washed, dried material for running the test depends on the maximum nominal size of the coarse aggregate. For this project, including all of the aggregates, the maximum nominal size of the coarse aggregate was less than 16 mm, and therefore, test samples were prepared according to the gradation presented in Table 2.14.

Table 2.12 Gradations Used for Micro-Deval Test

Sieve Size (Square Openings) Passing	Sieve Size (Square Openings) Retained On	Mass of indicated sizes, g Grade C
12.5 mm (0.5 in.)	9.5 mm (0.38 in.)	750
9.5 mm (0.38 in.)	6.3 mm (0.25 in.)	375
6.3 mm (0.25 in.)	4.75 mm (No. 4)	375
Total		1500±5

The sample was soaked in water for one hour. A jar mill was used for the revolving process. An abrasive charge consisting of 9.5 mm diameter steel balls was introduced into the jar mill. The total weight of the steel balls is approximately 5,000 gr. The jar mill revolved all the constituents at a rate of 100 rpm for one hour and 45 minutes at the presence of two liters of water. The abrasive charge (5,,000 gr.) does not change and is not dependent on the maximum nominal size (MNS) of the aggregate. However, the running time depends on the aggregate size. It varies between two hours for 19 mm MNS to 95 minutes for 12.5 mm MNS. At the end of the two hours, the steel balls were removed and the abraded aggregates were washed and sieved over the 4.75 mm (No. 4) and 1.18 mm (No.16) sieves. The material passing through the 1.18 mm (No.16) sieve was discarded. The remaining material was then weighted. The percent loss or Micro-Deval abrasion loss was calculated as the amount of material passing through the 1.18 mm sieve expressed as a percent by mass of the original sample. The following formula was used:

$$\text{Percent loss} = (A-B)/A \times 100 \qquad (2.4)$$

Where,

A = weight of the original sample before performing Micro-Deval Test, to the nearest 1.0 gr.
B = weight of the material retained on the 4.75 mm (No. 4) and 1.18 mm (No. 16) sieves, to the nearest 1.0 gr.

The Micro-Deval results were compared and correlated with different test results as will be discussed in the following chapter.

2.15 Acid Insoluble Test

The test procedure for acid insoluble residue is explained in Texas Test Method Tex-612-J, Acid Insoluble Residue for Fine Aggregates. The test finds the percent by weight of Hydrochloric Acid Insoluble residue in fine aggregates. For this specific test the fine aggregate is defined as a material with 100 percent passing the 0.38 in. (9.5 mm) sieve. Following is the main equation used for calculating the acid insoluble residue for fine aggregates.

$$\text{\% by weight acid insoluble residue} = \frac{100 \text{ x weight of residue in g.(oz..)}}{\text{weight of oven dried sample in g. (oz.)}} \qquad (2.5)$$

2.16 Comparison of Gradations before and after the HWTD Test

Following the BPT, asphalt binder extraction was performed in order to get the amount of aggregate left for proper comparisons between aggregate gradations before and after the HWTT. The material collected from the HWTD was proportioned according to the differences in weights of the specimens before and after the HWTT and BPT. Some of the fine material was lost during the cutting process and during the HWTD through drainage. This fine material was assumed to be passing through the No. 80 sieve. It was decided to equally proportion this lost material and add it to the material retained on the No. 80 sieve, the No. 200 sieve, and in the pan. The filter aid used in extraction was approximately 60 gr and this mass was considered properly during calculations.

The HWTD test is normally run on four SGC specimens simultaneously. As mentioned before, after several of the tests were successfully performed with four specimens in place, one of the linear variable differential transducers (LVDT) used for deformation measurement was damaged. It was decided to perform the test only with two specimens on one side of the equipment, i.e., with one wheel, to prevent substantial delay in the progress of the project. Therefore, for some of the sources, the four specimens were tested at two different times, two specimens per test.

Originally two extraction tests were performed on two different specimens per source. However, it was noticed that the results were extremely close between the two specimens, and therefore extraction was continued only on one specimen per source. For the first four sources, two extraction tests were performed per source (total of eight extraction tests). For the remaining seven sources, one extraction test was performed per source.

Chapter 3
Discussion of Results

For this research project, extensive aggregate testing as well as testing with the HWTD provided a considerable amount of valuable information. The analysis of the data was conducted in the light of the project objective: quantifying the aggregate degradation that occurred after tests with the HWTD.

3.1 Visual Observation of the Specimens

Visual evaluation of the specimens indicated moderate to severe damage because of testing specimens with a PG 64 binder at 50°C. This was indeed desired because the idea was evaluation of the aggregate toughness in the test through close interaction of the wheels with the aggregates. Figure 3.1 shows specimens before and after the test.

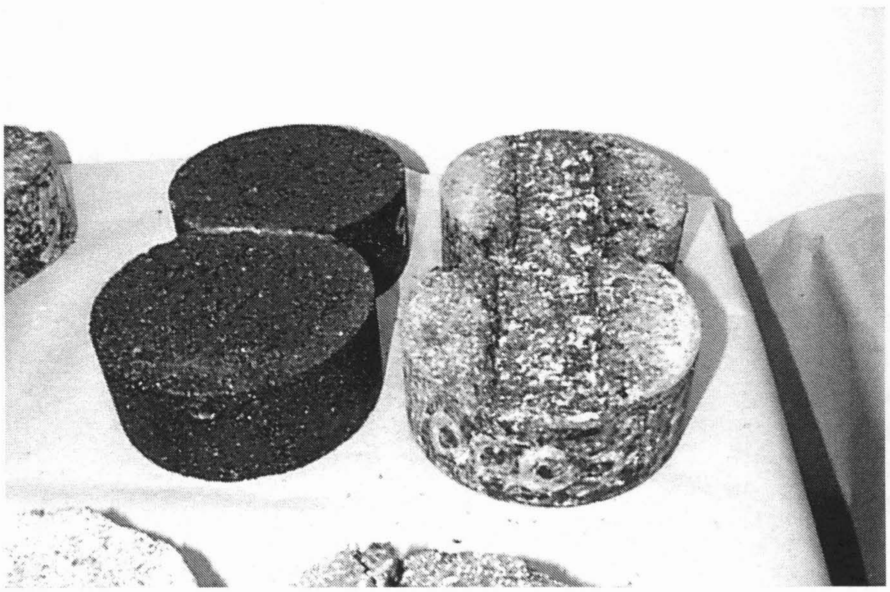


Figure 3.1 Specimens before and after HWTD Test

The severity of aggregate degradation varied for different sources. In general, they could be classified as high, intermediate, and low levels (Figures 3.2, 3.3, and 3.4, respectively).

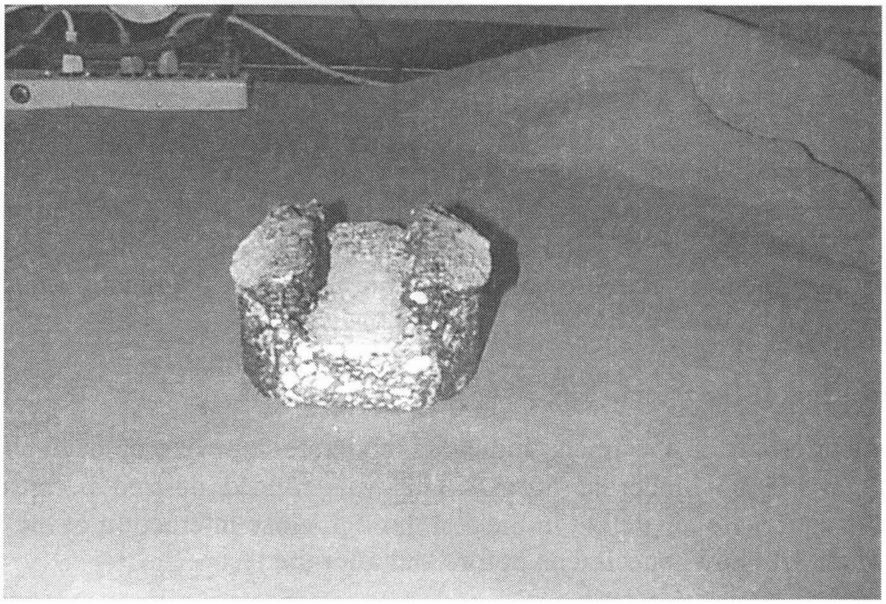


Figure 3.2 Specimen After HWTD Test (Smooth Surface – High Degradation)

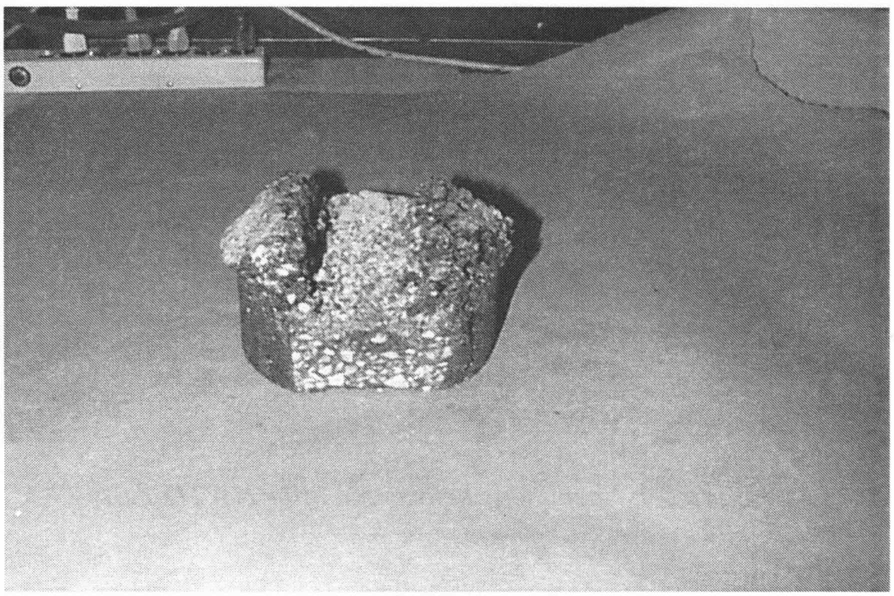


Figure 3.3 Specimen After HWTD Test (Intermediate Degradation)

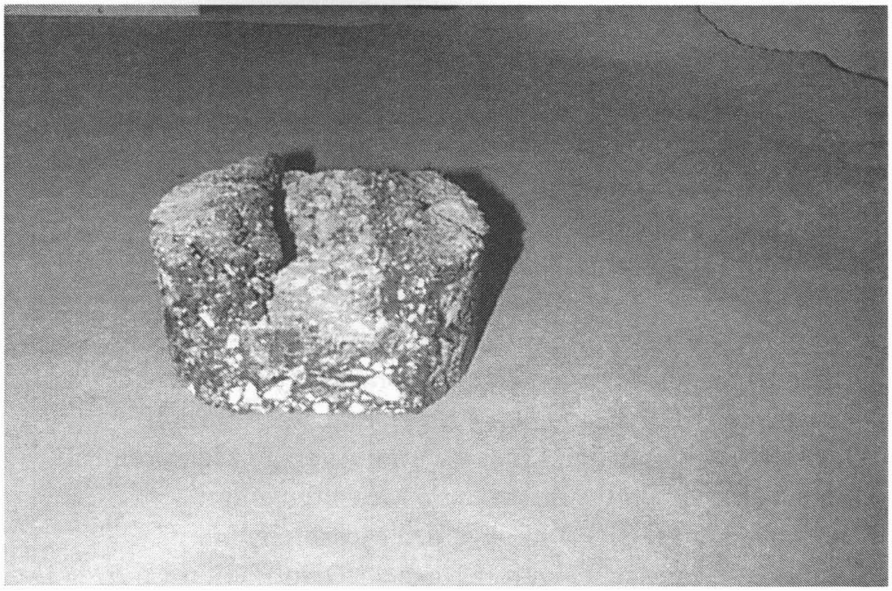


Figure 3.4 Specimen After HWTD Test (Rough Surface – Low Degradation)

3.2 Quantifying Aggregate Degradation

The aggregate gradations were determined before and after the wheel-tracking tests. A series of different parameters were calculated for these gradations to provide a means of quantitative comparison. The parameters used for this purpose included difference in gradation for specific aggregate sizes, area between gradation lines before and after the HWTD, and normalized differences. The intensity of aggregate degradation, as quantified by the preceding parameters, was correlated with aggregate properties such as L.A. abrasion, soundness loss, polish value from the British pendulum test (BPT), and Micro-Deval. This evaluation was performed knowing that not all correlations would be meaningful. Additional testing was also performed on the aggregates, such as acid insoluble, and solid polish value. The BPT was also used on the HWTD-tested specimens to evaluate its effectiveness in providing a measure of degradation or polishing. The BPT results were grouped differently based on the pendulum travel distance (1, 2, and 3 in.). These results were compared directly using BPT readings for different travel distances as well as weighted averages based on 3-in. travel distance.

The last set of data included in the analysis was the output information from the HWTD test. Different parameters from the output were calculated in order to find if any good correlation was possible. These parameters were the total deformation, deformation at stripping inflection point (SIP), creep slope, stripping slope, number of cycles to failure, number of cycles at SIP, and finally number of cycles at 17 mm of total deformation. These results were compared with area between gradation lines and L.A. abrasion.

The following are the analyses and correlations investigated during the course of the program:

- Analysis of Gradation before and after the HWTD
- Area between Gradation Lines vs. L.A. Abrasion
- Area between Gradation Lines vs. Polish Value
- Area Between Gradation Lines vs. Soundness Loss

- Area Between Gradation Lines vs. Micro-Deval Loss
- Difference in Gradation vs. L.A. Abrasion
- Difference in Gradation vs. Polish Value
- Difference in Gradation vs. Soundness Loss
- Difference in Gradation vs. Micro-Deval Loss
- Polish Value vs. Solid Polish Value
- Soundness Loss vs. Micro-Deval Loss
- Soundness Loss vs. Acid Insoluble
- Micro-Deval Loss vs. Acid Insoluble Residue
- Difference in No. 4 Sieve vs. L.A. Abrasion
- Normalized Difference in No. 4 Sieve vs. L.A. Abrasion
- Area Between Gradation Lines vs. 1 in. Average Measurements
- Polish Value vs. BPT 1 in. Average Measurements
- L.A. Abrasion vs. BPT 1 in. Average Measurements
- Number of Cycles at 17-mm Permanent Deformation vs. Area Between Gradation Lines
- Permanent Deformation at SIP vs. Area Between Gradation Lines

3.2.1 Analysis of Gradation before and after Tests with the HWTD

The gradation was checked for the aggregate batches before and after testing with the HWTD. This process was needed in order to find a method to quantify degradation. The following parameters were calculated as a measure of aggregate degradation:

Difference in gradations: defined as the difference between the percent cumulative passing for each sieve before and after the HWTD test.

Normalized difference: calculated as the normalized difference between gradations. The difference between percent passing for a specific test was divided by the original percent passing to obtain a normalized value.

Area between gradation lines: defined as the area between lines presenting gradations before and after the HWTD test. It was calculated through summing up the areas of trapezoids formed by gradation lines between consecutive sieve sizes.

The following is an example of how the preceding parameters were calculated. The results from the Vulcan aggregate are shown in this example (Table 3.1). The results for all of the aggregates are presented in Appendix A.

The graphic representation of the analysis for this aggregate source is presented in Figure 3.5. In this graph, the sieve size is raised to the 0.45 power. The percentage of the material passing the presented sieve sizes before and after the HWTD test are shown in the graph. The figures for all the aggregate sources are presented in Appendix A.

Table 3.1 Analysis of Gradation before and after the HWTD Test – Vulcan Agg.

Source: Vulcan				**Aggregate Type:**		Limestone
Sieve Size (mm)	Before HWTD Cumulative Passing (%)	After HWTD Cumulative Passing (%)	Difference in Gradation (%)	Normalized Difference	Area between Gradation Lines	Sieve Size ^0.45 (mm)
12.5	100.0	100.0	0.00	0.00	0.13	3.12
9.5	97.6	98.3	0.74	0.01	1.31	2.75
4.75	63.3	66.2	2.81	0.04	2.15	2.02
2	38.1	41.9	3.80	0.10	2.81	1.37
0.425	18.8	23.2	4.39	0.23	0.89	0.68
0.18	10.0	13.8	3.76	0.38	0.51	0.46
0.075	2.5	5.6	3.02	1.18	0.47	0.31
	0.0	0.0	18.51	1.95	8.26	SUM

For all the aggregates, it was found that the highest percent difference in aggregate gradation is on the finer sizes. This was expected since it represents the degradation of the course aggregate resulting in the fine material. The difference peaks between 0.425 and 0.18 mm sieves and decreases on the 0.075 mm sieve. This trend is observed on all the aggregates. Figure 3.5 provides a graphical presentation of this concept.

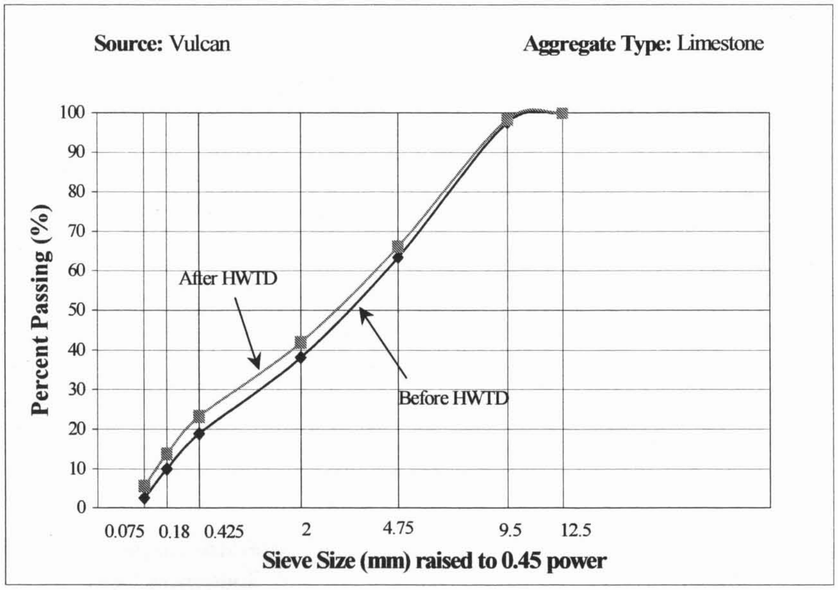


Figure 3.5 Comparisons of Aggregate Gradations before and after Testing with HWTD for Vulcan Limestone Aggregate

3.2.2 Area Between Gradation Lines vs. Los Angeles Abrasion

The L.A. abrasion test is used primarily to evaluate the aggregate toughness and its resistance to abrasion. The results for different aggregate sources are shown in Table 3.2. These results are directly from tests conducted on samples of aggregates received for this research. The summation of the area between gradation lines for the different aggregate sources tested are shown in the same table. A larger value for the area between gradation lines is an indication of larger level of degradation. A larger value of L.A. abrasion is also an indication of higher degradation.

From Figure 3.6 it can be observed that, as the L.A. abrasion increases, the area between gradation lines increases. In other words, the tougher aggregates show more resistance to abrasion under the wheel-tracking device. Two main groups of aggregates were distinguished from each other from the results shown in this figure. The aggregates with L.A. abrasion of more than 25 percent showed considerably more degradation under the HWTD wheel and correspond to loss area of over 12 percent. Group 1 included limestone and sandstone aggregates that showed high L.A. abrasion and high loss area compared with group 2 (gravel aggregates) that had lower L.A. abrasion and lower loss area. The granite aggregate from Pedernal source (in the upper left corner of the figure) does not follow the general trend. This aggregate indicates a very low level of abrasion, about 13 percent, but a high level of area loss under the wheel. Repeated tests for this source provided the same results.

Table 3.2 Aggregate Test Results and Degradation Analysis

Source	Agg.	LA Abr.	PV	SL	MD	AI	SPV	Dif. (%)	Norm. Dif.	Area (%)
Mirando	Gr	16	30	4	3	97	27	17.39	1.32	7.38
Hanson	Gr	19	31	5	3	98	30	7.92	1.3	3.18
Vulcan	Ls	25	29	4	10	1	21	18.51	1.95	8.26
Wright	Gr	16	28	1	1	95	27	17.82	3.49	6.86
Colorado	Ls	27	31	24	21	2	23	43.6	5.17	14.75
Vado / Mack	Gn	29	41	3	9	97	33	52.9	4.71	17.62
Pedernal	Bs/ Gn	13	45	4	15	96	39	38.3	2.44	18.43
Hoban	Rh	16	33	6	6	97	33	18.01	1.42	8.18
Meridian	Sa	29	37	9	7	97	33	31.14	2.45	12.87
Fordyce	Gr	16	30	4	2	85	28	13.53	1.72	5.66
TXI Bridgeport	Ls	28	35	15	18	2	24	27.46	1.82	13.12

Key:

Agg. Type:	aggregate type	PV:	Polish Value
Gr:	gravel	SL:	Soundness Loss
Ls:	limestone	MD:	Micro-Deval Loss
Gn:	granite	AI:	Acid Insoluble
Bs:	basalt	SPV:	Solid Polish Value
Rh:	rhyolite	Dif.:	Difference in Gradation
Sa:	sandstone	Norm.Dif.:	Normalized Difference
LA:	Los Angeles Abrasion	Area:	Area between Gradation Lines

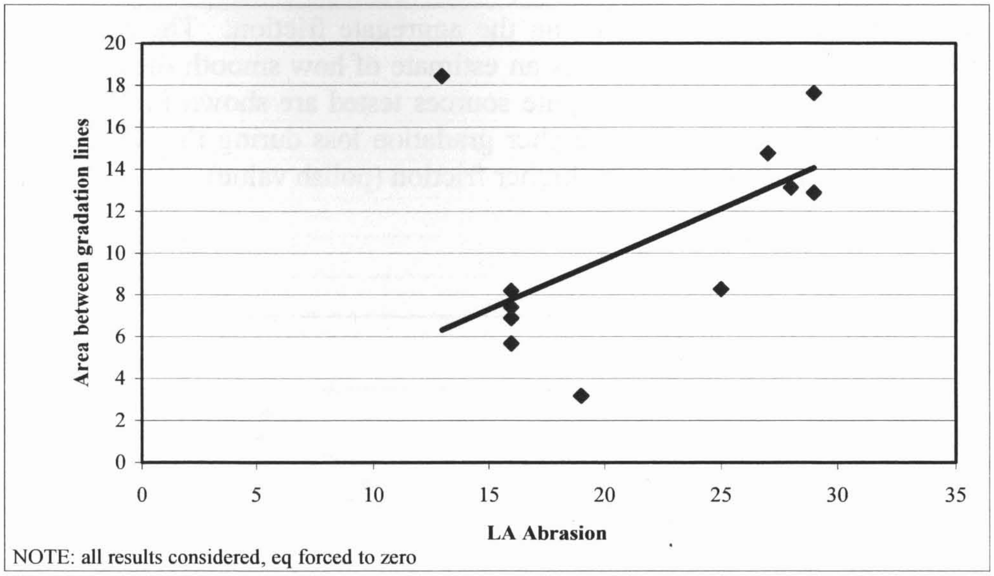


Figure 3.6 Correlation between Loss Area and L.A. Abrasion

This behavior could not be justified and explained the same way that behavior of the other aggregates could. It can be noticed that the correlation could be significantly improved if this aggregate is not included in the graph (Figure 3.7).

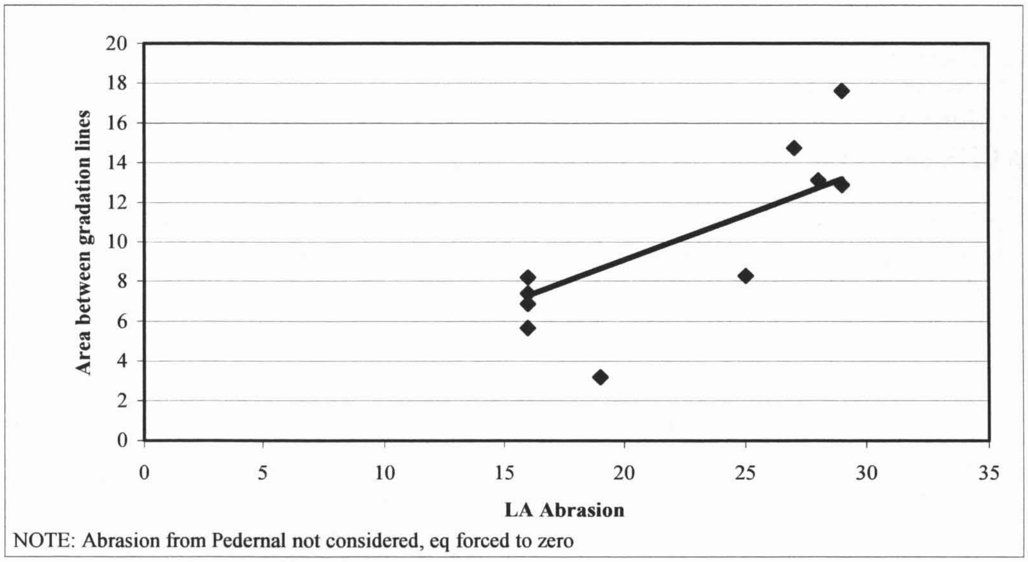


Figure 3.7 Correlation between Loss Area and L.A. Abrasion – Pedernal Excluded

Loss area refers to the area between gradation lines before and after the HWTD test. Within the body of this report these two terms are used interchangeably.

3.2.3 Area between Gradation Lines vs. Polish Value

The BPT is widely used for measuring the aggregate friction. The result is presented in terms of polish value. This value provides an estimate of how smooth the aggregate surface is. The polish results for the different aggregate sources tested are shown in Table 3.2. Figure 3.8 shows that, in general, aggregates with higher gradation loss during the HWTD test (presented by the loss area) are also aggregates with higher friction (polish value).

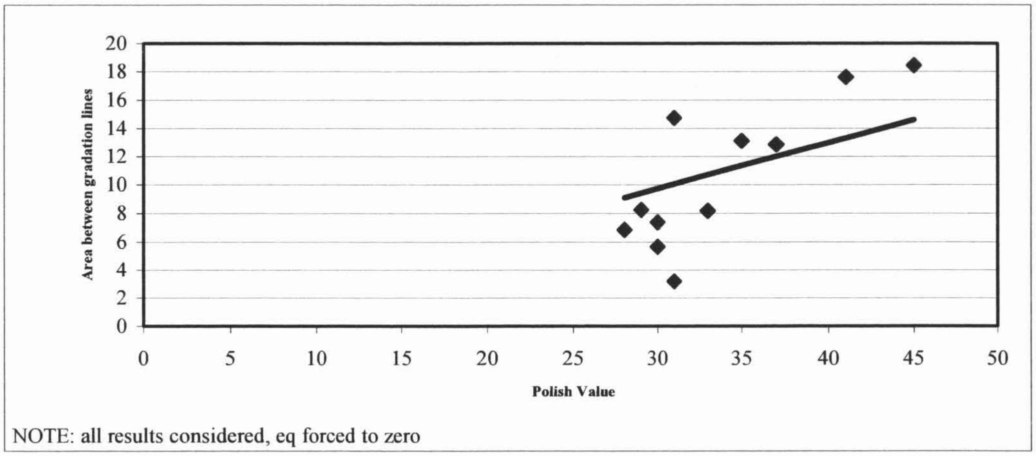


Figure 3.8 Correlation between Loss Area and Polish Value

The correlation is improved when the results for the aggregate from Hanson source are not considered (Figure 3.9).

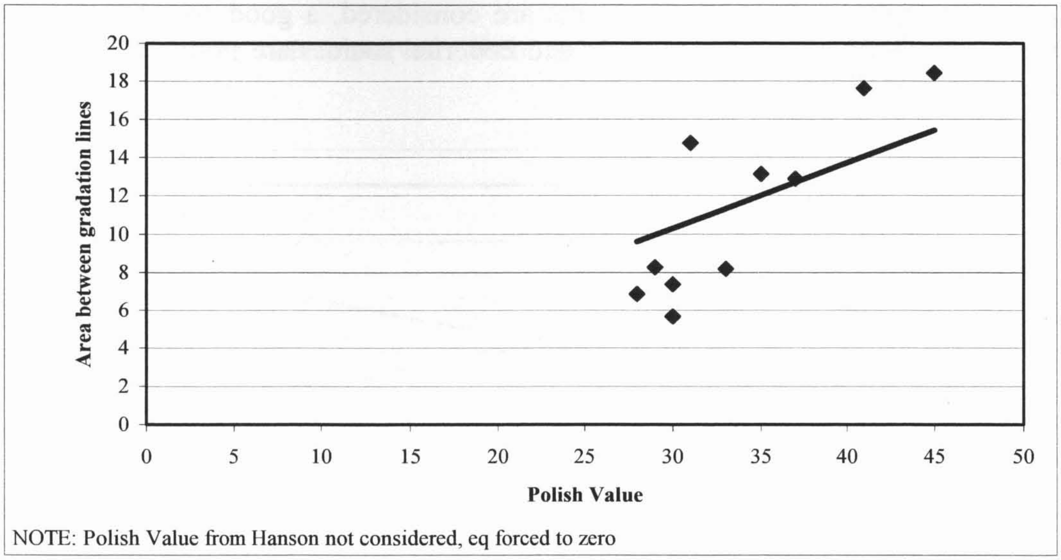


Figure 3.9 Correlation between Loss Area and Polish Value – Hanson Excluded

3.2.4 Area between Gradation Lines vs. Soundness Loss

The soundness loss is a measure of aggregate durability. This durability is a measure of how well an aggregate is able to resist cycles of freezing and thawing and/or wetting and drying without disintegrating or breaking down. The Soundness results for the different aggregate sources tested are shown in Table 3.2.

The factors affecting an aggregate soundness loss are not well presented in the HWTD test. Therefore, a strong correlation is not expected between this parameter and aggregate degradation. However, in general it is expected that most of the aggregates that are susceptible to breaking due to weathering and environmental effects also are susceptible to more degradation. Results comparing the loss area and soundness are shown in Figures 3.10 and 3.11.

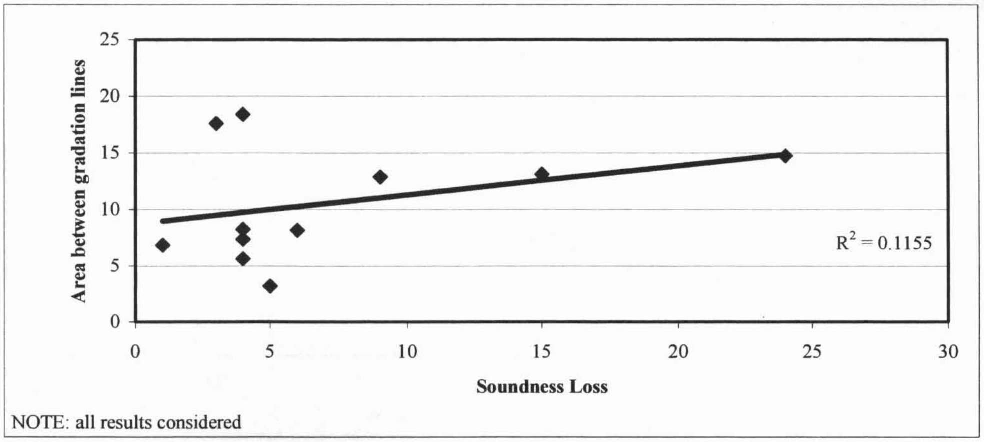


Figure 3.10 Correlation between Loss Area and Soundness Loss

In the first Figure, where all the results are considered, a good correlation is not found. When the results for aggregates from Vado and Pedernal sources are excluded, the correlation is somewhat improved (Figure 3.11).

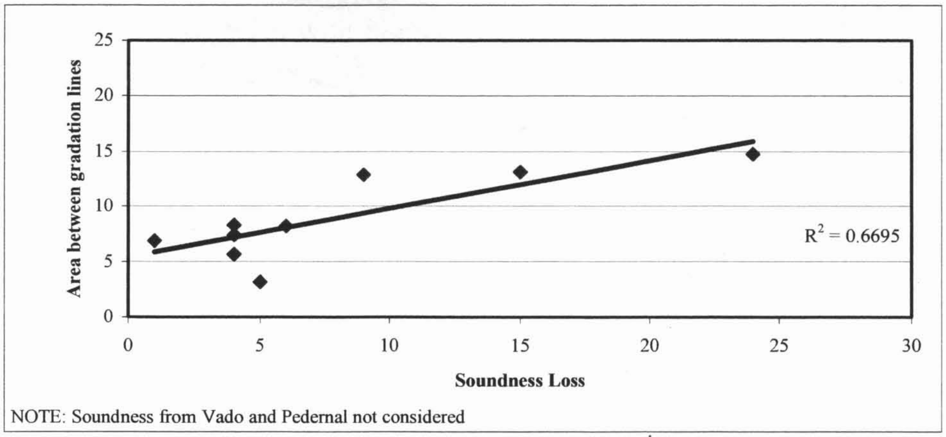


Figure 3.11 Correlation between Loss Area and Soundness Loss – Vado and Pedernal Excluded.

3.2.5 Area between Gradation Lines vs. Micro-Deval Loss

The Micro-Deval apparatus is used to test the resistance of fine/coarse aggregate to degradation by abrasion. The MDA furnishes information helpful in judging the suitability of fine/coarse aggregates subject to abrasive action and weathering. This equipment also measures the durability of mineral aggregates, and follows the same principle as L.A. abrasion test, including some weathering action on the aggregate. Therefore, the results from Micro-Deval should be comparable with the results from L.A. abrasion. The Micro-Deval results for different aggregate sources are shown in Table 3.2. The correlation between loss area and Micro-Deval is shown in Figures 3.12 and 3.13. A trend similar to that observed for L.A. abrasion is observed: As the Micro-Deval loss increases the area indicating degradation also increases.

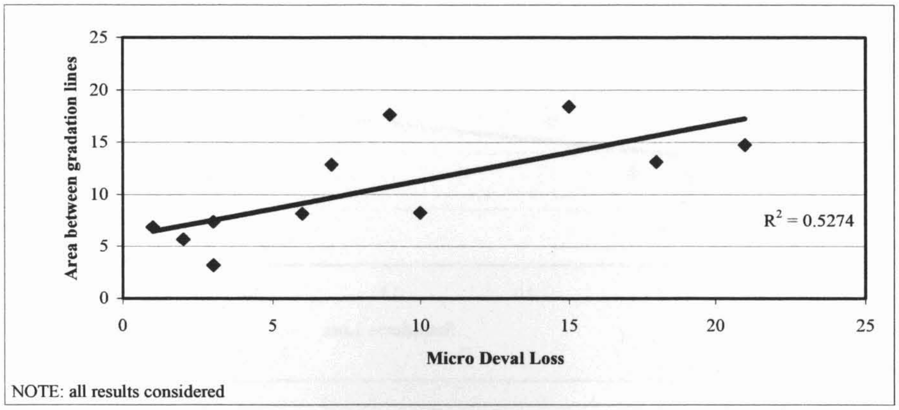


Figure 3.12 Correlation between Loss Area and Micro-Deval Loss

A better correlation was observed when the results from the Vado source were not considered.

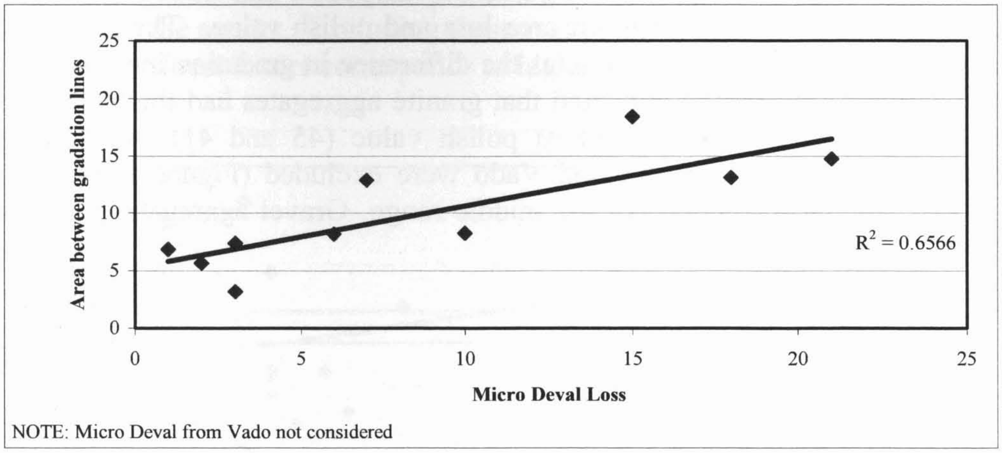


Figure 3.13 Correlation between Loss Area and Micro-Deval Loss - Vado Excluded

3.2.6 Difference in Gradation vs. Los Angeles Abrasion

The difference in gradation is considered to be the summation of all differences between the cumulative percent passing before and after the HWTD test. In other words, the change in percent passing was determined for every sieve size included in the sieve analysis. The summation of all these differences was the parameter used for comparing the results from different sources. The results are shown in Table 3.2. In general, higher differences in gradation (i.e more degradation) correspond to higher losses in L.A. abrasion (Figure 3.14).

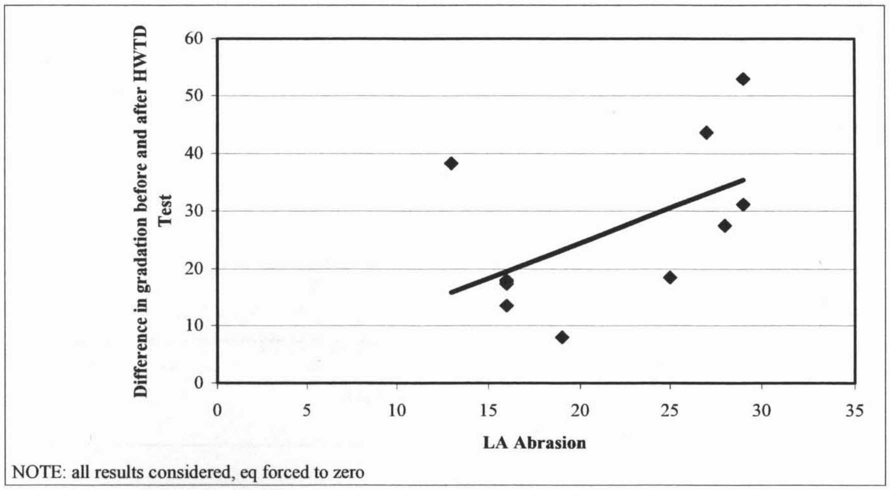


Figure 3.14 Correlation between Difference in Gradation and L.A. Abrasion

3.2.7 Difference in Gradation vs. Polish Value

The correlation between difference in gradation and polish value was found to be as good as the correlation found previously between area loss and polish value. The correlation using all results showed an increase in polish value as the difference in gradation increased (Figure 3.15). Close investigation of the results indicated that granite aggregates had the highest difference in gradation (38.3 and 52.9) and the highest polish value (45 and 41) from all sources. The correlation improved when Colorado and Vado were excluded (Figure 3.16). Limestone and sandstone aggregates were grouped in the middle range. Gravel aggregates were on the lower end of gradation differences.

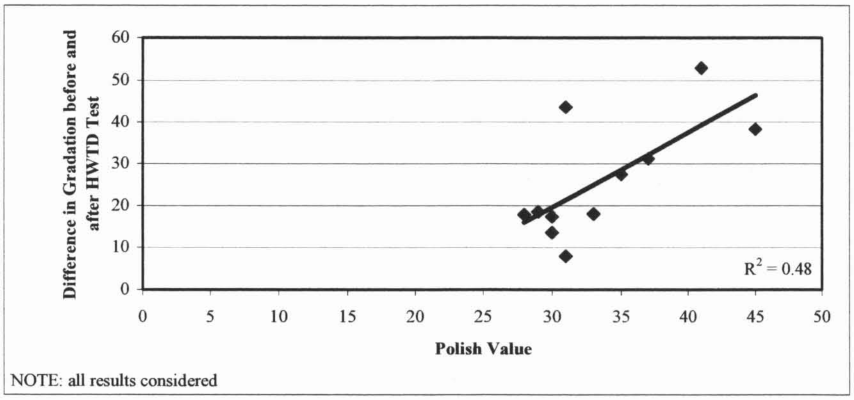


Figure 3.15 Correlation between Difference in Gradation and Polish Value

There was not a clear distinction between polish values for gravel and limestone aggregates. However, there was a clear difference between aggregate degradation for these two types of material, with limestone exhibiting a more abrasive behavior.

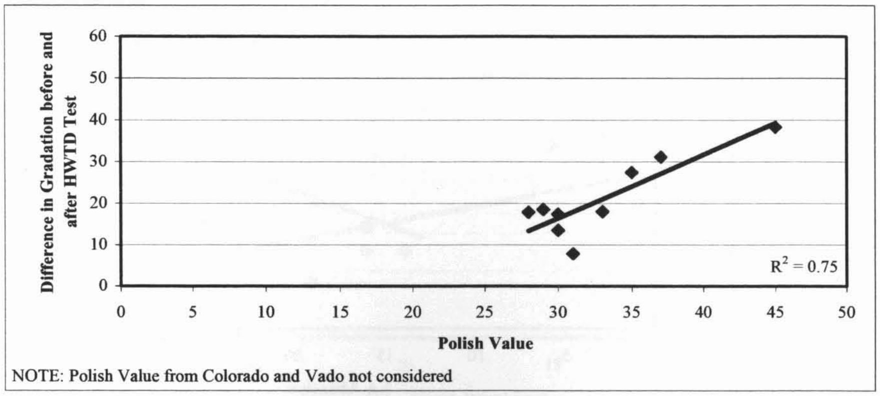


Figure 3.16 Correlation between Difference in Gradation and Polish Value – Colorado and Vado Excluded

3.2.8 Difference in Gradation vs. Soundness Loss

The relationship between difference in gradation and soundness loss was poor. A similar argument as explained for loss area (Figure 3.10) holds. The relationship is presented in Figure 3.17. Results from Vado and Pedernal, presented at the upper left corner of the graph, are specifically affecting the results. Excluding these two points (Figure 3.18), the trends seen in the data were higher soundness losses corresponds to higher gradation differences.

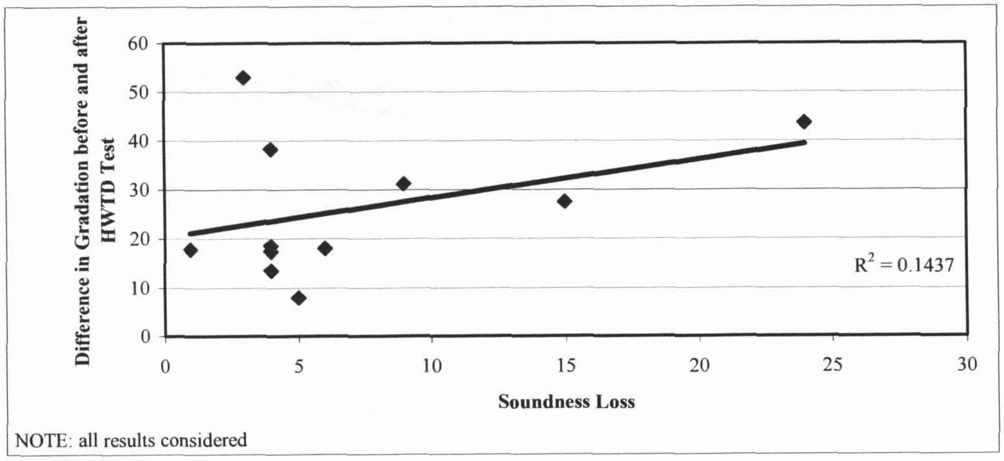


Figure 3.17 Correlation between Difference in Gradation and Soundness Loss

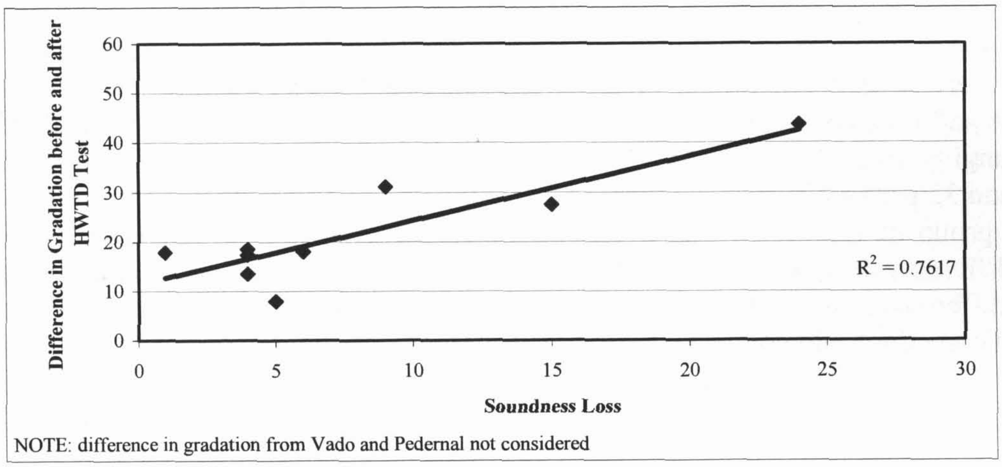
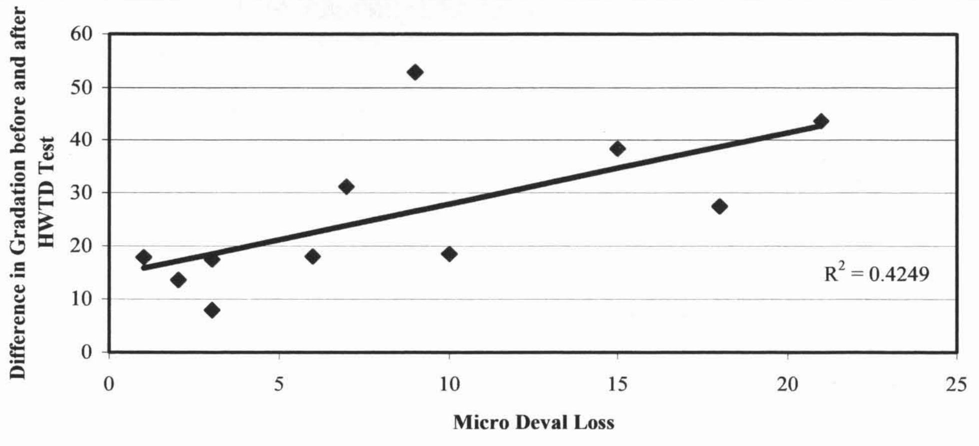


Figure 3.18 Correlation between Difference in Gradation and Soundness Loss – Vado and Pedernal Excluded

3.2.9 Difference in Gradation vs. Micro-Deval Loss

The relationship between the results from Micro-Deval test and difference in gradation is presented in Figure 3.19.



NOTE: all results considered

Figure 3.19 Correlation between Difference in Gradation and Micro-Deval Loss

The trend is very similar to the one shown for L.A. abrasion. As the Micro-Deval loss increases, difference in gradation increases.

The gravel aggregates are found in the lower part of the graph, showing a Micro-Deval Loss below 5 percent and difference in gradation between 7 percent and 18 percent. Rhyolite, sandstone and limestone aggregates were in the middle section of the Figure with Micro-Deval results ranging from 5 percent to 10 percent and differences in gradation results between 18 percent and 32 percent.

The group at the higher end is mostly limestone. The granite aggregate (Vado) had the highest difference in gradation (52.9 percent) with a Micro-Deval loss of about 9 percent. This result is different from the trend of most of the aggregates and is not justifiable. Correlation was improved once the Vado source was not included (Figure 3.20).

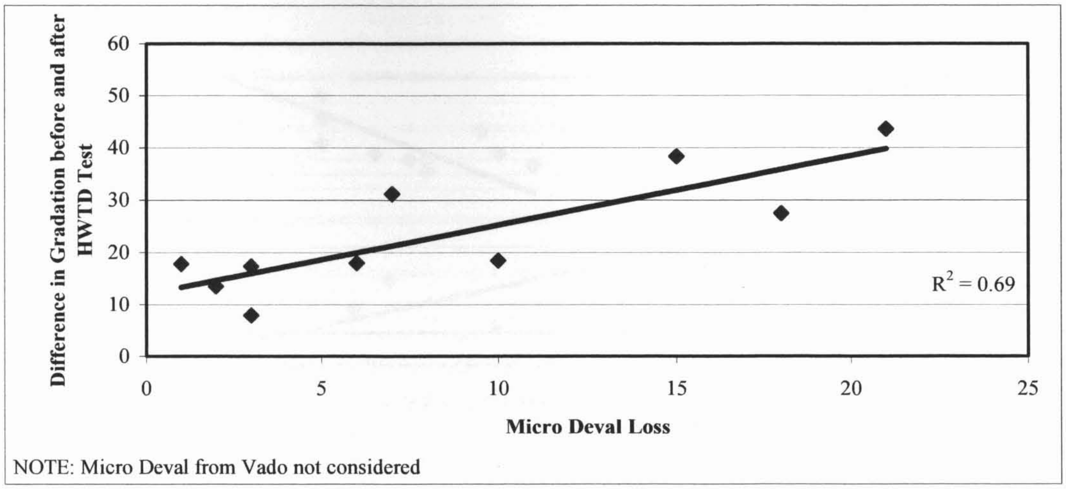


Figure 3.20 Correlation between Difference in Gradation and Micro-Deval Loss — Vado Excluded.

3.2.10 Polish Value vs. Solid Polish Value

Polish value and solid polish value should be directly proportional with a strong correlation. For the aggregates tested here, four aggregates experienced very similar polish values, and solid polish values ranging between 20 and 30. Three aggregate sources had close solid polish values, and polish values between 32 and 42. Two graphs are presented here (Figures 3.21 and 3.22). In the first graph, the equation is forced through origin assuming that an aggregate with extremely small polish value also has a small solid polish value. As a reminder, polish value is obtained through the use of cross-hatched tires while solid polish value results from using solid tires. In the second graph (Figure 3.22), the relationship is presented demonstrating a relatively good correlation with an r-squared value of about 0.6.

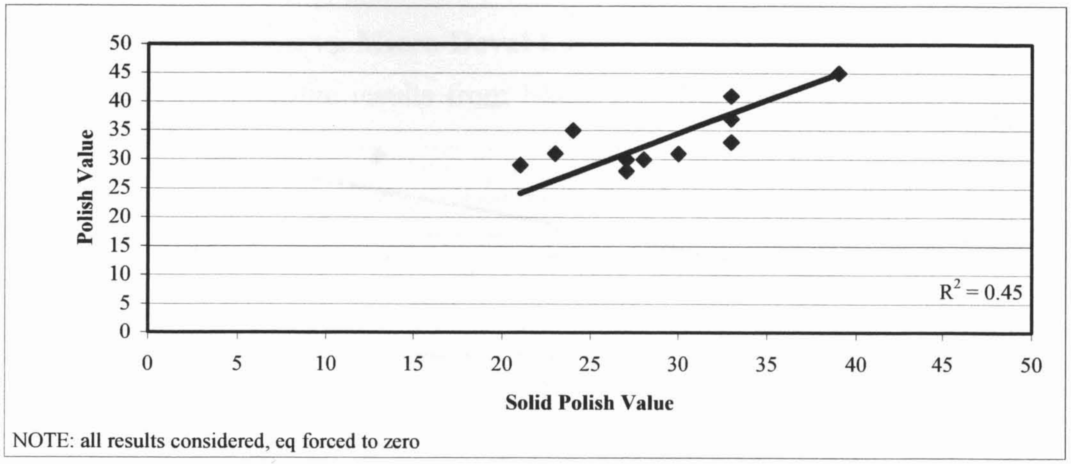


Figure 3.21 Correlation between Polish Value and Solid Polish Value – Equation Forced to Zero

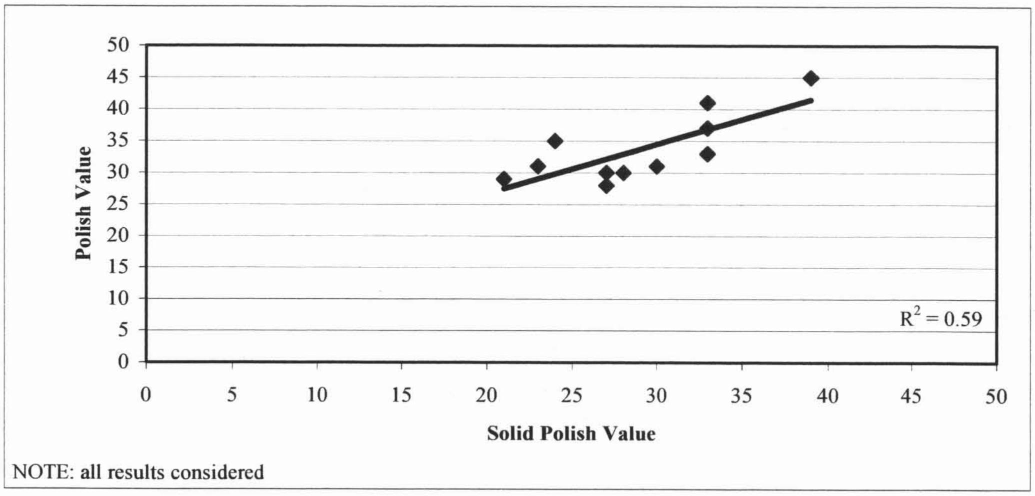


Figure 3.22 Correlation between Polish Value and Solid Polish Value

3.2.12 Soundness Loss vs. Micro-Deval

The Micro-Deval apparatus was used to determine the abrasion loss of coarse aggregate in the presence of water and an abrasive charge. This test is being evaluated by TxDOT as a possible alternative to the Magnesium sulfate soundness test. Therefore, the results should be comparable. The trend should see an increase on Micro-Deval whenever an increase on soundness loss occurs. In practice, it was found that some aggregates did not follow that trend (Figure 3.23). Vulcan (limestone), Pedernal, and Vado (granite) had Micro-Deval results between 9 and 15 for Soundness results between 2 and 4. These values do not follow the same trend followed by the other aggregate sources. Without considering these three sources, it is evident that two main groups can be visualized from the graph. The first group, with low Micro-Deval and soundness loss, is mostly gravel with the addition of rhyolite. The upper group is formed with limestone aggregates experiencing high Micro-Deval and soundness loss. It seems that there is a trend between the results from these two tests.

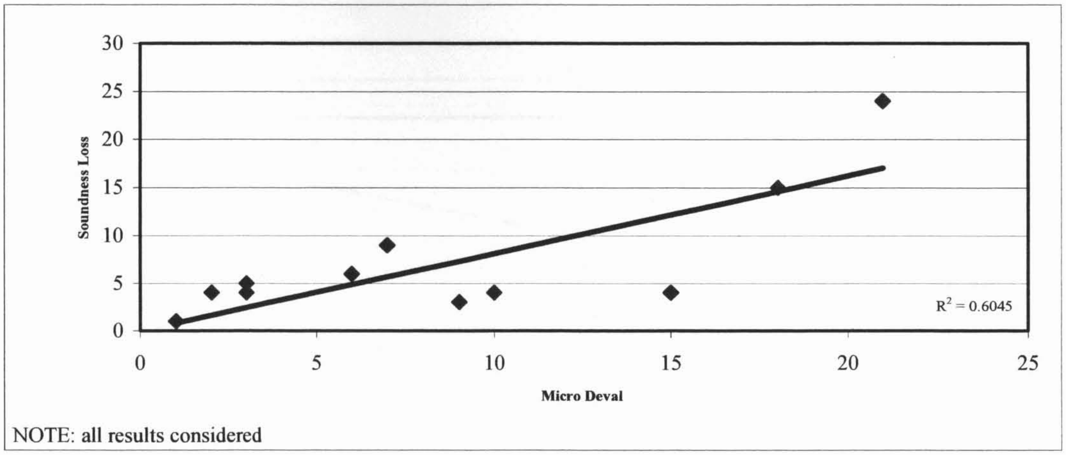


Figure 3.23 Correlation between Soundness Loss and Micro-Deval

3.2.13 Soundness Loss vs. Acid Insoluble

As mentioned previously, the soundness test measures aggregate resistance to disintegration or breaking by the action of sulfates. The acid insoluble test determines the percent by weight of hydrochloric acid insoluble residue in fine aggregates.

The acid insoluble results for the different aggregate sources tested are shown in Table 3.2. For this case, the comparison between soundness loss and acid insoluble did not show a good correlation (Figure 3.24).

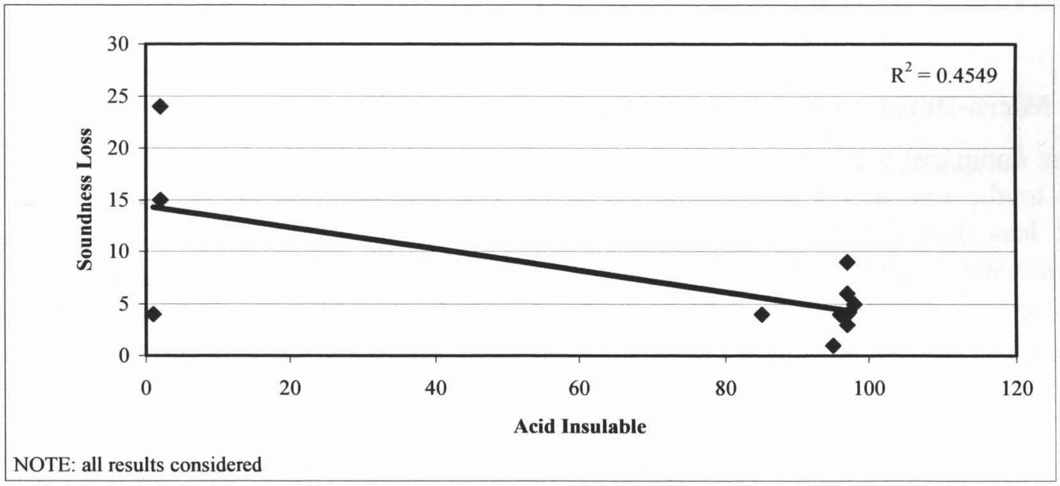


Figure 3.24 Correlation between Soundness Loss and Acid Insoluble

As shown in Figure 3.25, the correlation was improved by not considering the Vulcan aggregate.

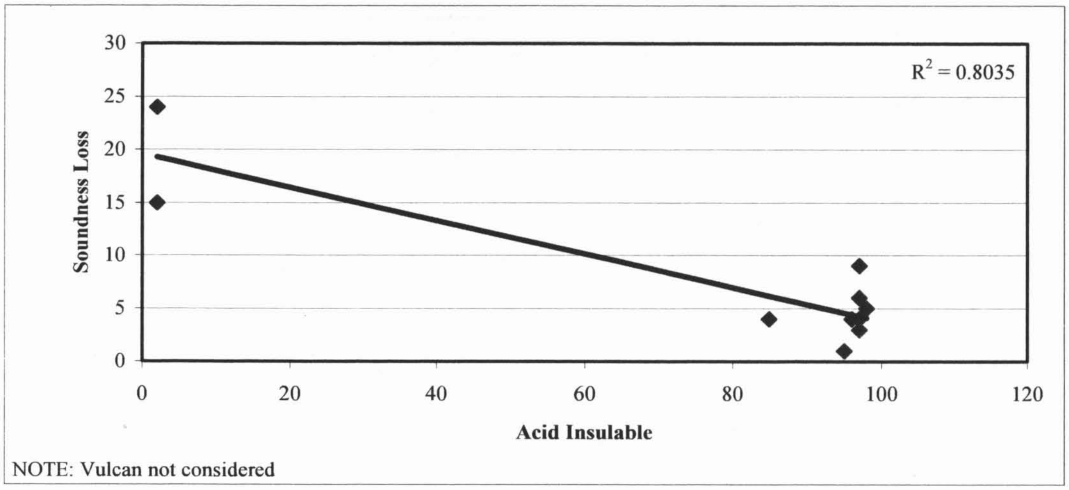


Figure 3.25 Correlation between Soundness Loss and Acid Insoluble Excluding Vulcan Aggregate.

Most of the aggregates at the lower right side of the Figure are gravel, granite, sandstone and rhyolite, with soundness loss between 1 and 10 percent and the acid insoluble residue between 80 and 100 percent. The two aggregates at the upper left side are limestone with soundness loss of over 15 percent and acid insoluble residue of about 2. A final decision on the relationship between these two parameters requires a larger number of aggregates.

3.2.14 Micro-Deval Loss vs. Acid Insoluble

The comparison between the Micro-Deval loss and acid insoluble residue follows a trend similar to the one described in section 3.13. The limestone aggregates with acid insoluble residue less than 5 percent delivered Micro-Deval losses between 15 and 25 percent. All aggregates with high level of insolubility had Micro-Deval losses below 10 percent. These were mostly gravel, granite, rhyolite and sandstone. One could not differentiate between these four aggregates based on the acid insoluble results. Figures 3.26 shows the relationship when all the results are considered while Figure 3.27 is for the case where aggregate from Pedernal and Vulcan are excluded.

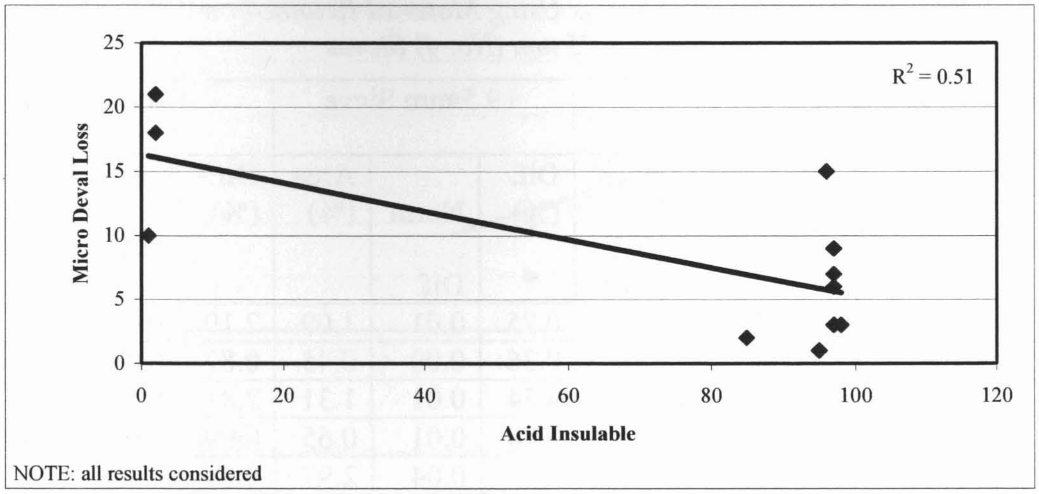


Figure 3.26 Correlation between Micro-Deval Loss and Acid Insoluble

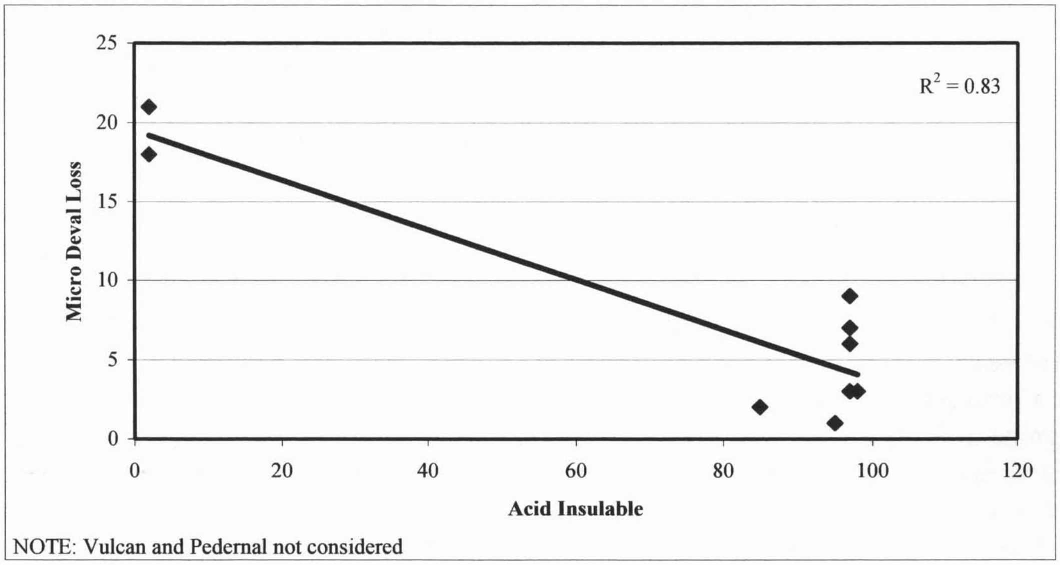


Figure 3.27 Correlation between Micro-Deval Loss and Acid Insoluble Residue– Vulcan and Pedernal Excluded

3.2.15 Difference in No. 4 Sieve vs. Los Angeles Abrasion

The material retained on sieves 9.5 mm (3/8") and 4.75 mm (No. 4) was used as an alternative for comparing the gradation before and after HWTD. The individual differences in gradation as well as normalized differences were considered for comparisons. The results are presented in Table 3.3.

Table 3.3 Degradation Analysis Using Material Retained on 9.5 mm (3/8") and 4.75 mm (No. 4) Sieves

			+9.5 mm Sieve			+No. 4 Sieve		
Source	Aggregate Type	L.A. Ab, %	Dif. (%)	Norm. Dif.	Area (%)	Dif. (%)	Norm. Dif.	Area (%)
Mirando	Gravel	16	0.75	0.01	1.09	2.19	0.04	1.86
Hanson	Gravel	19	0.36	0.00	0.45	0.87	0.02	0.64
Vulcan	Limestone	25	0.74	0.01	1.31	2.81	0.04	2.15
Wright	Gravel	16	0.78	0.01	0.65	0.99	0.02	1.07
Colorado	Limestone	27	3.10	0.04	2.97	4.95	0.10	2.89
Vado/Mack	Granite	29	3.07	0.05	2.87	4.71	0.12	3.47
Pedernal	Basalt/Granite	13	4.05	0.05	3.07	4.28	0.08	3.58
Hoban	Rhyolite	16	0.84	0.01	1.11	2.16	0.04	2.08
Meridian	Sandstone	29	0.32	0.00	1.39	3.46	0.06	2.98
Fordyce	Gravel	16	0.70	0.01	0.99	1.98	0.03	1.38
TXI Bridgep.	Limestone	28	0.35	0.00	1.84	4.63	0.07	3.75

LA: Los Angeles Abrasion
Dif.: Difference in Gradation
Norm.Dif.: Normalized Difference
Area: Area between Gradation Lines

A good correlation was not obtained when using the material retained on the 9.5 mm (3/8") sieve. However, when using the results for the 4.75 mm (No. 4) sieve, a clear trend could be observed between the gradation difference and L.A. abrasion. Two main groups of data are easy to recognize in Figure 3.28. The lower part of the Figure includes data for gravel, which has been recognized as a tough and nonabrasive aggregate over the years. A change of about 0.5 to 2.5 in the percent material retained on 4.75 mm (No. 4) sieve corresponds to L.A. abrasion between 15 and 20 percent. The second group of results, mostly located at the upper right corner of the graph, corresponds to a gradation difference of 2.5 to 5 percent and L.A. abrasion loss of 25 to 30 percent. This group included aggregates such as limestone and sandstone.

An improvement is noticed in the correlation when the results from Perdernal source are excluded. This granite/basalt material is considered tough with little susceptibility to abrasion, as shown by the L.A. abrasion value of 13. However, it is not clear why this material is exhibiting a high loss in gradation based on the percent retained on the 4.75 mm (No. 4) sieve. For the other aggregates, a trend is observed.

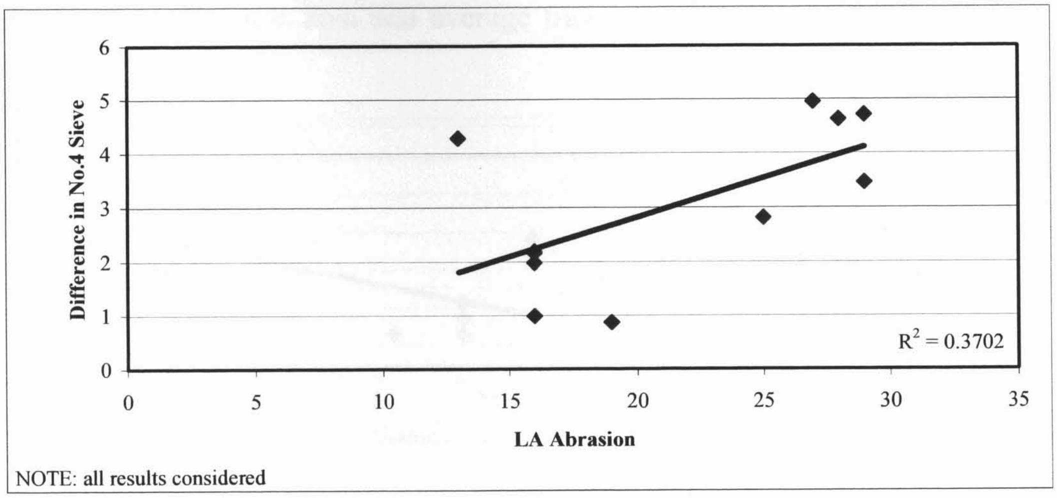


Figure 3.28 Correlation between Difference in No. 4 Sieve and L.A. Abrasion

3.2.16 Normalized Difference in No. 4 Sieve vs. L.A. Abrasion

The normalized difference in gradation was the last parameter used for quantifying the aggregate degradation. Two steps were followed to calculate this parameter. First, the percentage of the material passing a specific sieve after the HWTD is subtracted from the percent passing that sieve before the HWTD. This value is defined as the difference in gradation, which is divided by the percent material passing the sieve before the HWTD to obtain the normalized difference. The reason for this normalization was to create the same scale for carrying the comparison of gradations. A summary showing the results for 4.75 mm (No. 4) and 9.5 mm (3/8") sieves is presented in Table 3.3. For the specific case shown, the normalized difference for 4.75 mm (No. 4) sieve is compared with the L.A. abrasion. A similar trend to that of section 6.16 was found. Again, Figure 3.29 presents all results while Figure 3.30 presents the results excluding the Pedernal source.

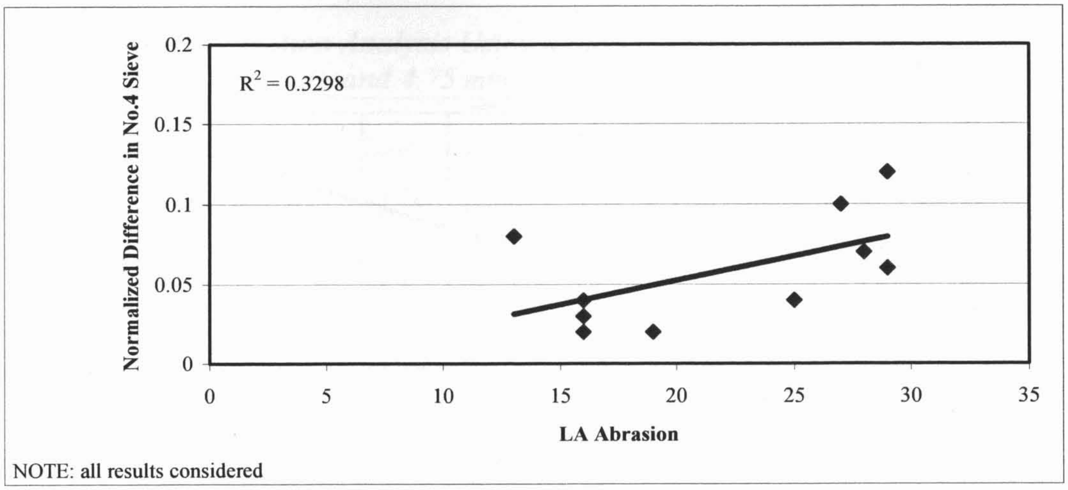


Figure 3.29 Correlation between L.A. Abrasion and Normalized Difference in No. 4 Sieve

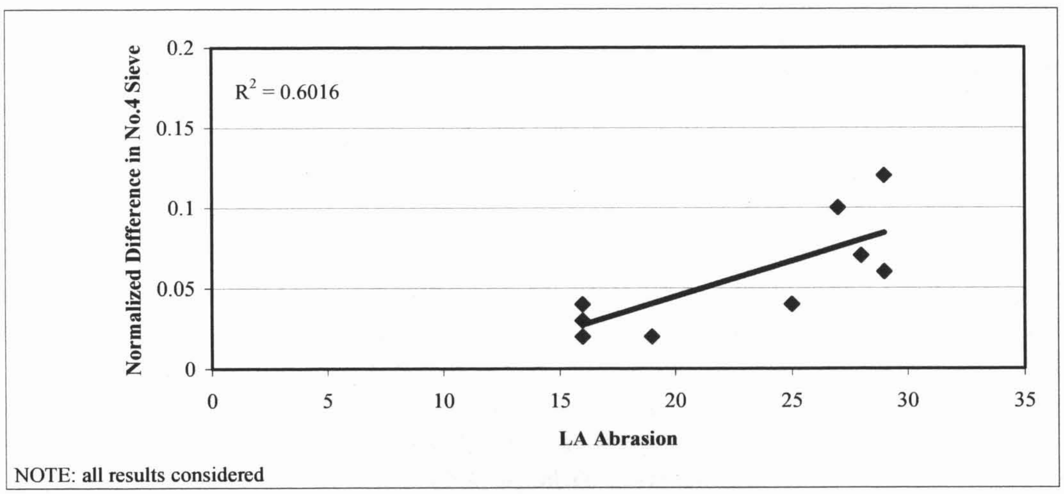


Figure 3.30 Correlation between L.A. Abrasion and Normalized Difference in No. 4 Sieve – Pedernal Excluded

3.2.17 Area between Gradation Lines vs. 1 in. Average Measurements

The BPT was used to measure the polishing and friction effect of performing the HWTD test on the specimens. The results were recorded at travel distances of 1, 2, and 3. For this specific case, the 1 in. measurements were recorded four times running the slider on the wheel-tracked surface. The average of these fourmeasurements was used as the 1 in. average measurement value for each source. The group of results was then plotted against any other measured property to find if a good correlation was possible. A better correlation was obtained when using results from specimens made only with the Coastal Binder. Table A.11 (Appendix A) presents the results for surface contacts of 1, 2, and 3 in. for the BPT. Figure 3.31 shows the relationship between the loss area and average travel distance of one-in. for specimens with coastal binder only.

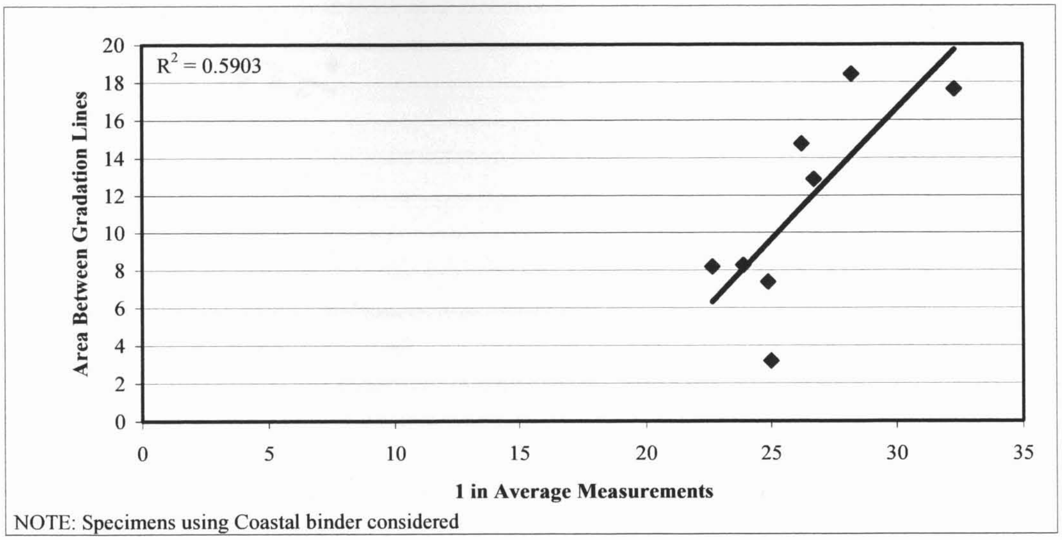


Figure 3.31 Correlation between Area and 1 in. Average Measurements from BPT

Limestone and gravel specimens experienced basically similar results for 1 in. average travel (polish values of 23 and 26). In conclusion, there was not a clear difference between gravel and limestone aggregates when testing with the BPT. Sandstone aggregates experienced a higher BPT reading (27) than gravel.

The main idea behind using the BPT for wheel-tracked specimens was to see if the equipment was capable of providing a measure of aggregate degradation through frictional resistance of the surface. Visual observation of specimens tested for this study indicated that a smoother surface was obtained through wheel tracking when softer aggregate was used. A smooth surface is expected to provide less resistance to the movement of the pendulum, and therefore deliver a lower polish value. However, this scenario did not occur and it did not become possible to provide the same contact area for both smooth and rough surfaces. As a result, for short travel distances such as 1 in., the measurement was actually related to the texture and frictional property of the aggregate rather than softness of the aggregate and smoothness of the surface. For longer travel distances such as 3 in., the contact area was smaller for rough surfaced specimens compared to smooth specimens and therefore, the measured values were affected by not only the properties of the aggregate but also with the distance of travel.

3.2.18 Polish Value vs. 1 in. Average Measurements

The results presented in Table A.11 of Appendix A confirm that when using the BPT on wheel tracked specimens, the measure is more representative of the friction and polishing of the aggregate than the specimen surface roughness. This is better represented in Figure 3.32 where with increase in the aggregate polish value, the average polish value for one-in. BPT measurement on the specimen is increased.

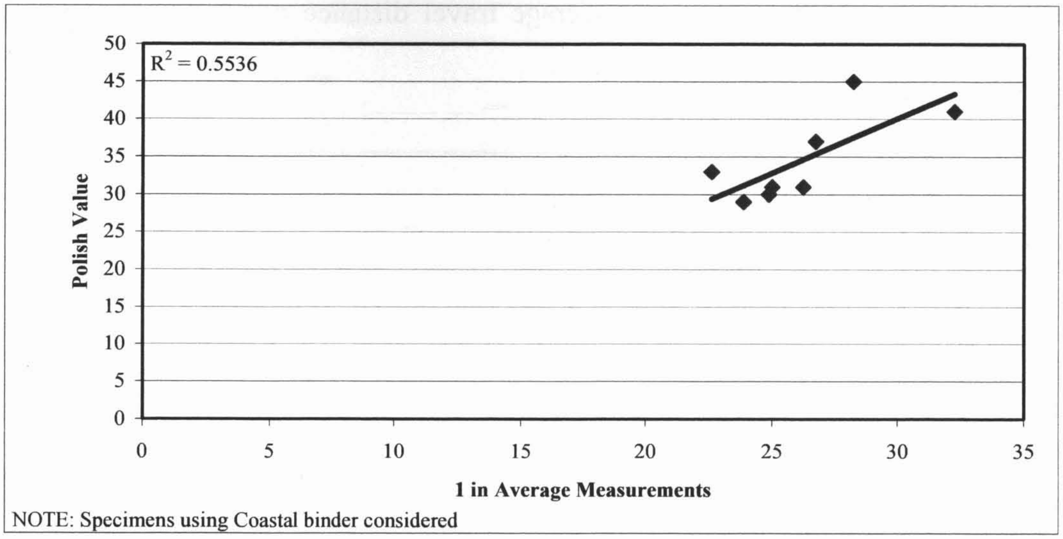


Figure 3.32 Correlation between Polish Value and 1 in. Average Measurements from BPT

The results show the same trend comparing polish value using Texas Test Method Tex-438-A and using the BPT on wheel tracked specimens from HWTD.

There was not a clear differentiation between sandstone, limestone and gravel results. Granite aggregates were the highest and some limestone aggregates were on the lower part of the graph. It was clear that when the travel length increased (from 1 in. to 3 in.) the variability increased and the correlation was not so strong.

3.2.19 L.A. Abrasion vs. 1 in. Average Measurements from BPT

The original idea of using the BPT on Hamburg wheel tracked specimens was to investigate the effectiveness of the BPT in discriminating between different levels of degradation for different materials. Figure 3.33 indicates that aggregates with higher abrasion tend to have less friction based on 1-in travel length..

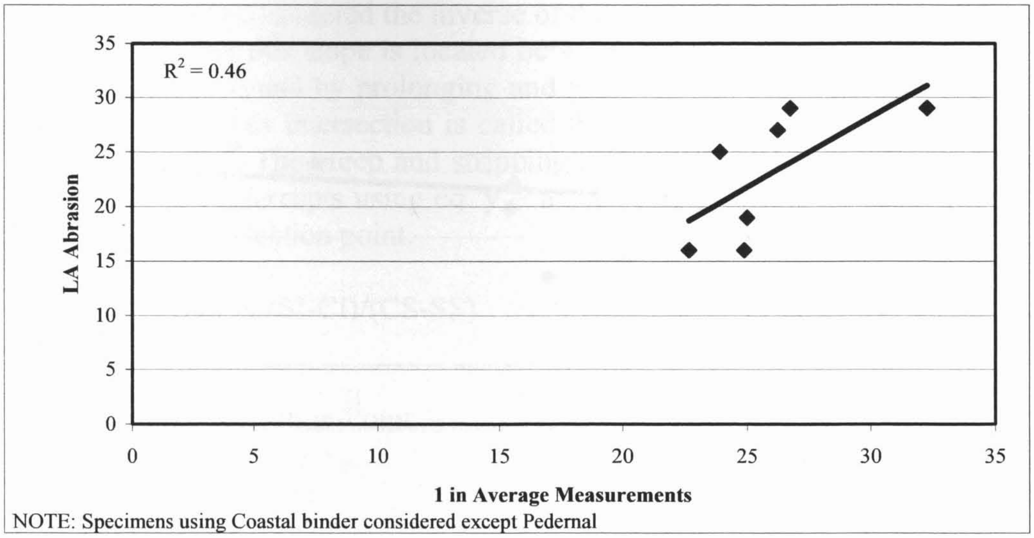


Figure 3.33 Correlation between L.A. Abrasion and 1 in. Ave. Measurements from BPT – Pedernal Excluded

3.2.22 Number of Cycles at Failure vs. Area between Gradation Lines

All the results from the HWTD tests can be found in Table B.1 (Appendix B). Possible comparisons were tabulated and displayed in order to find out if any meaningful correlation could be developed. In most cases poor correlations were found. Two plots are discussed using the data from the HWTD test. For the sake of analysis, it was considered necessary to use the number of cycles at 17 mm of permanent deformation as a parameter for comparison rather than the 20 mm deformation at which the test stops. The reason was that the data is recorded at different cycle intervals depending on the stage. Beyond 1,000 cycles, the data is recorded at 100 cycle intervals. If the maximum allowable deformation of 20 mm is reached at a cycle before the recording interval is reached, the number of cycles for the 20 mm deformation is not recorded. From the output tables, it was found that the number of cycles at 17 mm of deformation could be used as a common parameter for evaluating the number of repetitions close to failure for all the specimens. As shown in Figure 3.34, a clear trend could not be found even though for all the specimens shown in this graph the test temperature was the same (50°C), and binder was the same (Coastal PG 64-22). Possibly, the results are also affected by other factors such as the aggregate shape, gradation, and binder content. If these variables were controlled, probably a better correlation could be found. In general, it is expected to see a higher number of cycles for aggregates with higher resistance to abrasion.

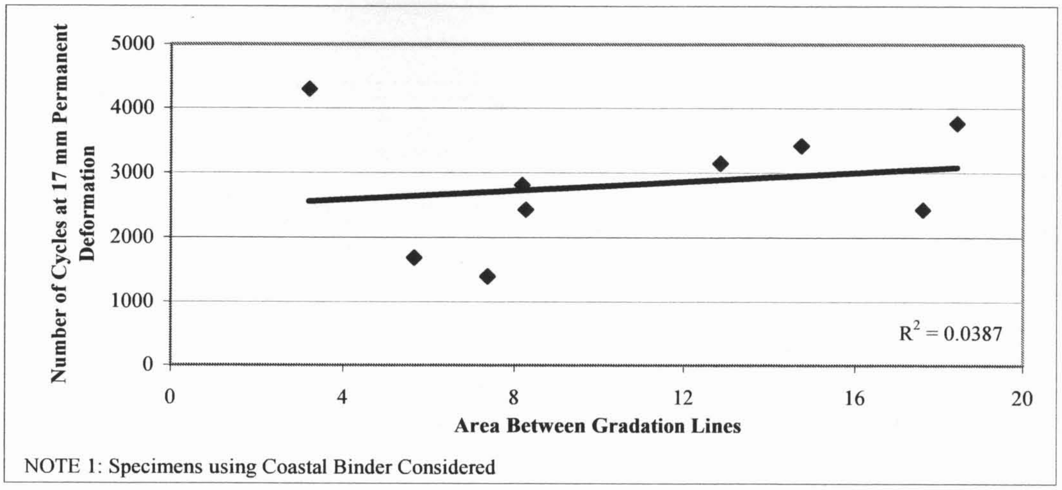


Figure 3.34 Correlation between Number of Cycles at Failure and Area

3.2.23 Permanent Deformation at SIP vs. Area between Gradation Lines

The relationship between the area between gradation lines, indicating degradation, and permanent deformation at the SIP (Stripping Inflection Point) is presented in Figure 3.36. As mentioned before, the results are affected by the aggregate shape, aggregate gradation, binder content, and binder stiffness. In general, it should be expected to observe a higher permanent deformation at SIP when a softer or more degradable material is used, i.e. higher area between gradation lines. However, such a trend is not observed based on the results shown in Figure 3.35 possibly as a result of other contributing factors.

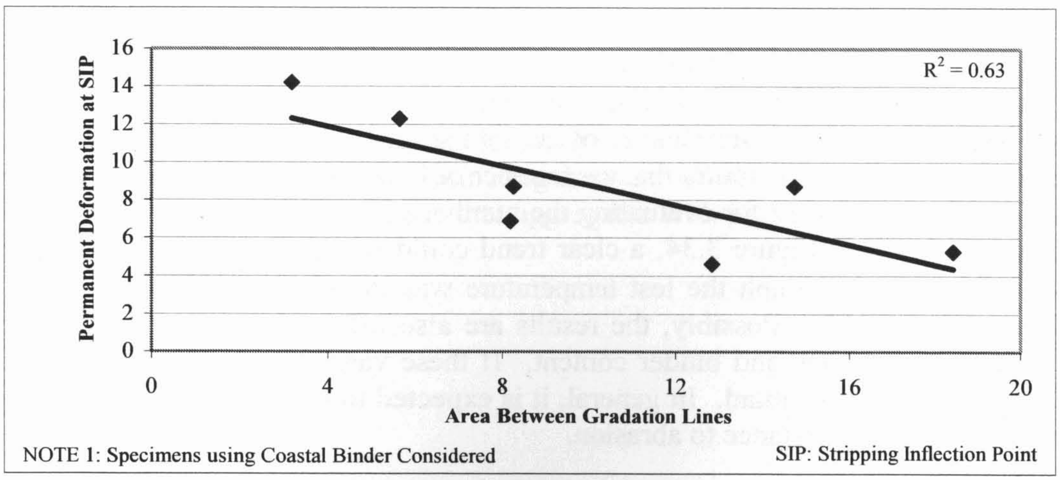


Figure 3.35 Correlation between Permanent Deformation at SIP and Area

The creep and stripping slopes were also compared with L.A. abrasion and the area between gradation lines. Similar correlations were observed. The creep slope is considered to be located between the post compaction and stripping regions on the HWTD output figure, and is considered the inverse of the rate of deformation in the linear sector of the deformation curve.

The stripping slope is also considered the inverse of the rate of deformation in the linear sector of the deformation curve, but this slope is located between the SIP and the end of the deformation readings. The SIP can be found by prolonging and intercepting both creep and stripping slopes. The number of passes at this intersection is called the SIP. It is related to the resistance of the HMA to moisture damage. The creep and stripping slopes were calculated using the regression analysis. The slopes and intercepts using eq. y = a + bx were used in the following formula for calculating the stripping inflection point.

$$SIP = (SI-CI)/(CS-SS) \qquad (3.1)$$

Where,

SIP: Stripping Inflection Point.
SI: Intercept at Stripping
CI: Intercept at Creep
CS: Creep Slope
SS: Stripping Slope

The HWTD test output was stored as a binary file. This file was converted into an ASCE file in order to analyze the data. Four different parameters were displayed: number of cycles, displacements (permanent deformation) at left and right sides of the specimen, and temperature. The results were used to find three specific parameters: creep slope, stripping slope and stripping inflection point. An example of one of the plots follows (Figure 3.36).

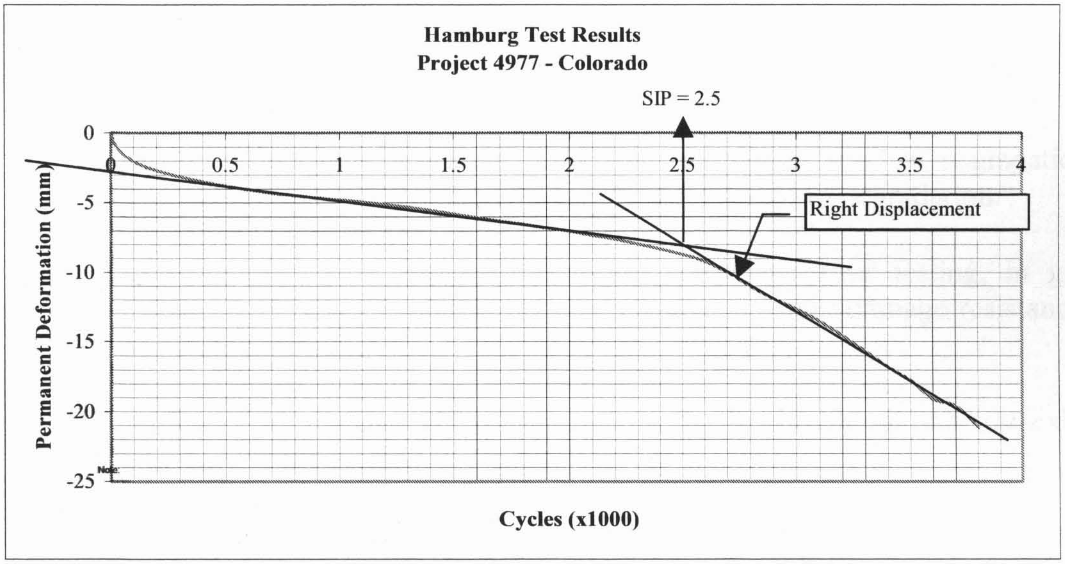


Figure 3.36 An Example of the Relationship between Permanent Deformation and No. of Cycles from HWTD Test (Results from Colorado Materials.)

3.3 Classification of Degradation from HWTD

Based on visual observation, numerical values, and all the comparisons and correlations found through this study, it was possible to determine three main levels of degradation: severe, moderate, and mild. The ranges were defined to quantify, to some extent, the level of degradation. The parameters included for this purpose were area between gradation lines (loss area), difference in gradation before and after the HWTD test, L.A. abrasion loss, Micro-Deval loss, soundness loss, and polish value. Table 3.4 shows the ranges defined based on the results of this research study. Two main groups of data were encountered in the comparisons. The two groups were separated by a gap where moderate degradation was defined. It is necessary to mention that the limits and ranges defined in Table 3.4 are based only on the test results for a limited number of sources studied in this research. The results could vary significantly as new information becomes available through further research.

An important issue to be addressed is the binder stiffness which has a significant effect on the mix behavior in the HWTD. It is possible that in case of using a stiff binder and low testing temperature, the mix might not manifest any degradation for all or some of the aggregates considered in this study.

Table 3.4 Classification of Aggregate Degradation Levels in the HWTD

Level of Degradation	Loss Area	Difference in Gradation (%)	L.A. Abrasion Loss (%)	Micro Deval Loss (%)	Soundness Loss (%)	P.V. Loss (%)
Severe	>13	>27	>25	>12	>16	>40
Moderate	8-13	19-27	20-25	5-12	7-16	34-40
Mild	<8	<19	<20	<5	<7	<34

Chapter 4
Conclusions and Recommendations

4.1 Activity Summary

A research study was undertaken for one year to evaluate the relationship between aggregate properties and the results from the Hamburg Wheel Tracking Device (HWTD). This is the device mainly used to determine the moisture susceptibility of the hot mix asphalt concrete (HMAC). Eleven aggregates were included in the study. Three limestone aggregates, four gravel aggregates, one sandstone, three igneous rocks (granite, basalt, and rhyolite) were considered in the study.

A series of tests were performed on the aggregates. The tests included magnesium sulfate soundness, Micro-Deval loss, L.A. abrasion, and polish value. Asphalt-aggregate mixtures were prepared according to specific mix designs received from various districts. The mixtures were compacted with the aid of a Superpave gyratory compactor. The prepared specimens were tested with the HWTD. The HWTD tested specimens were evaluated by the British pendulum equipment to quantify the aggregate polishing caused by the HWTD. The final step included performing gradation analysis on the extracted aggregates to evaluate the changes from the original gradation caused by the damage produced by the HWTD.

4.2 Conclusions

The following conclusions are drawn based on the extensive tests conducted for this research study and the analysis conducted on the test results.

- In general, limestone aggregates exhibited the highest level of degradation and gravel aggregates demonstrated the toughest resistance to degradation.

- Based on the visual observation of the specimens after testing, in general, limestone aggregates exhibited relatively better moisture damage resistance than the gravel aggregates.

- Aggregates with higher polish value from the British Pendulum test exhibited higher L.A. abrasion loss

- A strong correlation was observed between the polish value and the solid polish value.

- In general, aggregates with higher degradation also had higher L.A. abrasion and higher Micro-Deval loss.

For the type of binder and the test temperature used in this study, it was possible to determine three main levels of degradation in the HTWD: severe, moderate and mild. Table 3.4

from Chapter 3, presented below, shows the ranges observed on the aggregate results from this research study.

Level of Degradation	Loss Area	Difference in Gradation (%)	L.A. Abrasion Loss (%)	Micro Deval Loss (%)	Soundness Loss (%)	P.V. Loss (%)
Severe	>13	>27	>25	>12	>16	>40
Moderate	8-13	19-27	20-25	5-12	7-16	34-40
Mild	<8	<19	<20	<5	<7	<34

4.2 Implementation and Recommendations

Aggregate characteristics play a major role regarding performance of HMAC. Investigating aggregate behavior under the rolling wheels in the laboratory provides valuable information regarding the aggregate toughness and how it may behave once placed in the hot mix asphalt concrete in the field. Including aggregates of different sources in this study provided a valuable database of such information. The results of this research project can be used to improve specifications for utilizing aggregates in HMAC, and to provide better means of controlling the quality of the aggregates to be utilized. Tests of the study could be conducted for other binders and temperatures. If the same trend in observed, then the results could be used to develop a set of criteria for selection of aggregates based on the results from the HWTD. It is perceived that TxDOT investigates the possibility of including such criteria into specifications.

The method used to develop the results presented in the preceding table is based on quantifying the change in the aggregate gradation after exposure to the tracking wheels of the Hamburg device. This change in aggregate gradation is captured and quantified through the concept of loss area, defined as the area between gradation lines before and after the wheel tracking. The results presented in the preceding table should be validated through field investigation. Once such validation is established, the results could be implemented in discriminating between high and low quality aggregates.

This one-year study provided valuable information in regard to the relationship of the aggregate degradation in the HWTD and aggregate properties. This research provides a strong and useful foundation for further evaluation of the HWTD potential in identifying aggregate properties. It is recommended that the following four activities be pursued to enhance the findings of this study and to use these findings.

1. The study should be expanded to include a larger number of aggregates from different sources.

2. Rather than using different aggregate gradations for different aggregates, a single gradation should be used to reduce the number of variables affecting the results.

3. One of the outputs from the HWTD is the deformation profile of the specimen upon completion of the test. Current TxDOT software does not store the digital information on this profile. A close look at this profile through this research indicated that this deformation profile has great potential for differentiating between

different aggregates once the shape of the profile is quantified. It is proposed that during further research, the profile should be taken into account. For this purpose, it is important that the software be upgraded to a level that it becomes possible to store the digital information of the profile in the system.

4. A series of test sections should be built under the same climatic and traffic conditions, to evaluate the aggregate behavior and to validate the results from the HWTD. Different aggregates will be used in these sections with the same gradation and the same binder.

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Appendix A

Table A.1 Analysis of Gradation before and after the HWTD Test – Mirando

Source: Mirando **Aggregate Type:** Gravel

Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
12.5	100.0	100.0	0.00	0.00	0.14	3.12
9.5	90.7	91.4	0.75	0.01	1.09	2.75
4.75	56.4	58.6	2.19	0.04	1.86	2.02
2	33.0	36.6	3.53	0.11	2.40	1.37
0.425	22.3	25.8	3.48	0.16	0.86	0.68
0.18	11.0	15.4	4.42	0.40	0.56	0.46
0.075	5.0	8.0	3.02	0.61	0.47	0.31
	0.0	0.0	17.39	1.32	7.38	SUM

The results are for specimen B2

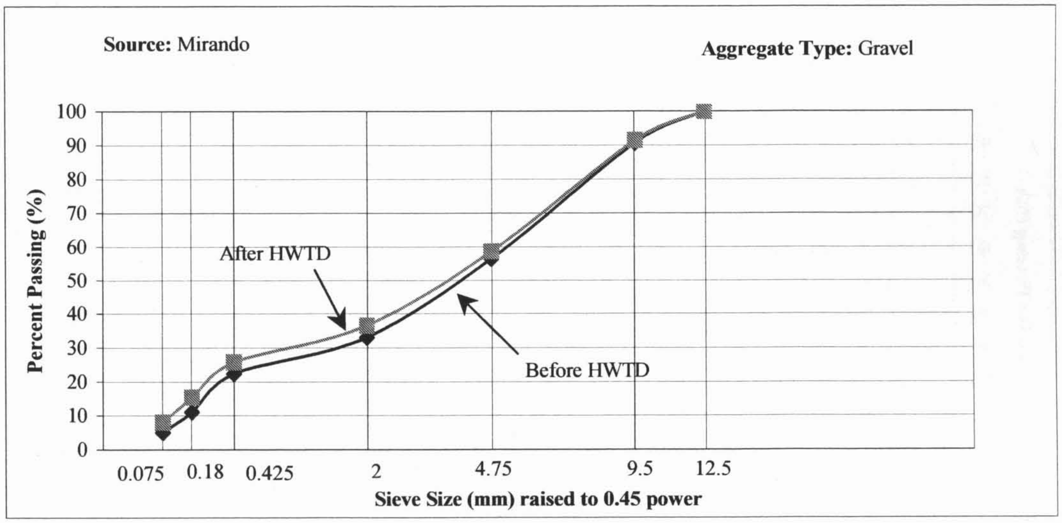

Figure A.1 Comparison of Gradations before and after Testing with HWTD - Mirando

Table A.2 Analysis of Gradation before and after the HWTD Test - Hanson

Source: Hanson **Aggregate Type:** Gravel

Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
22.4	100.0	100.0	0.00	0.00	0.23	4.05
9.5	79.9	80.3	0.36	0.00	0.45	2.75
4.75	57.2	58.1	0.87	0.02	0.64	2.02
2	36.2	37.3	1.08	0.03	0.85	1.37
0.425	20.5	21.9	1.39	0.07	0.41	0.68
0.18	11.3	13.7	2.35	0.21	0.32	0.46
0.075	1.9	3.8	1.88	0.97	0.29	0.31
	0.0	0.0	7.92	1.30	3.18	SUM

The results are for specimen RND4

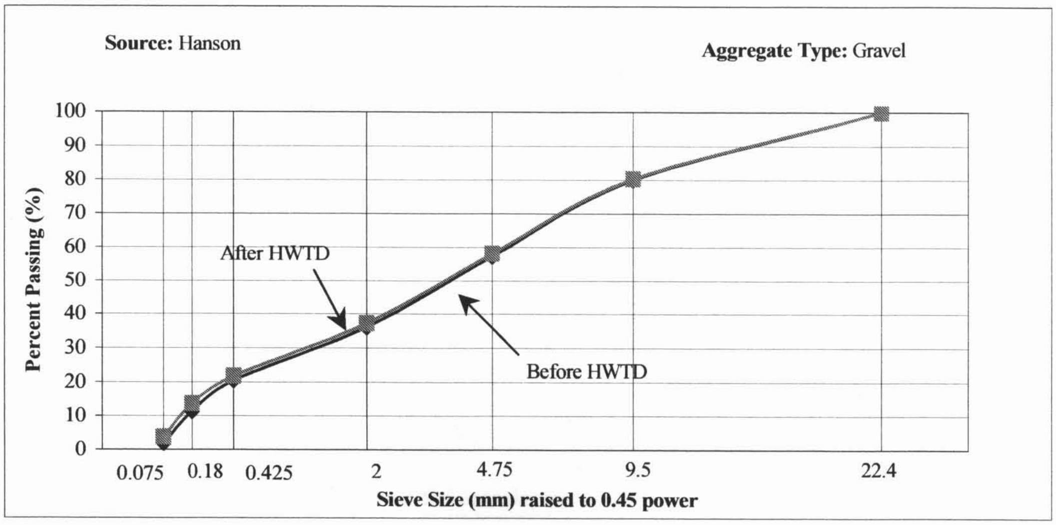

Figure A.2 Comparison of Gradations before and after testing with HWTD – Hanson

Table A.3 Analysis of Gradation before and after the HWTD Test – Wright

Source:	Wright			**Aggregate Type:**		Gravel
Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
22.4	100.0	100.0	0.00	0.00	0.51	4.05
9.5	78.9	79.6	0.78	0.01	0.65	2.75
4.75	59.1	60.0	0.99	0.02	1.07	2.02
2	36.1	38.4	2.30	0.06	2.19	1.37
0.425	13.4	17.5	4.08	0.30	0.99	0.68
0.18	5.4	10.5	5.04	0.93	0.73	0.46
0.075	2.1	6.8	4.63	2.17	0.72	0.31
	0.0	0.0	17.82	3.49	6.86	SUM

The results are for specimens B3 and RND1

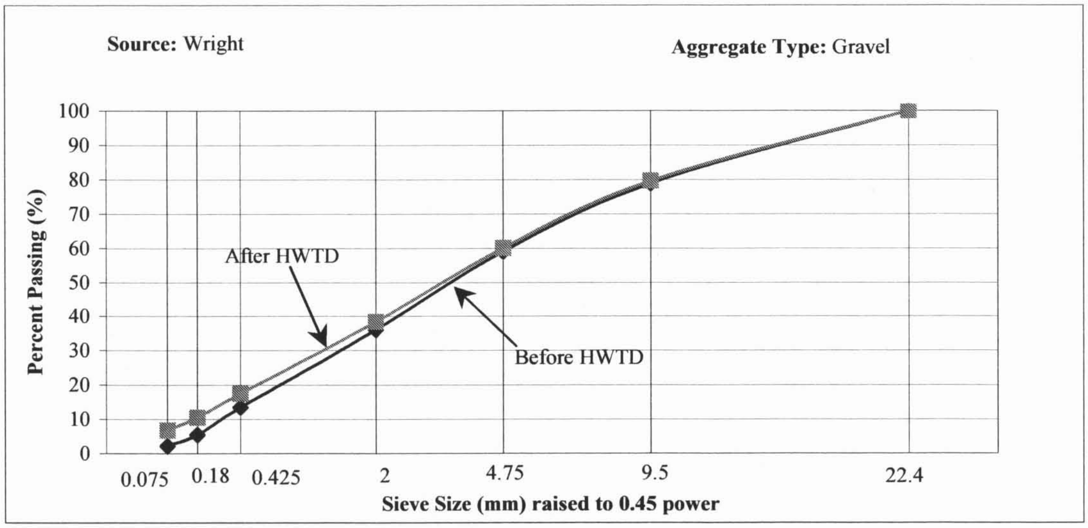

Figure A.3 Comparison of Gradations before and after Testing with HWTD – Wright

Table A.4 Analysis of Gradation before and after the HWTD Test – Colorado

Source:	Colorado			**Aggregate Type:**		Limestone
Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
25	100.0	100.0	0.00	0.00	0.00	4.26
19	100.0	100.0	0.00	0.00	0.46	3.76
12.5	93.6	95.0	1.41	0.02	0.82	3.12
9.5	77.4	80.5	3.10	0.04	2.97	2.75
4.75	51.7	56.7	4.95	0.10	2.89	2.02
2.36	36.6	42.3	5.68	0.16	2.36	1.47
1.18	24.0	30.3	6.27	0.26	1.82	1.08
0.6	13.0	19.6	6.57	0.50	1.35	0.79
0.3	7.3	13.5	6.10	0.83	0.89	0.58
0.15	4.0	9.3	5.29	1.34	0.54	0.43
0.075	2.2	6.4	4.22	1.93	0.66	0.31
	0.0	0.0	43.60	5.17	14.75	SUM

Specimens B3 and RND1

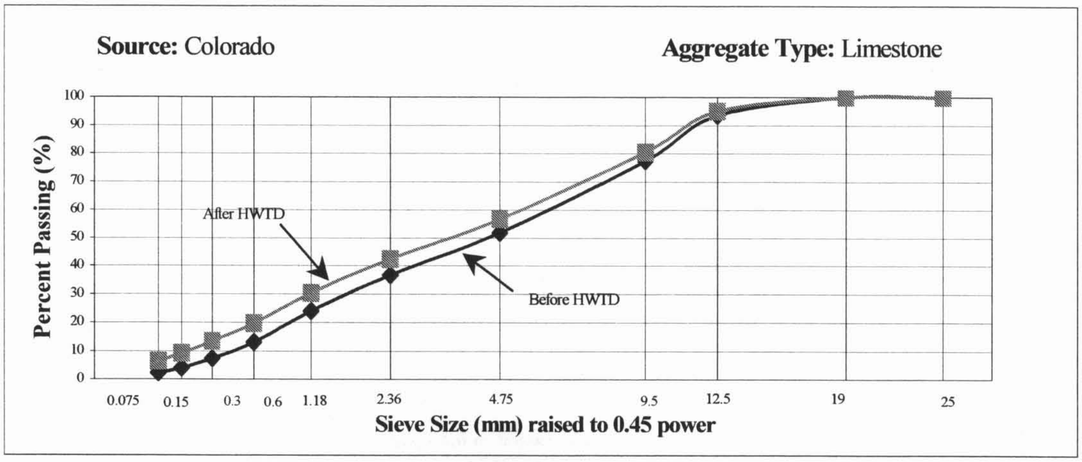

Figure A.4 Comparison of Gradations before and after testing with HWTD – Colorado

Table A.5 Analysis of Gradation before and after the HWTD Test – Vado/Mack

Source:	Vado/Mack			**Aggregate Type:**		Granite
Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
25	100.0	100.0	0.00	0.00	0.15	4.26
19	97.3	97.9	0.61	0.01	0.63	3.76
12.5	80.0	81.4	1.33	0.02	0.80	3.12
9.5	63.6	66.7	3.07	0.05	2.87	2.75
4.75	39.7	44.5	4.71	0.12	3.47	2.02
2.36	25.0	33.0	8.04	0.32	3.22	1.47
1.18	16.2	24.5	8.30	0.51	2.34	1.08
0.6	11.1	19.3	8.28	0.75	1.69	0.79
0.3	8.1	15.7	7.58	0.93	1.07	0.58
0.15	6.4	12.5	6.16	0.97	0.63	0.43
0.075	4.7	9.5	4.83	1.04	0.75	0.31
	0.0	0.0	52.90	4.71	17.62	SUM

Specimen B1

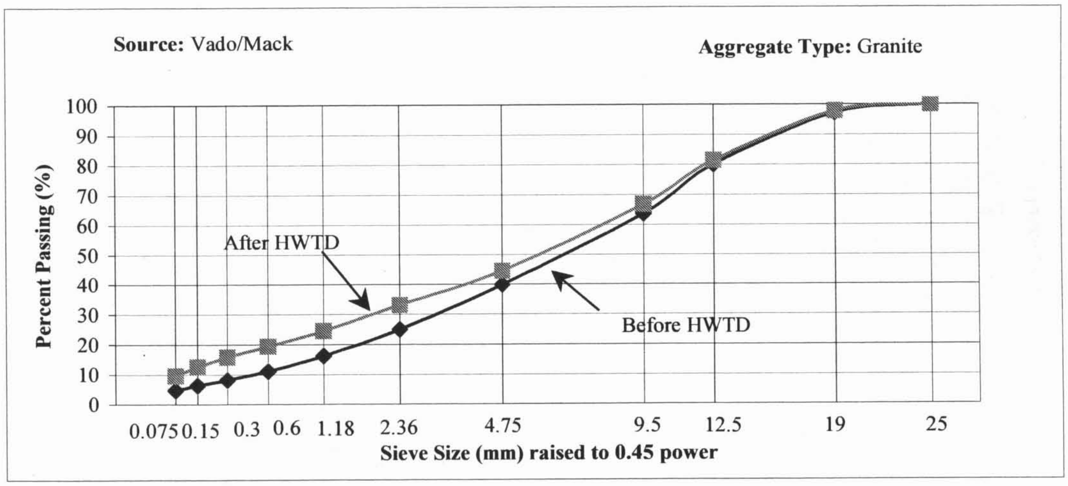

Figure A.5 Comparison of Gradations before and after testing with HWTD – Vado/Mack

Table A.6 Analysis of Gradation before and after the HWTD Test - Pedernal

Source: Pedernal **Aggregate Type:** Basalt/Granite

Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
22.4	100.0	100.0	0.00	0.00	2.62	4.05
9.5	75.6	79.6	4.05	0.05	3.07	2.75
4.75	52.1	56.4	4.28	0.08	3.58	2.02
2	33.8	40.6	6.73	0.20	5.19	1.37
0.425	17.2	25.6	8.41	0.49	1.82	0.68
0.18	12.2	20.5	8.28	0.68	1.12	0.46
0.075	7.0	13.6	6.55	0.94	1.02	0.31
	0.0	0.0	38.30	2.44	18.43	SUM

Specimen RND3

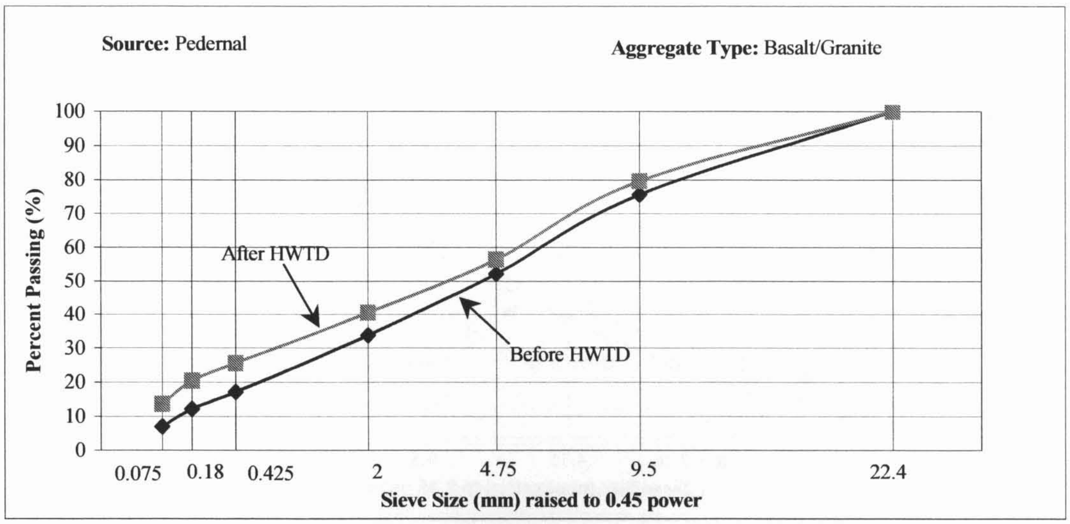

Figure A.6 Comparison of Gradations before and after testing with HWTD – Pedernal

Table A.7 Analysis of Gradation before and after the HWTD Test - Hoban

Source: Hoban **Aggregate Type:** Limestone

Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
22.4	100.0	100.0	0.00	0.00	0.05	4.05
12.5	99.5	99.6	0.10	0.00	0.17	3.12
9.5	88.3	89.1	0.84	0.01	1.11	2.75
4.75	55.8	58.0	2.16	0.04	2.08	2.02
2	23.7	27.9	4.23	0.18	3.05	1.37
0.425	10.9	15.6	4.66	0.43	0.91	0.68
0.18	8.7	12.4	3.69	0.42	0.45	0.46
0.075	6.9	9.2	2.32	0.34	0.36	0.31
	0.0	0.0	18.01	1.42	8.18	SUM

Specimen RND3

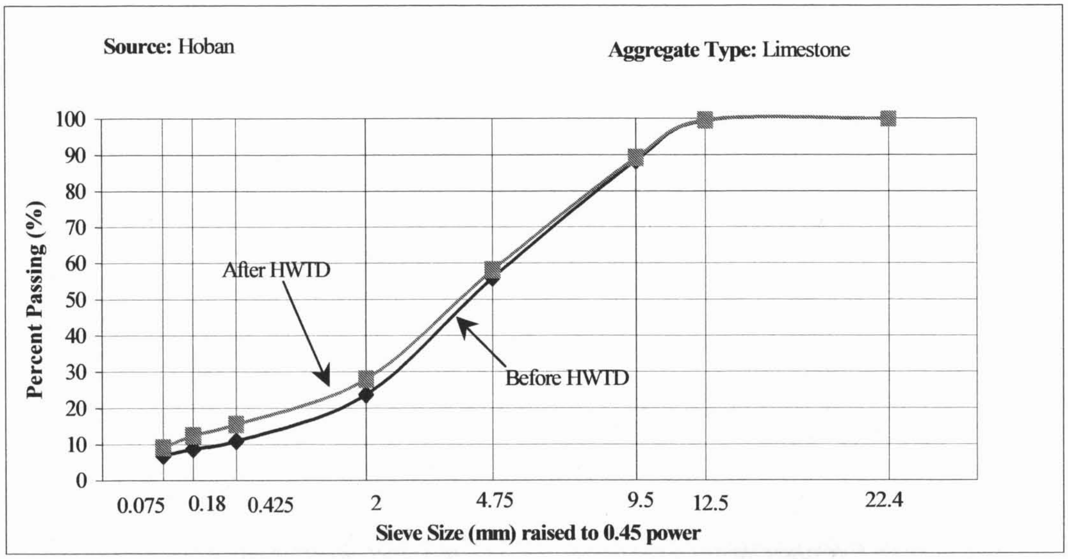

Figure A.7 Comparison of Gradations before and after testing with HWTD Hoban

Table A.8 Analysis of Gradation before and after the HWTD Test - Meridian

Source: Meridian **Aggregate Type:** Sandstone

Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
16	98.0	97.7	-0.30	0.00	0.08	3.48
12.5	89.9	90.6	0.76	0.01	0.20	3.12
9.5	83.5	83.8	0.32	0.00	1.39	2.75
4.75	61.8	65.3	3.46	0.06	2.98	2.02
2	40.5	46.3	5.72	0.14	4.68	1.37
0.425	23.8	31.7	7.94	0.33	1.79	0.68
0.18	13.4	21.9	8.49	0.63	1.00	0.46
0.075	3.7	8.5	4.75	1.28	0.74	0.31
	0.0	0.0	31.14	2.45	12.87	SUM

Specimen B1

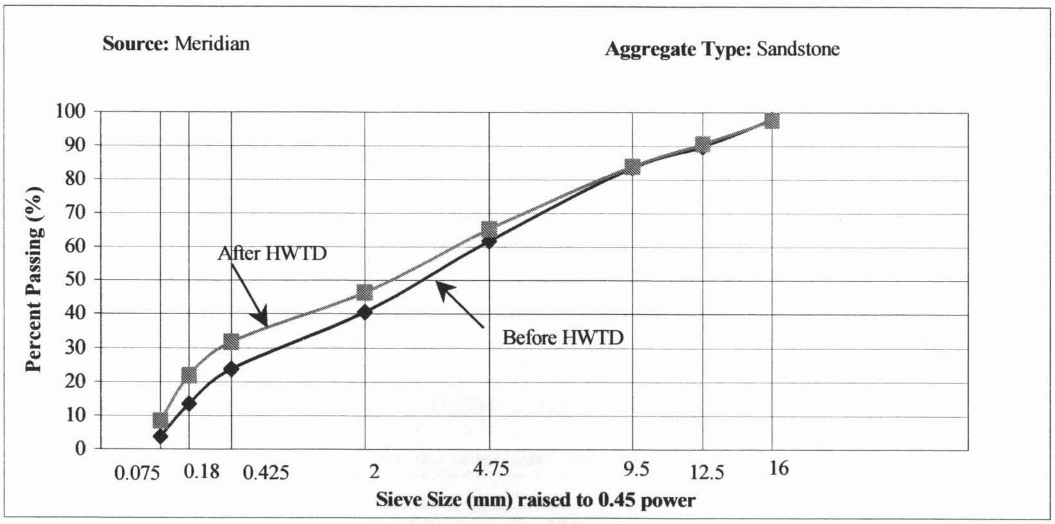

Figure A.8 Comparison of Gradations before and after testing with HWTD Meridian

Table A.9 Analysis of Gradation before and after the HWTD Test - Fordyce

Source: Fordyce **Aggregate Type:** Gravel

Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
12.5	99.9	99.9	-0.01	0.00	0.13	3.12
9.5	94.5	95.2	0.70	0.01	0.99	2.75
4.75	61.4	63.4	1.98	0.03	1.38	2.02
2	39.5	41.8	2.26	0.06	1.65	1.37
0.425	20.9	23.4	2.54	0.12	0.64	0.68
0.18	8.6	11.9	3.31	0.39	0.45	0.46
0.075	2.4	5.2	2.73	1.11	0.43	0.31
	0.0	0.0	13.53	1.72	5.66	SUM

Specimens B2 and B3

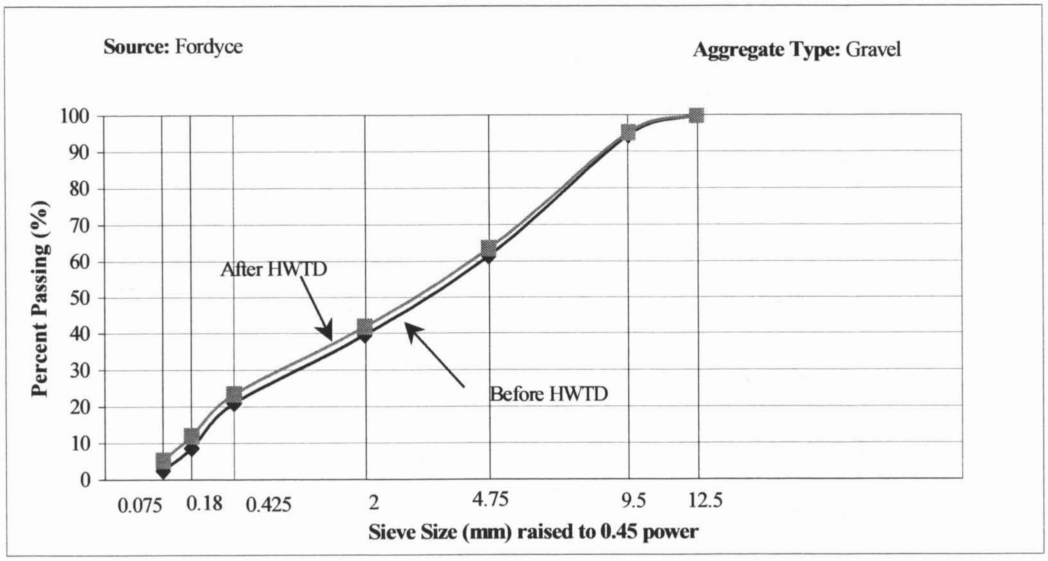

Figure A.9 Comparison of Gradations before and after Testing with HWTD Fordyce

Table A.10 Analysis of Gradation before and after the HWTD Test – TXI – Bridgeport

Source: TXI Bridgeport **Aggregate Type:** Limestone

Sieve Size (mm)	Before HWTD Cummulative Passing (%)	After HWTD Cummulative Passing (%)	Difference in gradation (%)	Normalized Difference	Area between gradation lines	Sieve Size ^0.45 (mm)
12.5	100.0	100.0	0.00	0.00	0.06	3.12
9.5	98.5	98.8	0.35	0.00	1.84	2.75
4.75	63.4	68.0	4.63	0.07	3.75	2.02
2	37.1	44.0	6.90	0.19	5.10	1.37
0.425	17.5	25.4	7.96	0.46	1.45	0.68
0.18	10.4	15.8	5.37	0.51	0.57	0.46
0.075	3.8	6.1	2.24	0.59	0.35	0.31
	0.0	0.0	27.46	1.82	13.12	SUM

Specimens B1 and B2

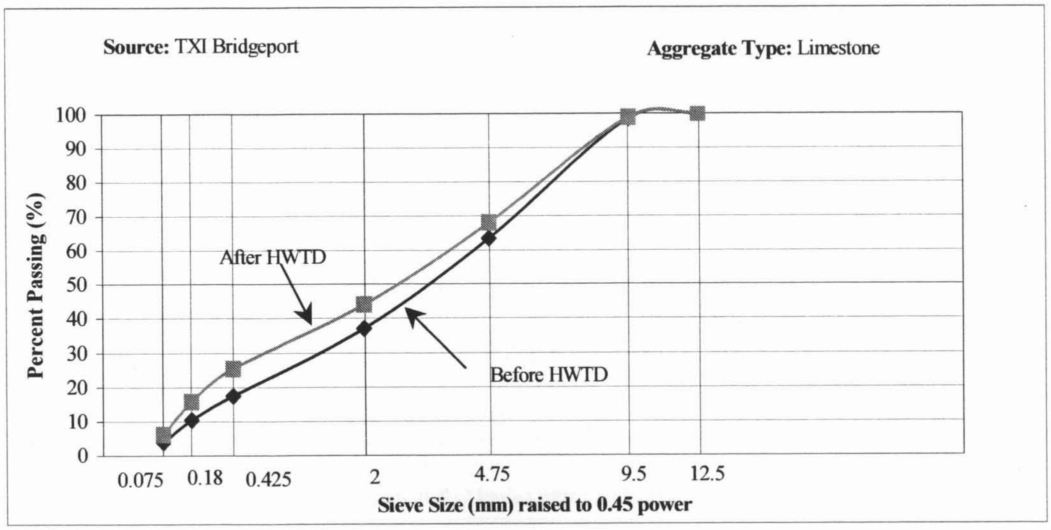

Figure A.10 Comparison of Gradations before and after testing with HWTD – TXI – Bridgeport

Appendix B

Table B.1 Hamburg Wheel Tracking Device Test Results Using Output

					Stripping Inflection		Point			
Aggregate Source	Total Deformation mm	Creep Slope	Stripping Slope	No.Cycles to failure	Deformation mm	No.Cycles	SIP	No.Cycles at 17 mm	Area Between Grad. Lines	Los Angeles Abrasion
Vulcan	21.52	0.0033	0.0079	3600	8.70	1984	1.984	2430	8.26	25
Colorado	21.15	0.002	0.0097	3800	8.70	2501	2.501	3420	14.75	27
Hoban	22.39	0.0034	0.0069	3600	6.88	1333	1.333	2813	8.18	16
Hanson	21.42	0.002	0.0070	5200	14.20	3698	3.698	4300	3.18	19
Mirando	21.39	0.011		2000				1390	7.38	16
Fordyce	20.72	0.0057	0.0269	1900	12.30	1450	1.450	1680	5.66	16
Vado	21.98	0.007		3400				2430	17.62	29
Pedernal	21.71	0.0014	0.0061	4300	5.26	1805	1.805	3765	18.43	13
Meridian	21.76	0.0016	0.0059	3500	4.62	1120	1.120	3145	12.87	29

Note: All sources were tested using Coastal Binder PG 64-22 and 50 C temperature on HWTD Test
SIP: Stripping Inflection Point

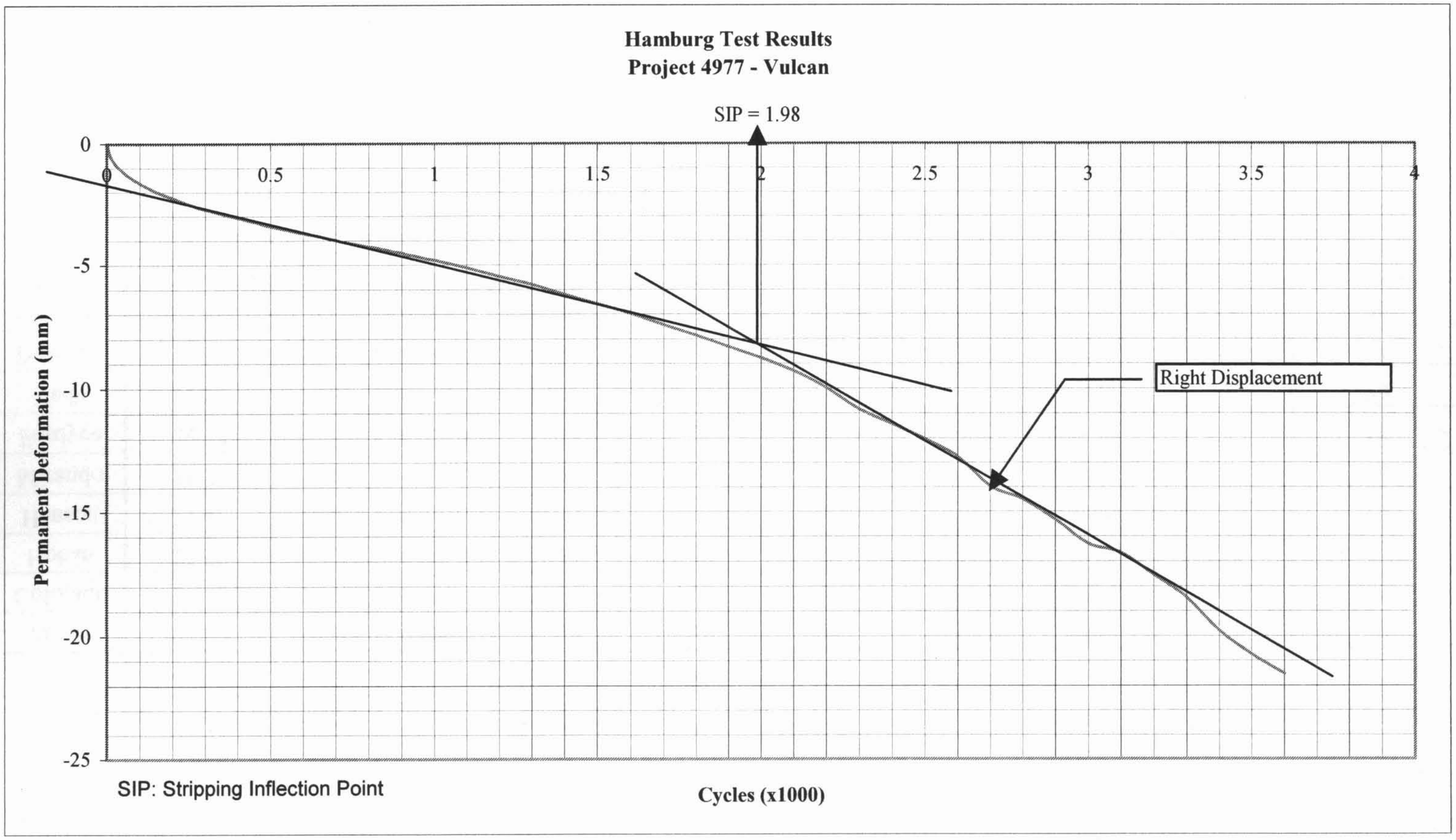

Figure B.1 Relationship between Permanent Deformation and No. Cycles Using Output from HWTD Test – Vulcan

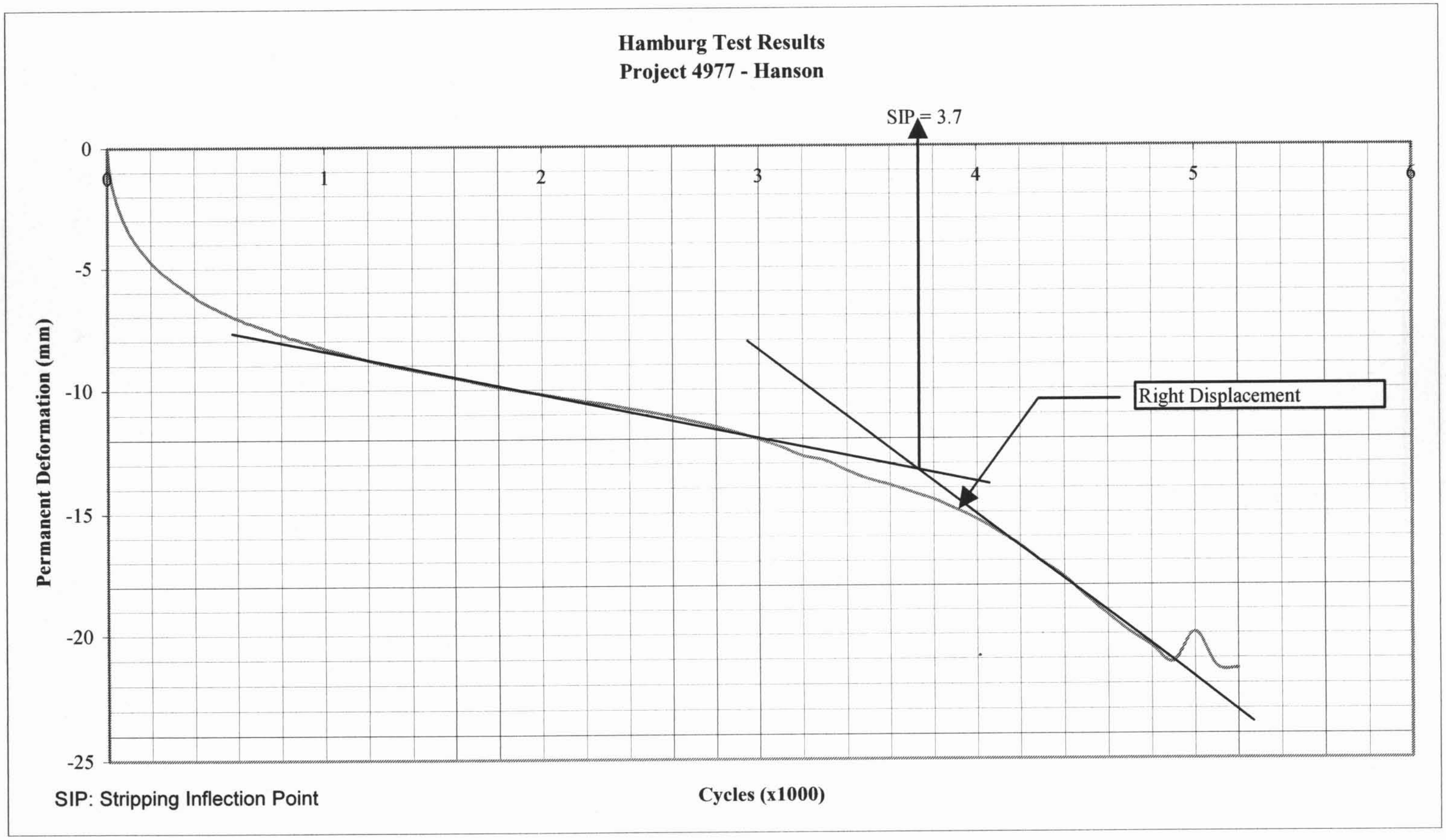

Figure B.2 Relationship between Permanent Deformation and No. Cycles Using Output from HWTD Test – Hanson

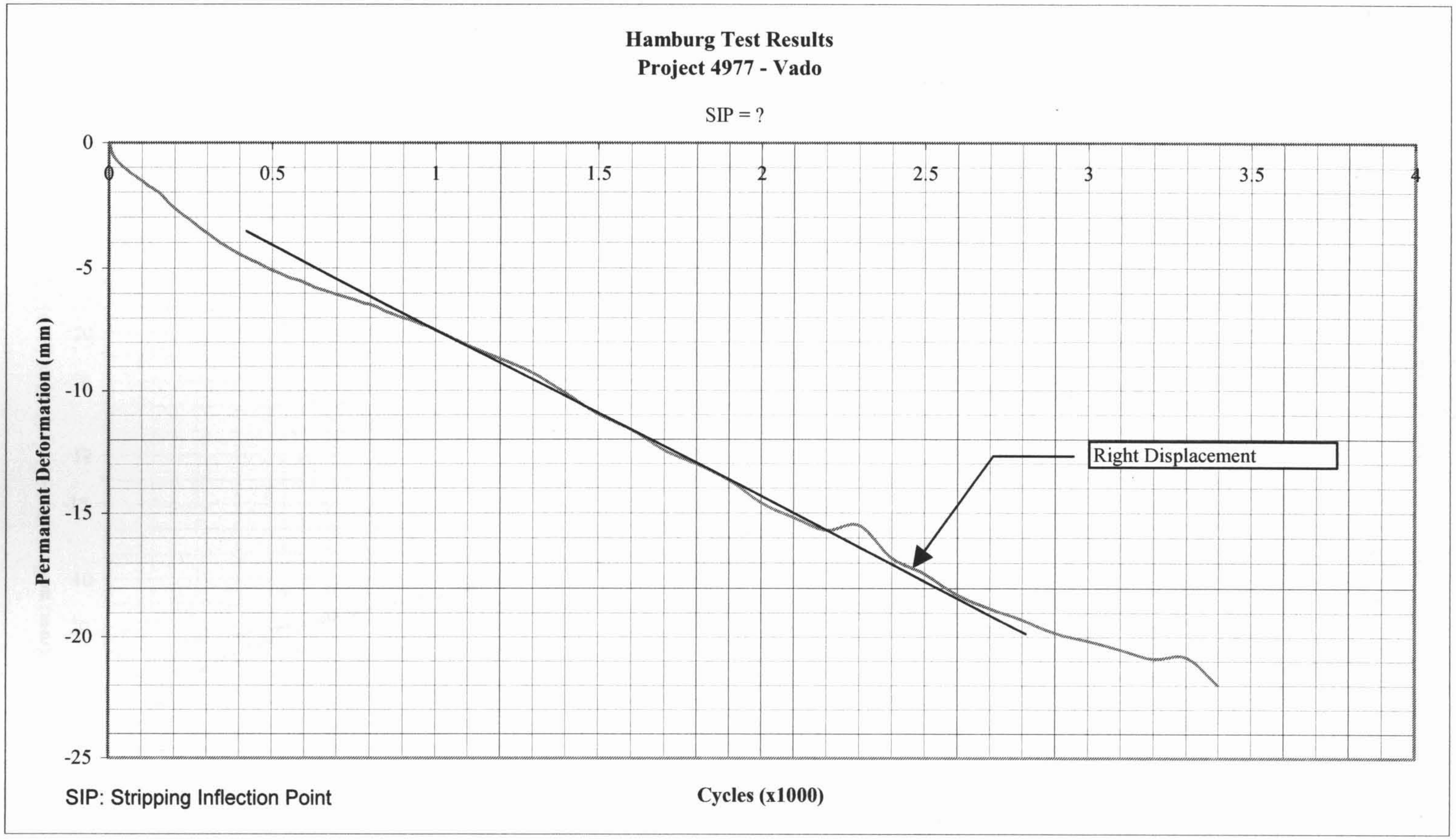

Figure B.3 Relationship between Permanent Deformation and No.Cycles Using Output from HWTD Test – Vado/Mack

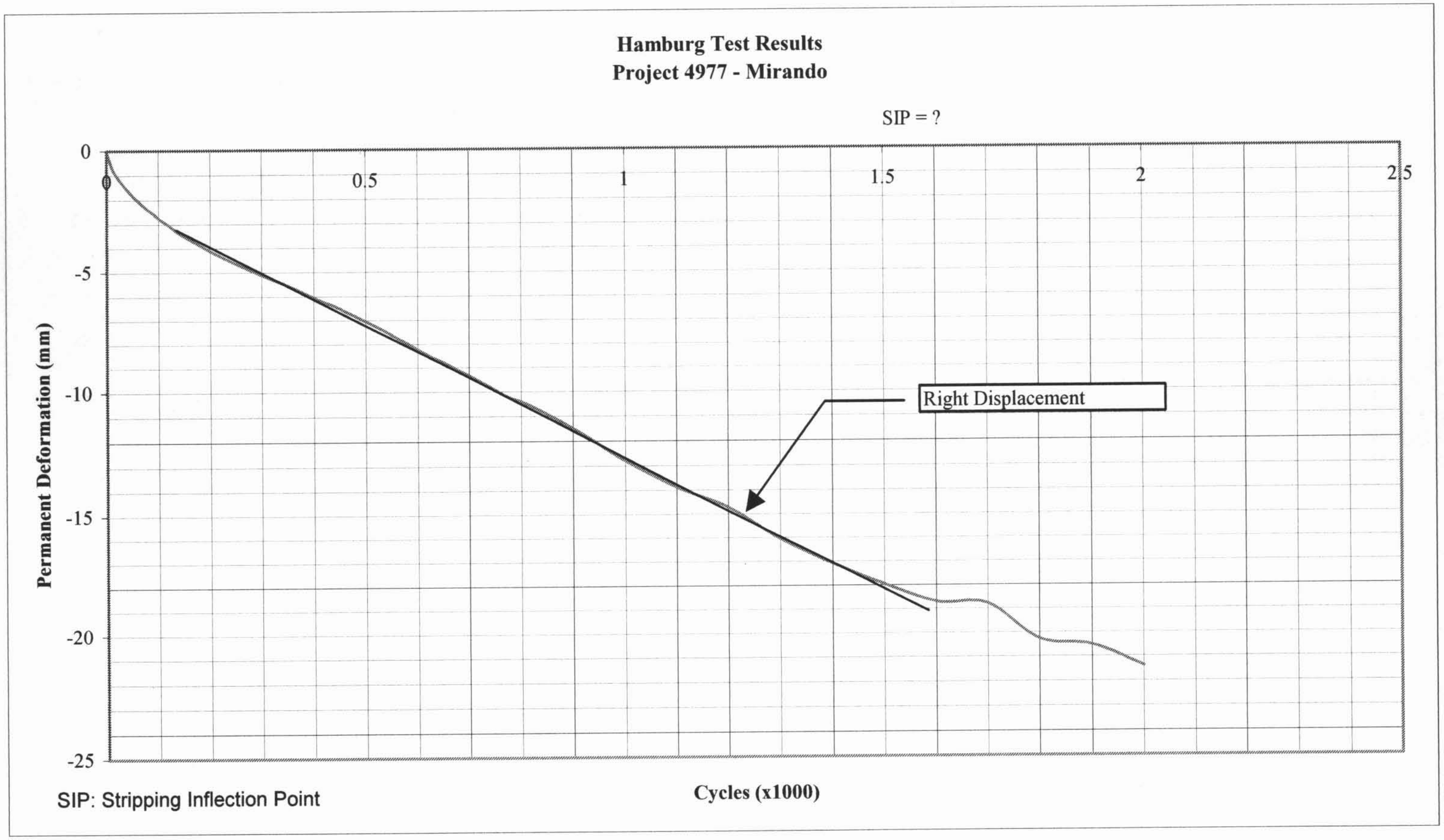

Figure B.4 Relationship between Permanent Deformation and No. Cycles Using Output from HWTD Test - Mirando

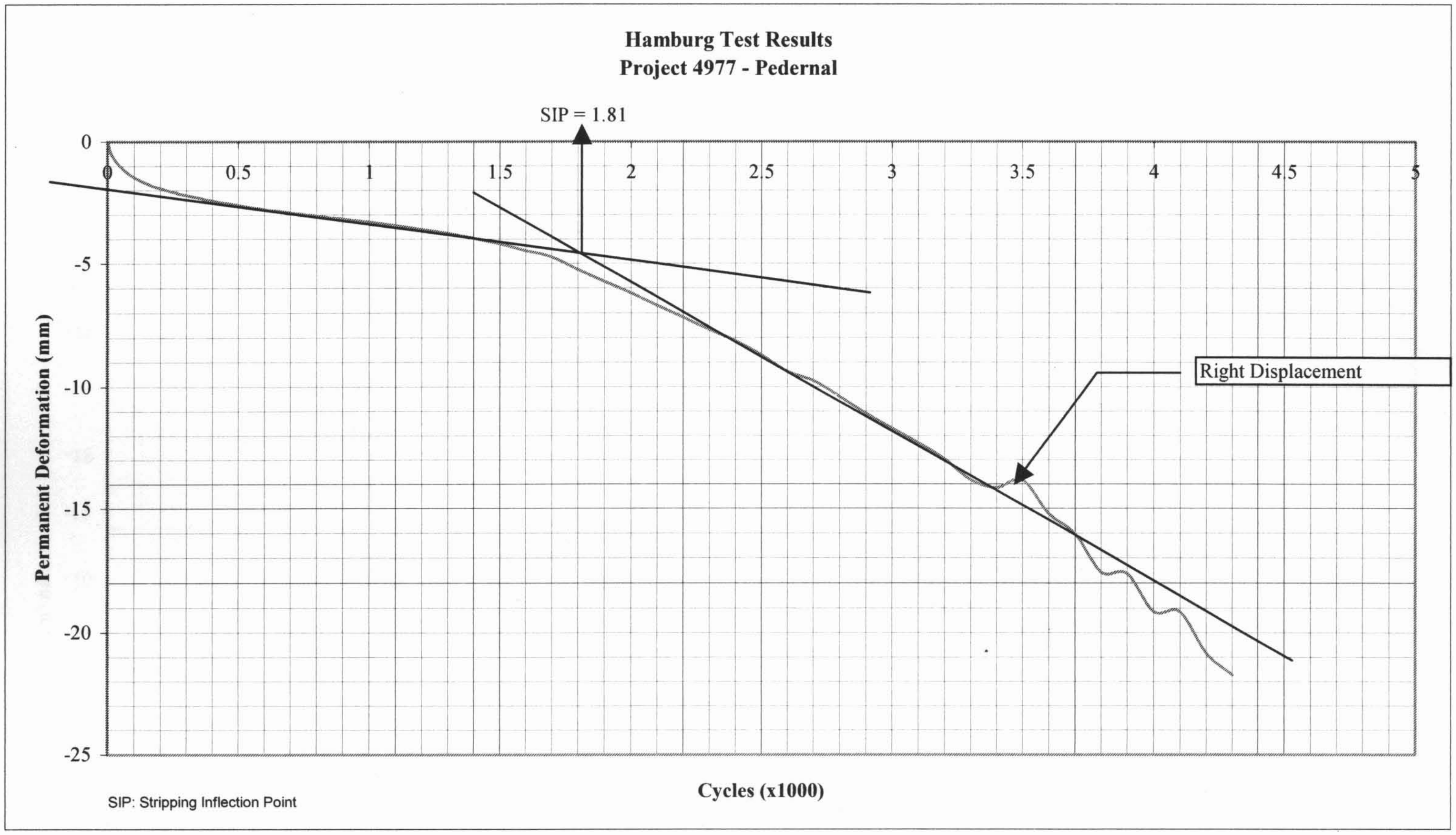

Figure B.5 Relationship between Permanent Deformation and No. Cycles Using Output from HWTD Test - Pedernal

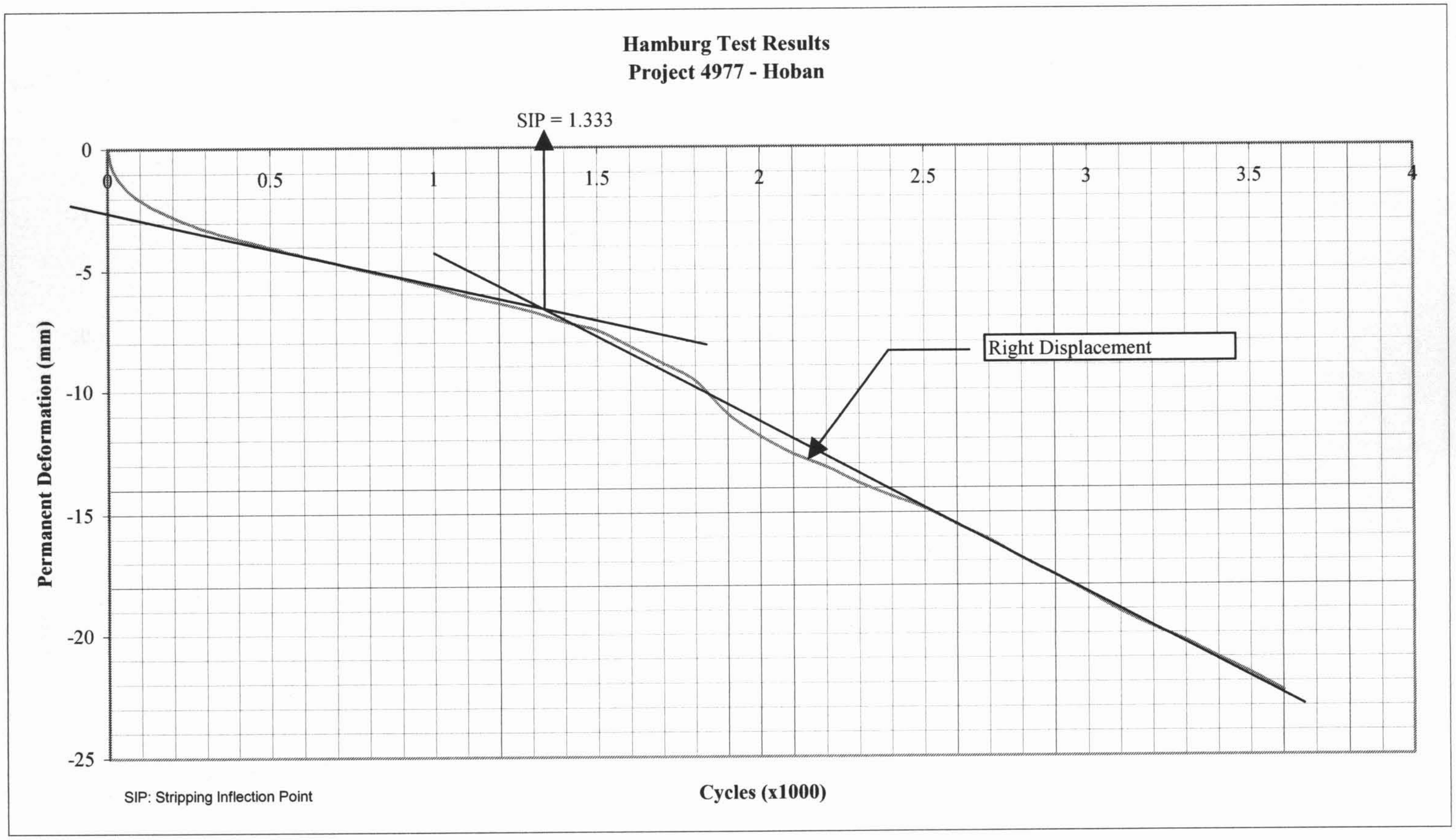

Figure B.6 Relationship between Permanent Deformation and No. Cycles Using Output from HWTD Test - Hoban

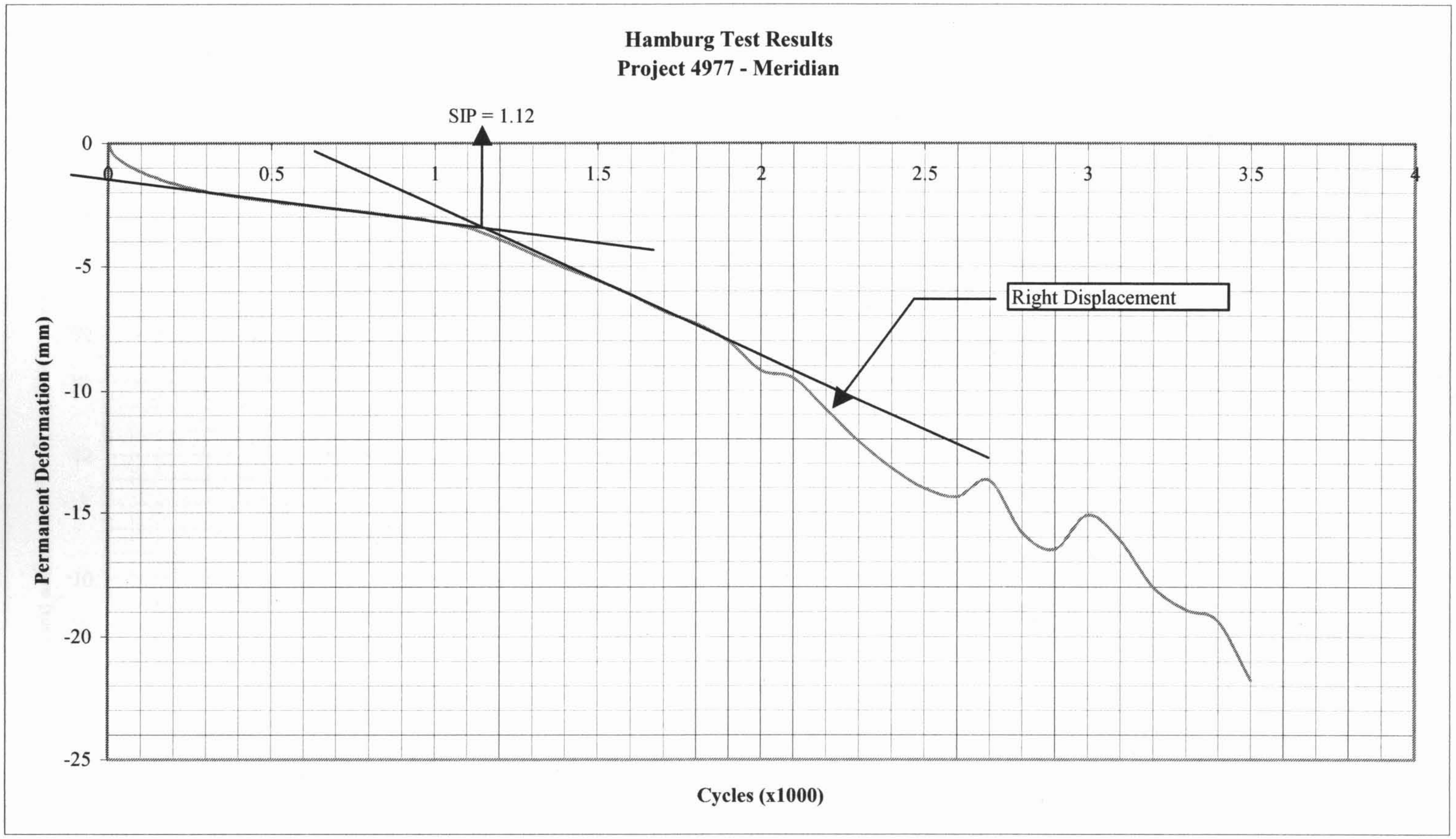

Figure B.7 Relationship between Permanent Deformation and No. Cycles Using Output from HWTD Test - Meridian

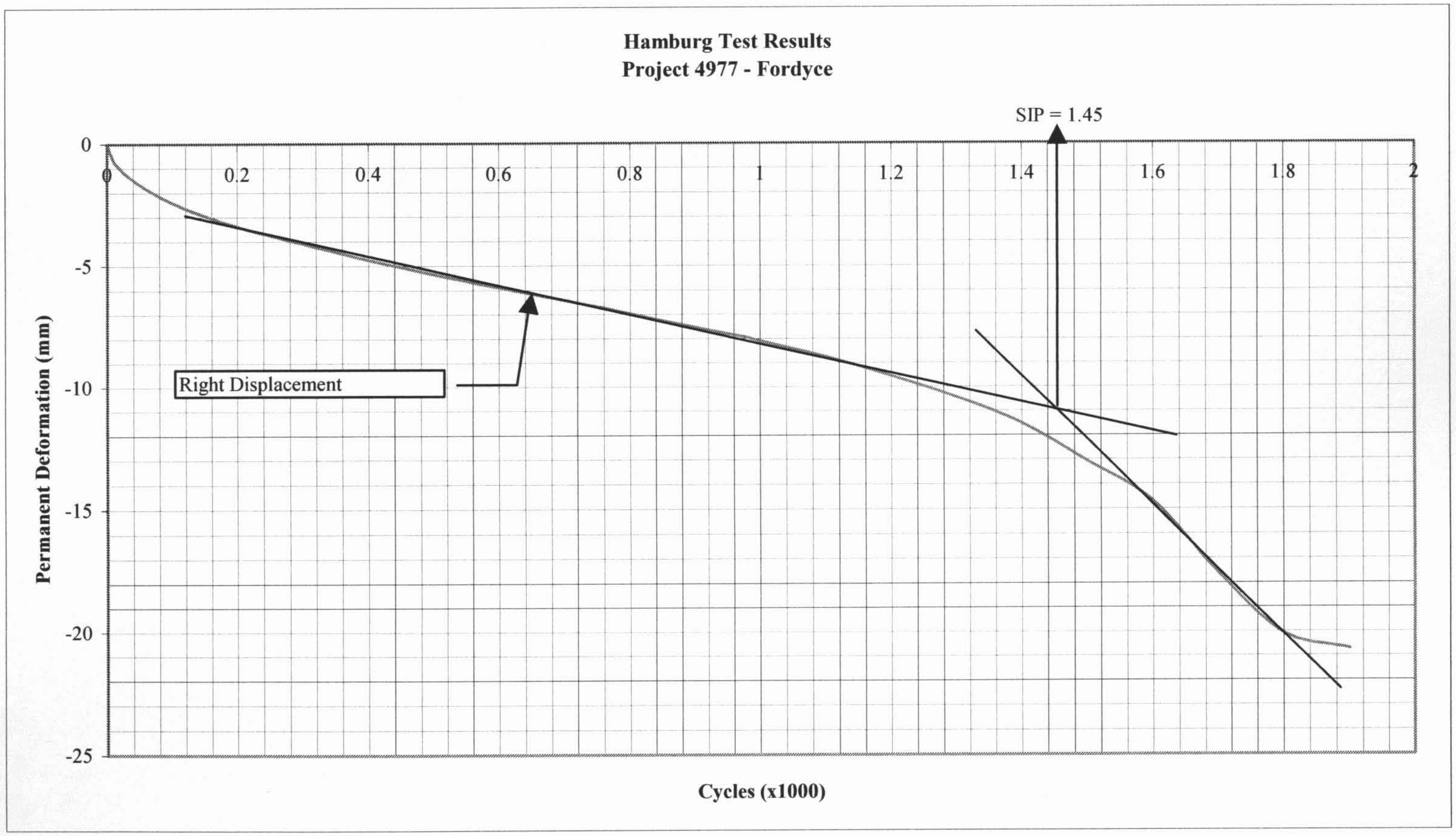

Figure B.8 Relationship between Permanent Deformation and No. Cycles Using Output from HWTD Test - Fordyce