Technical Report Documentation Page

1. Report No. FHWA/TX-05/0-1707-7	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle HAMBURG WHEEL-TRACKING DATABASE ANALYSIS		5. Report Date March 2006 Published: November 2007
		6. Performing Organization Code
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9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Project 0-1707
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Technical Report: February 2003-September 2004
		14. Sponsoring Agency Code

15. Supplementary Notes

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

Project Title: Long-Term Research on Bituminous Coarse Aggregate

URL: http: //tti.tamu.edu/documents/0-1707-7.pdf

16. Abstract

This report outlines statistical analyses done to investigate whether the Hamburg wheel-tracking device (HWTD) can be used to validate durability tests such as the magnesium sulfate soundness (MSS) and Micro-Deval tests. Researchers manipulated and merged the Hamburg test database and aggregate properties database of the Texas Department of Transportation (TxDOT) to provide the basis for statistical analysis. The qualitative visual examinations of plots of aggregate properties and Hamburg wheel-tracking device performance, based on soundness resistance, suggest that MSS and Micro-Deval tests do not correlate well with Hamburg test results. However, single variable correlations between aggregate properties and Hamburg test performance indicate that both soundness and Deval tests have weak correlation with Hamburg test performance in that appropriate trends could be observed with final Hamburg results (deformation or number of wheel passes). These findings suggest that aggregate durability has some influence on the performance of the bituminous mix in the Hamburg test. The effects of aggregate, binder grade, mix type, and additive on HWTD results were also evaluated. The HWTD test parameters investigated included rutting, slope of the rutting curve, and the area beneath the rutting curve at specific cycles. Based on the results of the analysis, it was observed that the dominant factors influencing Hamburg test performance are those that stiffen the mix, particularly stiffer performance grades (PG) and additives such as lime.

17. Key Words Hamburg Wheel-Tracking Device, Pavement Performance, Aggregates	18. Distribution Statement No restrictions. This document is available to the public through the NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	150	

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

HAMBURG WHEEL-TRACKING DATABASE ANALYSIS

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Report 0-1707-7
Project 0-1707
Project Title: Long-Term Research on Bituminous Coarse Aggregate

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

March 2006
Published: November 2007

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. Additionally, this report is not intended for construction, bidding, or permit purposes. Dr. Dallas N. Little (TX# 40392) is the principal investigator for the project.

ACKNOWLEDGMENTS

This project has been initiated and sponsored by TxDOT and FHWA. The financial support of TxDOT is greatly appreciated. The authors thank TxDOT project director, Caroline Herrera, for her guidance. Special thanks are extended to Richard Izzo and Dale Rand of TxDOT for their great assistance in providing the Hamburg Wheel-Tracking Device database.

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CHAPTER 1. INTRODUCTION

The challenge facing any state Department of Transportation (DOT) is to produce a rut resistant mix to build or repair their roads. To ensure a rut resistant mix, proper mixture design is essential. The Superpave mixture design system addresses this issue by developing a volumetric mixture design along with a performance prediction model. Although the Superpave system was developed under the Strategic Highway Research Program (SHRP) during the early 1990s, only part of it has been implemented thus far. Most state DOTs have already adopted, or are in the process of implementing, the binder selection and volumetric mix design of the Superpave system; however, the performance prediction model is not ready for implementation yet. Therefore, most highway agencies rely on other forms of simulative strength tests to complement the volumetric mix design. There are several laboratory strength tests available to predict field-rutting potential. The most common type of laboratory test used in the United States is the loaded wheel tester (LWT), which directly simulates the wheel passes expected in the field. Other commonly used tests are:

- asphalt pavement analyzer (APA);
- Hamburg wheel-tracking device (HWTD);
- French rutting tester (FRT);
- PURWheel; and
- model mobile load simulator.

Engineers could use these tests to verify mixture design as well as quality control/quality assurance (QC/QA) purposes. These tests are not being used to predict actual field rutting; rather, they are used to verify the mix through pass/fail criteria (*1, 2, 3*).

The Texas Department of Transportation has successfully used the Hamburg Wheel-Tracking Device in their mixture selection for several years. TxDOT modified the test specimen configuration so that the wheel-tracking was accomplished on a test specimen composed of two specimens compacted in the Superpave gyratory compactor. A database called “Hamburg Database” stores the results of these HWTD tests for future analysis. The HWTD was developed in Hamburg, Germany. It is extensively used as a specification requirement to ensure adequate rutting and stripping resistance for roadways in Germany. It is used as a "Proof Test" to complement mix design procedures (*1*).

Researchers can use the HWTD to predict the moisture susceptibility of hot mix asphalt (HMA) pavement. Various variables influence the test results, amongst them:

- quality of aggregates,
- testing temperature, and
- asphalt cement stiffness.

These variables are considered important to the moisture resistance of a pavement in the field. A 1993 Colorado Department of Transportation (CDOT) study comparing several test methods found that Hamburg test results gave the best correlation to field rutting caused by moisture sensitivity (*4*).

Aggregates constitute 94-95 percent by weight of the hot mix asphalt mixtures; therefore, the properties of aggregates have significant impact on the performance of HMA pavement. Often pavement distress, such as rutting and stripping, can be traced directly to improper aggregate selection and use. Clearly, aggregate selection based on the results of proper aggregate tests is necessary for attaining the desired performance. Many of the current aggregate tests, such as soundness/durability tests, were developed to empirically characterize aggregate properties without necessarily strong relationships to the performance of final products incorporating an aggregate (*5*). Other drawbacks of soundness tests are prolonged test duration and difficulties replicating results. There is a need to identify and recommend tests that are related to HMA performance. Engineers designed and fabricated the laboratory wheel-tracking devices to simulate mixture stripping and rutting potential conditions, as well as pavement loading. These devices require less time and effort to achieve the tests compared to other aggregate tests. Moreover, test results show the potential for the wheel-tracking devices to evaluate the rutting and stripping of asphalt mixtures under various temperatures and moisture conditions (*4*). Hence, the primary focus of this project is to investigate what the HWTD will indicate about the effect of aggregate durability.

Objective

The objective of this project was to evaluate TxDOT's Hamburg test database and investigate the possibility of using the HWTD to validate durability tests such as magnesium sulfate soundness (MMS) and Micro-Deval (MD). The evaluation process consisted of identifying the key variables that influence the test results. Another objective of this project was to investigate the possible effect of aggregate durability properties on Hamburg test results.

Scope of Research

The objective of this project was accomplished through investigating two TxDOT databases:

- Hamburg test database, and
- aggregate properties database.

Researchers collected data contained in these two databases over a period of time from regular testing to meet the specification. Since the two databases are generated without any predetermined purpose, they are most likely to have very minimum bias toward this analysis. However, researchers encountered limitations and difficulties while trying to use the two databases, which eventually reduced the number of available data for analysis. The merge process was difficult to achieve because only few data points had a perfect match between the two databases. Missing information in some data was another drawback of the Hamburg database. Finally, it is important to mention that there was no laboratory test and no experimental plan made or involved in this project.

CHAPTER 2. REVIEW OF BACKGROUND INFORMATION

Background

The City of Hamburg, Germany, based on a similar British device that had a rubber tire, originally developed the Hamburg Wheel-Tracking Device in the 1970s. Helmut-Wind Incorporated, of Hamburg, finalized the test method and developed specification requirements to measure rutting and stripping susceptibility. The HWTD measures the combined effects of rutting and moisture damage (stripping) by rolling a steel wheel across the surface of an asphalt concrete slab that is immersed in hot water (generally held at 40 or 50 ºC). Susceptibilities to rutting and moisture are based on pass/fail criteria (*1*).

The test required 9450 wheel passes at a temperature of 40 °C or 50 °C. Researchers found that after increasing the number of wheel passes to 19,200, some mixtures could deteriorate due to moisture damage shortly after 10,000 passes. Therefore, greater than 10,000 wheel passes were generally needed to show the effect of moisture damage (*6*).

Equipment and Procedure

This device, shown in Figure 2.1, tests two slabs simultaneously with two reciprocating solid steel wheels. Slabs are 12.6 inches (320 mm) long and 10.24 inches (260 mm) wide; they can be 1.5, 3, or 4.7 inches (38, 76, or 119 mm, respectively) thick. The wheels have a diameter of 8 inches (203 mm) and width of .90 inches (22.87 mm). Test specimens are typically compacted to 7±1 percent air voids using a linear kneading compactor. The test uses a water chamber as a means of obtaining the required test temperature. The water temperature can be set from 25-70 °C, with 50 °C being the most common test temperature (*7, 8*).

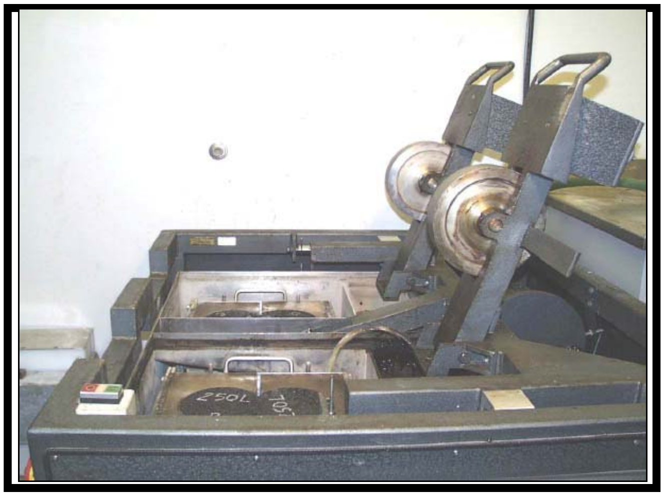


Figure 2.1. Hamburg Wheel-Tracking Device.

The load consists of applying a 158 lb (705 N) force and the average contact stress is approximately 0.73 MPa with a contact area around 38 in. (970 mm^2). This contact pressure simulates the effect produced by a rear tire of a double-axle truck. The contact area increases with rut depth, and thus the contact stress is variable.

Test specimens, shown in Figure 2.2, are tracked back and forth under the applied stationary loading. Testing is typically accomplished for a total of 20,000 passes or until .79 in. (20 mm) of deformation, whichever occurs first. The average speed of each wheel is approximately 1.1 km per hour. Each wheel travels approximately 320 mm before reversing direction, and the device operates at 53 ± 2 wheel passes per minute (*7, 5*).

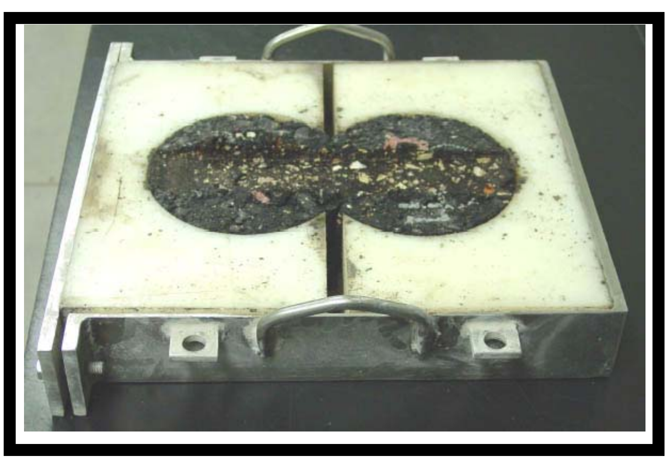
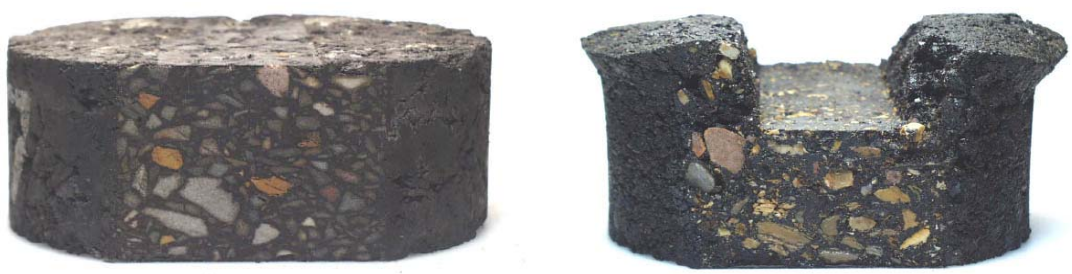


Figure 2.2. Top View of Test Specimen for HWTD.

A linear variable differential transformer measures the rut depth in each slab automatically and continuously and has an accuracy of 0.01 mm. Approximately 6.5 hours are needed to apply 20,000 wheel passes; however, the device will automatically stop if the rut depth (deformation) in the slab exceeds 30 mm. The total time to perform a test from start to finish, including specimen fabrication, is three days. TxDOT has adopted this test and recommended a maximum allowable rut depth of 12.5 mm at 20,000 passes for PG-76 or higher, at 15,000 passes for PG-70 and at 10,000 passes for PG-64 or lower. Figure 2.3 shows two typical test specimens at the end of the test; they are:

a) a passing sample with 7 mm accumulated rut depth at 20,000 wheel passes, and
b) a failed sample with rut depth failure of 12.5 mm reached at 15,000 wheel passes.



a) Passed sample. b) Failed sample.

Figure 2.3. Typical Test Specimens with Different Rut Depths.

Test Results and Data Interpretation

Results obtained from the HWTD, as shown in Figure 2.4, consist of:

- rut depth,
- post-compaction,
- creep slope,
- stripping inflection point (SIP), and
- stripping slope.

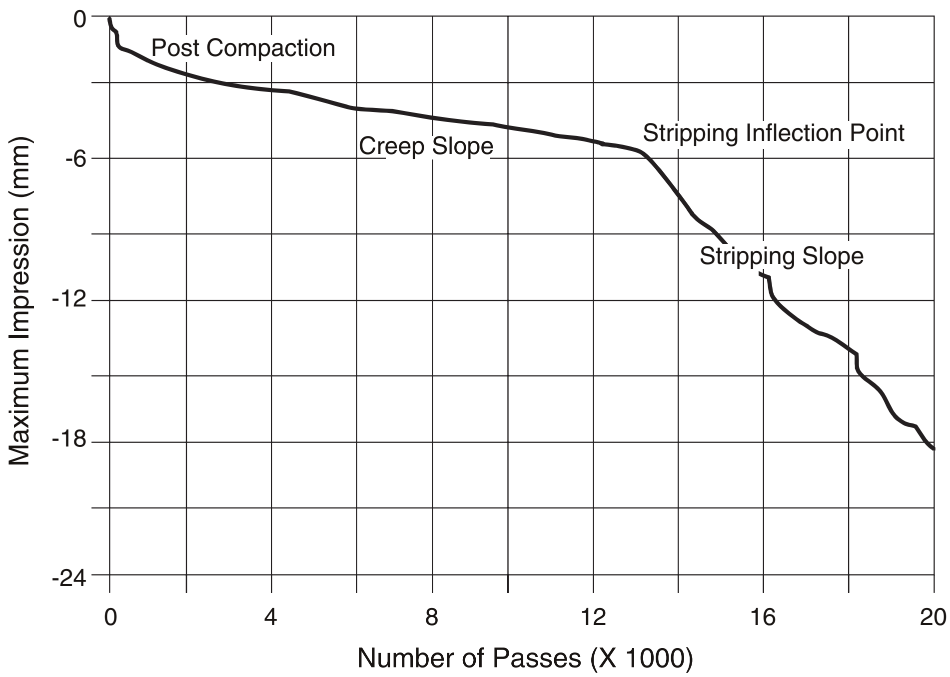


Figure 2.4. Typical Hamburg Wheel-tracking Test Results.

The post-compaction consolidation is the deformation in millimeters at 1000 wheel passes and occurs rapidly during the first few minutes of the test. This test is referred to as the post-compaction consolidation because it is assumed that the wheel is densifying the mixture within the first 1000 wheel passes.

The creep slope is the inverse of the deformation rate within the linear region of the deformation curve after post compaction and prior to stripping (if stripping occurs). The creep slope measures rutting susceptibility. It measures the accumulation of permanent deformation primarily due to a mechanism other than moisture damage.

The stripping slope is the inverse of the deformation rate within the linear deformation of the deformation curve, after the stripping began. The stripping inflection point is the number of wheel passes corresponding to the intersection of the creep slope and the stripping slope. The stripping slope measures the accumulation of permanent deformation due to moisture damage. It is used to estimate the relative resistance of the HMA sample to moisture-induced damage. In other words, this is the number of wheel passes at which moisture damage starts to dominate performance. The lower the inverse stripping slope the more severe the moisture damage (*7,6*).

Both the creep slope and the stripping slope use inverse slopes so that these slopes can be reported along with the number of wheel passes at the stripping inflection point. Higher creep slopes, stripping points, and stripping slopes indicate less damage.

The final region on the curve shown in Figure 2.4, called the tertiary region, indicates where the specimen is rapidly failing. The tertiary region of the curve appears to be primarily related to moisture damage, rather than to other mechanisms that cause permanent deformation, such as viscous flow. Mixtures that are susceptible to moisture damage also tend to start losing fine aggregates around the stripping inflection point.

Comparison of Test Results with Field Performance

A study conducted by the CDOT and FHWA's Turner-Fairbank Highway Research Center (*9*) demonstrates the following:

- There is excellent correlation between the stripping inflection point and the known stripping performance.
- Good pavements had stripping performances generally greater than 10,000 passes.
- Results show that HWTD is sensitive to aggregate properties that include clay content, high dust-to-asphalt ratios, and dust coating on the aggregates. This result suggests that aggregate quality is important to obtain passing results.
- Most of the asphalt cements failed in the HWTD with poorer aggregate. As a result, asphalt cement cannot be expected to overcome aggregate deficiencies.
- When a mix fails, the aggregate quality should be investigated. Test results in HWTD are sensitive to aggregate quality.
- Results from the HWTD are sensitive to asphalt cement stiffness; the stripping inflection point occurred at a larger number of passes. Moisture resistance improves as asphalt cement stiffness increases.
- The testing temperature should be selected based on the high temperature environment the pavement will experience.

- Anti-stripping additives to some extent improve the results from the HWTD with all of the mixes.

Durability Testing of Aggregates

The long-term durability characteristics of aggregates are generally determined using soundness tests. The magnesium sulfate soundness test is one of the common methods of evaluating the durability of aggregates. The Micro-Deval test is another viable candidate to use as an alternative aggregate durability test. Both of these tests provide a measure of an aggregate's ability to resist weathering forces. National Cooperative Highway Research Program (NCHRP) Study No. 4-19 concludes that magnesium sulfate soundness and Micro-Deval tests are the best test methods that correlate with field performance of HMA in terms of raveling, popouts, or potholing. The study also concluded that among all the tests that measure the durability of aggregates, Micro-Deval and magnesium sulfate soundness tests proved to be more able to separate good and fair aggregates from poor aggregates. Therefore, these two tests have been recommended in lieu of the Los Angeles (LA) abrasion test, sodium sulfate soundness test, and other soundness tests such as freeze-thaw loss and durability index (*10*).

The test procedure for the magnesium sulfate soundness test consists of immersing a sample of aggregate into a sulfate solution for a period of time, usually 16 - 18 hours, to saturate the aggregate void structure. Next, the aggregate is drained and dried to a constant mass. The temperature of the sulfate solution immersion is such that the salts within the solution crystallize (freeze) in a manner that simulates ice crystallization. This crystallization causes expansive forces within the pore structure of the aggregate and, thus, causes degradation of the aggregate sample. Five immersion/drying cycles are typically utilized to provide a durability indication, as a percent loss of specified size particles, for the aggregate source. The Micro-Deval test, on the other hand, consists of soaking a sample in two liters of water for a minimum of one hour prior to testing. Both aggregate and water are included in the drum during the test. The drum is rotated at a rate of 100 ± 5 rpm for two hours. The sample is washed, oven dried, and its loss calculated as the amount of material passing the 1.18 mm mark (*11*, *12*).

The magnesium sulfate soundness test method, although widely used, suffers from two significant drawbacks. First, the test procedures take a minimum of 6 days to compute. Second, questions have been raised regarding the repeatability, reproducibility, and precision of this test method (*13*). The Micro-Deval test, although proven to be more precise and more repeatable than the magnesium sulfate soundness test, takes about 24 hours to compute, and correlation and the field performance are still not well established (*11*). Therefore, at the minimum, a laboratory performance test such as the Hamburg wheel-tracking device test may be used to validate aggregate durability measures. The Hamburg test examines the aggregate properties' effect on asphalt mixes by subjecting aggregates to similar loading and environmental patterns that the aggregates will experience in the field. Such a test allows controlled interaction between the aggregates and other factors contributing to asphalt mix performance.

CHAPTER 3. DATABASE DESCRIPTION

The Texas Department of Transportation provided Texas Tech University with a Hamburg test database to analyze and study the feasibility of using such a test as a laboratory measure of aggregate durability in hot mix asphalt. In addition to the Hamburg test data, TxDOT also provided aggregate durability properties' data as measured by the magnesium sulfate soundness and the Micro-Deval tests.

TxDOT Hamburg Wheel-Tracking Test Database

The platform for the TxDOT Hamburg wheel-tracking database is Microsoft Access. A total of 1213 data points are available, and each point includes 39 different fields of information. Some of the most important fields are:

- project identification number,
- aggregate source,
- aggregate pit,
- aggregate identification code,
- testing temperature,
- binder type,
- modifier,
- additive,
- mix type,
- aggregate type (mineralogy),
- specimen type,
- test type, and
- Hamburg test results.

The Hamburg results include number of passes and corresponding deformation values. It is important to note here that the Hamburg test results are usually expressed in terms of number of passes instead of cycles, where a cycle is equivalent to two passes. Other important Hamburg test parameters such as creep slope, stripping inflection point, and stripping slope data were not available in this database. In general, each sample was subjected to 20,000 passes or 12.5 mm deformation, whichever comes first. If a sample reaches 12.5 mm deformation before 20,000 passes, it is considered to have failed. In other words, samples that “passed” will have deformation less than 12.5 mm in 20,000 passes.

All data points used for the purpose of this project are included in the “data” table from the TxDOT historical database. Table 3.1 summarizes fields’ headers and example values for each variable group. For detailed information, please refer to tables in Appendix A.

Table 3.1. Fields Description of TxDOT Hamburg Database.

ID	Field Name	Description	Example Values	Comments
1	FN	Test number	01500851	
2	Date	Data entry date	6/10/2002	
3	TestDate	Test run date		
4	DateSamp	Sample collection date		
5	DateRec	Sample received date		
6	District	TxDOT district's name	San Antonio	
7	County	County name	Bexar	
8	CSJ	Control section job	0915-12-237	
9	FPN	Federal project number	CUS 915-12-237	
10	Highway	Highway number	US 87	
11	Engineer	TxDOT engineer in charge	Frank Holzmann	
12	Mix Producer		Vulcan	
13	Contractor		E.E. Hood	
14	Mix Type	Aggregate gradation type	B, C, D	
15	Spec Item	Specification item number	3117	
16	Aggregate Type	Mineralogy aggregate type	Gravel, Igneous	
17	AggProdID	Aggregate producer	Amarillo Rd.	Source of agg.
18	AggLocID	Producer location	4DG's	Pit name
19	PCN	Production code number	507805	
20	Grade	Asphalt grade	PG 64-22	Binder type
21	AC Content	Asphalt content, %	3.4 – 8.8	
22	Modifier	Modifier types	Latex (SBS)	
23	Additive	Additive types	None, Lime, Liquid	
24	AC Source	Asphalt source	Texas Ind.	
25	AddAmt	Additive content, %		
26	Additive Source			
27	Specimen Type		Lab, plant mix	
28	Test Type		Design, research	
29	Test Temp	Test, temperature, ^{0}C	40, 50	
30	Cycles	No. of passes	1000 – 200,000	
31	LeftDef	Left deformation	0.42 - 125	
32	RightDef	Right deformation	0 - 22	
33	Photo		?	Not available
34	MixIDMarks	Mix ID mark		
35	Comments			
36	Prog		?	No data available
37	Rutted	Field core information	Rutted/Unrutted	
38	Traffic	Estimated traffic volume	Low, Moderate	
39	Machine	Type of Hamburg machine	Old, New (PMW)	

The TxDOT Hamburg database suffers from a considerable number of missing data for both samples' information as well as test results. In other words, not all data points have all 39 fields of information. Another drawback is the outlier values mainly found in the test results' fields. These are extremely high values that could be due to typing errors or in some cases are the results of specialized tests for research purposes. Therefore, a clean-up process was carried out to eliminate missing data and outliers to keep the analysis results unbiased. Table 3.2 summarizes the outliers discarded from the Hamburg test database.

Table 3.2. Outliers Values in Hamburg Database.

No. of Passes		**Avg. Deformation**	
Outliers	Frequency	Outliers	Frequency
20,000 – 60,000	15	12.5 - 15	10
60,000	5	15 - 22	17
87,000	2	125	1
200,000	2		

Main Variables and Predominate Parameters

Performance of HMA mix primarily depends upon the properties of the mixture and not so much upon the individual properties of the binder or aggregate. In fact, the mix may fail even when the asphalt binder and aggregate are adequate because of use of poor compaction or incorrect binder content or some other problem associated with the mixture *(8)*. Several variables are identified in the Hamburg database that were expected to significantly interact and affect rutting potential. These variables were identified as variables that may have a major effect over permanent deformation (rut depth). Later chapters in this report present detailed discussion of the effect of each variable. For the purpose of this project, only variables that have values (parameters) over 10 percent frequent occurrence were considered.

Following are the main variables considered in this analysis:

- Mix Type – B, C, and D;
- Aggregate Type – Gravel, Igneous, and Limestone-Dolomite;
- Binder Type – PG 64-22, PG 70-22, and PG 76-22;
- Test Temperature – 40 ^{o}C and 50 ^{o}C; and
- Additives – None, Lime, and Liquid,

Next are the outcome results:

- Number of Passes; and
- Average Deformation – Average of left- and right-wheel deformation in mm.

Cleanup Process for the Hamburg Database

TxDOT's Hamburg wheel-tracking test database was first cleaned of missing values. Missing values were in the form of either blank-cells - <null>, or (Blank) was typed instead. After removal of missing values, data were checked for outliers and removed accordingly. The cleaning process was performed particularly for major variables such as mix type, aggregate type, binder type, test temperature, and additive type. Unfortunately, 373 data points were eliminated using this technique. As a result, only 840 data points were left and used in the analysis. Table 3.3 shows in detail the process involved in eliminating missing values and outliers; only the main variables are presented. For example, (Blank) values and blank-cells that indicate missing data are 222 and 30 data points, respectively, for the aggregate type category. When these values were discarded, only 961 data points were left. Appendix C presents general statistics for the Hamburg database after cleanup.

Table 3.3. Missing Data Removal Process.

Variable Groups	Type of Data Removed	Number of Data Removed	Number of Data Points Left
Aggregate Type	(Blank)	222	991
	″	30	961
Mix Type	(Blank)	24	937
	″	4	933
Grade (binder type)	(Blank)	35	898
	″	4	894
Test Temperature	″	1	893
Additive	″	10	883
Number of Wheel Passes	″	26	857
	Outliers	9	848
Avg. Deformation	″	1	847
	Outliers	7	840

Table 3.4 shows descriptive statistics for the test results in the Hamburg database after discarding missing data and outliers.

Table 3.4. General Statistics for the Cleaned Database.

	Wheel Passes	Avg. Deformation
N	840	840
Mean	17,222.27	7.519
Std. Deviation	5023.18	4.016
Minimum	1900	0.8
Maximum	20,000	12.5

Table 3.5 summarizes information on predominant parameters after discarding all missing values and outliers. It can be noted that despite the cleaning process, each parameter has preserved its percent appearance within ± 5 percent of the original database.

Table 3.5. Predominant Parameters after Discarding Missing Values and Outliers.

Variable Groups	Parameters	Frequency	%
Mix Type	Type B	66	7.9
	Type C	296	35.2
	Type D	225	26.8
	Other	253	30.1
Aggregate Type	Gravel	183	21.8
	Igneous	143	17
	Limestone-Dolomite	389	46.3
	Other	125	14.9
Binder Type	PG 64-22	179	21.3
	PG 70-22	216	25.7
	PG 76-22	315	37.5
	Other	130	15.5
Test Temperature (^{0}C)	40	133	15.8
	50	707	84.2
Additive Type	None	200	23.8
	Lime	406	48.3
	Liquid	201	23.9
	Other	33	3.9

Pass/Fail Concept

The Texas Department of Transportation usually performs Hamburg wheel-tracking tests to predict pavement performance before using it to build or repair a road. If the mixture passes a rut-resistance test, it can be used on a road; but if it fails, the search continues until a good mixture is found (*11*). TxDOT uses a simplified pass/fail criterion to demonstrate mixtures that passed or failed the test. For example, a mix that passed the test has a very low susceptibility to rutting. The pass group is characterized by the samples that achieved 20,000 wheel passes before reading 12.5 mm rut. The fail group has the samples in which the rut depth reached 12.5 mm before attaining 20,000 passes. Table 3.6 illustrates the pass/fail statistics based on different variables.

Table 3.6. Statistics for Pass/Fail Criteria Based on Different Variables.

Main Variables	Frequency	% Occurrence	Passing Samples (Wheel Passes = 20,000) [Total data points 585]		Failing Samples (Avg. Deflection = 12.5 mm) [Total data points 254]	
Mix Type		Out of 840	Freq.	% Passed	Freq.	% Failed
Type B	67	7.9	39	58.2	28	41.8
Type C	296	35.2	220	74.3	76	25.7
Type D	225	26.8	137	60.9	86	38.2
Others *	253	30.1	189	74.7	64	25.3
Aggregate Type						
Gravel	183	21.8	119	65.0	63	34.4
Igneous	143	17.0	125	87.4	18	12.6
Limestone-Dolomite	389	46.3	247	63.5	142	36.5
Others *	125	14.9	94	75.2	31	24.8
Binder Type						
PG 64-22	179	21.3	86	48.0	93	52.0
PG 70-22	216	25.7	144	66.7	72	33.3
PG 76-22	315	37.5	265	84.1	50	15.9
Others *	130	15.5	90	69.2	39	30.0
Test Temperature						
40	133	15.8	120	90.2	13	9.8
50	707	84.2	465	65.8	241	34.1
Additive						
None	200	23.8	113	56.5	87	43.5
Lime	406	48.3	331	81.5	75	18.5
Liquid	201	23.9	123	61.2	76	37.8
Others*	33	3.9	18	54.5	16	48.5

* Consist of PG 58-22, PG 64-28, PG 70-28, PG 76-16, and PG 76-28.

TxDOT Aggregate Properties Database

Texas Tech University also received another database for aggregate properties. This dataset was essential to investigate if aggregate has a predominant influence on the performance of mixes in the Hamburg test. Aggregate durability properties (MSS and MD) are the primary factors that researchers considered for this matter. Relevant information was extracted from the Aggregate Quality Monitoring Program (AQMP) found in the Excel file provided by TxDOT. This database contained 126 data points wherein 117 are usable. This database also has several fields of information such as:

- aggregate source,
- aggregate pit,
- aggregate production code,
- LA abrasion value,
- 5-cycle magnesium sulfate soundness loss, and
- Micro-Deval loss.

There is a set of values for each aggregate property, e.g., there are 10 to 11 values of magnesium sulfate and Micro-Deval loss for each aggregate source. Each of these values represents different batches of aggregate tested at different periods of time. To establish the relationship between Hamburg test results and aggregate properties, a data reduction was made because a one-to-one matching of the two datasets was not possible. As a result, the mean MSS and MD were calculated based upon the 10 or 11 values that exist for each different aggregate source.

As previously mentioned, only 117 records were left after discarding missing values. The cleaning process only involved fields that contained information related to magnesium sulfate soundness and Micro-Deval tests. Table 3.7 shows information for fields that were kept and used in the analysis. The table also shows the range of values for a number of calculated fields such as average, minimum, maximum, and max-min.

Table 3.7. Fields Description of TxDOT Aggregate Properties Database.

ID	Field Name	Description	Comments
1	Source	Aggregate sources	Aggregate producer
2	Pit	Pit Location	Producer location
3	Prod Code	Production Code Number	
4	Lab Numbers	Lab code assigned to each sample	
5	MSS1-MSS11	Magnesium Sulfate Soundness test results: 1-11	
6	Avg. MSS	Average of MSS1-MSS11	Calculated
7	Min MSS	Minimum of MSS1-MSS11	Calculated
8	Max MSS	Maximum of MSS1-MSS11	Calculated
9	Max-Min MSS	Difference between Max. and Min. MSS	Calculated
10	MD1-MD11	Micro-Deval test results: 1-11	
11	Av MD	Average of MD1-MD11	Calculated
12	Min MD	Minimum of MD1-MD11	Calculated
13	Max MD	Maximum of MD1-MD11	Calculated
14	Max-Min MD	Difference between Max. and Min. MD	Calculated

Table 3.8 shows descriptive statistics for durability test results, the average magnesium sulfate soundness, and Micro-Deval loss for the whole database.

Table 3.8. Descriptive Statistics for MSS and MD.

	Avg. MSS	Avg. MD
N	117	117
Mean	10.8	13.2
Median	8.0	12.0
Std. Deviation	8.9	7.3
Minimum	1.0	1.8
Maximum	51	34

Merging Databases

The objective of this analysis was to investigate the possible effect of aggregate durability on Hamburg test results. To achieve this objective, the two databases were merged based on the aggregate source, pit name, and aggregate production code. Only a small number of data points have a perfect match with these three parameters in both databases. Other data points have missing information for at least one of the three parameters in one or both databases. Another number is very close, but not a perfect match, e.g., they have differences in spelling and abbreviations. In addition, there are a number of aggregate sources that the Hamburg test samples use but do not have any representation in the "aggregate database." Due to these difficulties or limitations, it was not possible to use the Microsoft Access merging option. Instead, average MSS and MD values were manually added to the Hamburg database based on the best match obtained for the following three aggregate parameters: aggregate source, pit, and production code. Averages of MSS and MD loss values were used in the merging operation since there was no way of matching a particular aggregate batch in the "aggregate database" with that in the "Hamburg database." After merging and discarding missing values, 462 data points were left when combining the results from Hamburg, and MSS and MD tests.

Difficulties and Limitations

This section discusses some of the limitations and difficulties encountered while attempting to merge the two databases. In addition, a detailed discussion is presented for the process involved in merging the Hamburg wheel-tracking test database with the aggregate properties database. It is important to understand the procedure involved in linking the two databases, which will facilitate the replication of the output dataset for any further investigation. To successfully complete the merging process between the two databases, the Hamburg as well as the aggregate properties databases were cleaned of missing data and outliers. Another important issue to consider is the common fields used in the merging procedure.

Table 3.9 summarizes the data used in the merging process. Unfortunately, only 462 records were used out of 840 usable data points that exist in the Hamburg database. One reason is that the Hamburg database contained a large number of missing data in one of the common fields used to make the link - "aggregate location" (pit name). This field contained 543 missing data, in addition to 208 data with mismatch information - data that were not included in the aggregate properties database, therefore, reducing the number of useful information into 462 data points.

Table 3.9. Mismatching Data Found in Both Databases.

Info in Hamburg database				Info in Aggregate properties database		
Count	**AggLocID**	**AggProdID**	**Product Code Number**	**Pit**	**Source**	**Product Code Number**
21	4DG's	Jobe	507805	4DG	Amarillo	507805
2	Apple, OK	Meridian Aggr *Sandstone		Apple, OK	Meridian	
2	Arena	Pioneer / Hanson Aggr (Pioneer) *Gravel		Arena	Pioneer	1304509
23	Bridgeport	Texas Ind.	224904	Bridgeport	TXI	224904
2	Bridgeport	Pioneer	224904	Bridgeport	Pioneer	224902
2	Brownlee	Delta Materials	1402704	Brownlee	Delta	1402704
17	Brownwood	Vulcan Materials *Igneous	2302501	Brownwood	Vulcan	2302501
2	Bundy	Lipham	2517308	Bundy	Lipham	2517308
2	Cameron	Brazos Valley S&G	1716606	Cameron	Brazos Valley	Z170003
4	Cooperton, OK	Dolese Bros. *Sandstone	50415	Cooperton	Dolese	50415
2	D. Garcia	Upper Valley *Limestone	2110905	D. Garcia	Upper Valley	2110905
55	Davis, OK	Hanson Aggr. (Western Rock) *Igneous	50439	Davis	Hanson	50439
7	Dow Chem.	Word, Dean	1402702	Dow	Word	1402702
2	Eagle Mills	Hanson Aggr. *Gravel	50119	Eagle Mills	Gifford-Hill	50119
11	Eastland	Vulcan Materials *Limestone	2306805	Eastland	Vulcan	2306805
1	Feld	Tex Cr. Stone *Limestone	1424602	Feld	Tex Cr Stone	1424602
10	FM 1604	Vulcan Materials *Igneous		Fm 1604	Vulcan	1501506
8	Helotes	Vulcan Materials *Igneous	1501514	Helotes	Vulcan	1501514
12	Hoban	Trans-Pecos *Limestone	619502	Hoban	Trans-Pecos	619502
23	Hunter	Colorado Materials	1504605	Hunter	Colorado	1404605
1	Johnson	Baker, E. D.		Johnson	E.D. Baker	411807
10	Knippa	Vulcan Materials *Limestone		Knippa	Vulcan	
11	Little River	Hanson Aggr. (Gifford-Hill) *Limestone	50114	Little River	Gifford-Hill	50114
8	Mill Creek	Meridian Aggr *Sandstone	50433	Mill Creek	Meridian	50433
20	Murphy	Fordyce Co.	1323505	Murphy	Fordyce	1323505
3	Pedernal	Hanson Aggr. (Western Rock) *Igneous	540309	Pedernal	Hanson	50309
12	Perch Hill	Hanson Aggr. (Gifford-Hill) *Limestone	224901	Perch Hill	Gifford-Hill	224901

Table 3.9. Mismatching Data Found in Both Databases (continued)

Info in Hamburg database				Info in Aggregate properties database		
Count	**AggLocID**	**AggProdID**	**Product Code Number**	**Pit**	**Source**	**Product Code Number**
13	Realitos	Wright Materials	2106701	Realitos	Wright	2106701
4	Richard Spur	Hanson Aggr. *Limestone		Richard Spur	Dolese	50405
23	Rothwell	Jordan Paving *Limestone	2509704	Rothwell	Jordan	Z250009
3	SkyHi (Maddox)	Young Const.	914709	Maddox	Young	914709
32	Snyder, OK	Meridian Aggr. *Igneous		Snyder	Meridian	50435
8	Stringtown,	Stringtown Materials	50407	Stringtown	Stringtown	50407
29	Sweet 16	Bay, Inc.	2106706	Sweet 16	Bay	2206706
3	Tascosa	Pioneer (Western S&G)		Tascosa	Pioneer	418004
5	Tehuacana	Vulcan Materials *Limestone	914708	Tehuacana	Vulcan	914708
3	Thrasher	Thrasher S&G	2517302	Thrasher	Thrasher	2517302
12	Troy	Meridian Aggr *Sandstone	50434	Troy	Meridian	50434
14	Turner	CSA	722611	Turner	CSA	Z070008
1	Weir	Alamo Conc.	1424603	Weir	Alamo	
5	Wood	Capitol Aggr. *Gravel		Wood	Capitol	1424604

As discussed earlier, the two common fields that were considered in joining the two databases are the "AggLocID" from the Hamburg database and the "Pit" from the aggregate properties database. For verification purposes, the "AggProdID," along with the "PCN" (production code number), were matched with the corresponding data found in the "Source" fields and "Prod Code" fields. By doing so, one data point from the aggregate database was linked manually to several data points from the Hamburg database one at a time.

Description of Hamburg-Aggregate Database

The product of merging the two databases was a new database that contains 462 data points. The new database combines the information from the Hamburg database and the pertinent attributes selected from the aggregate properties database such as MSS and MD. We will refer to this new database as the Hamburg and aggregate properties (HAP) database. Table 3.10 summarizes the descriptive statistics for this new database.

Table 3.10. Descriptive Statistics for HAP Database.

	Wheel Passes	Avg. Deformation	Avg. MSS	Avg. MD
N	462	462	462	462
Mean	17,033.7	7.6	8.67	11.56
Median	20,000	7.0	4.75	8.5
Std. Deviation	5129.43	4.07	6.77	7.33
Minimum	20,000	0.84	1.0	1.8
Maximum	20,000	12.5	25.3	30.5

Table 3.11 illustrates Pass/Fail criteria for the HAP database. When comparing the results in Tables 3.6 and 3.11, which represent the two databases primarily used in this project, manually joining the two databases preserved the integrity of the original TxDOT Hamburg database without duplicating the data. For example, a relative comparison of the limestone-dolomite in the two tables indicates that in Table 3.6, limestone-dolomite comprises 46.3 percent of the total aggregate types, whereas in Table 3.11 this is only 44.8 percent. The difference ratio (3 percent) falls within the (5 percent) expected, which was discussed in section 3.4. Appendix D presents general statistics for the new HAP database after cleanup.

Table 3.11. HAP Database after Application of Pass/Fail Criteria.

Main Variables	Frequency	% Occurrence	Passing Samples (Wheel Passes = 20,000) [Total data points 310]		Failing Samples (Avg. Deflection = 12.5) [Total data points 151]	
Mix Type		Out of 462	Freq.	% Passed	Freq.	% Failed
Type B	45	9.7	29	64.4	16	35.6
Type C	134	29	86	64.2	48	35.8
Type D	127	27.5	82	64.6	44	34.6
Others	156	33.8	113	72.4	43	27.6
Aggregate Type						
Gravel	124	26.8	77	62.1	47	37.9
Igneous	98	21.2	87	88.8	11	11.2
Limestone-Dolomite	207	44.8	120	58.0	86	41.5
Others	33	7.1	26	78.8	7	21.2
Binder Type						
PG 64-22	105	22.7	52	49.5	53	50.5
PG 70-22	131	28.4	87	66.4	43	32.8
PG 76-22	170	36.8	141	82.9	29	17.1
Others	56	12.1	30	53.6	26	46.4
Test Temperature						
40 ºC	71	15.4	60	84.5	11	15.5
50 ºC	391	84.6	250	63.9	140	35.8
Additive Type						
None	105	22.7	54	51.4	51	48.6
Lime	244	52.8	195	79.9	49	20.1
Liquid	104	22.5	59	56.7	44	42.3
Others	9	2	2	22.2	7	77.8

CHAPTER 4. EFFECT OF TEST TEMPERATURE

The Texas Department of Transportation usually performs Hamburg wheel-tracking tests at 50 °C, but occasionally they have conducted this test at 40 °C. The selection of these test temperatures relates to the temperature the pavement will experience. However, since the environmental zones for the state of Texas are not constant, different high temperature grading for asphalt cements are used. TxDOT predominantly uses three performance-graded binders for their mixes: PG 64-22, PG 70-22, and PG 76-22. The purpose of this section is to determine the influence of testing temperature on results obtained from the Hamburg test.

The TxDOT Hamburg database has 840 usable data points after eliminating missing value data points. Of these, only 133 tests were performed at 40 °C and the remaining 707 tests were performed at 50 °C. Table 4.1 clearly shows that tests performed at 40 °C show a higher percent of passing than those performed at 50 °C.

Table 4.1. Summary Statistics for Tests Performed at Different Temperatures.

		Pass			**Fail**		
Test Temperature	Total N	N	%	Avg. Deformation	N	%	Avg. no. of Passes
40 °C	133	120	90.2	4.65	13	9.8	15,053.9
50 °C	707	465	65.2	5.56	242	34.1	10,624

This trend is presented graphically in Figure 4.1. Ninety percent of the samples have the passing rate for 40 °C testing temperature, whereas only 66 percent of the samples had a passing rate at 50 °C. This result obviously indicates that the testing temperature is an important factor for pass/fail criteria selection.

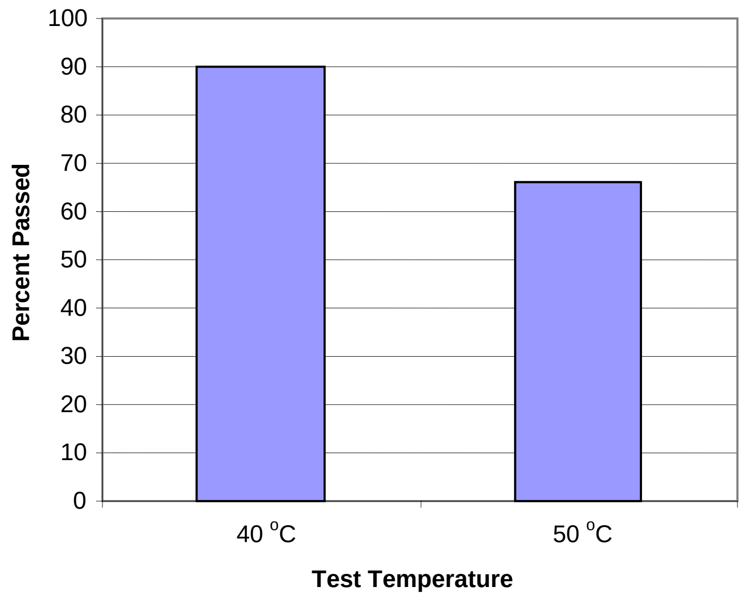


Figure 4.1. Percentage of Samples Passed at Different Temperatures.

There is a significant difference in performance between the samples tested at 40 °C and 50 °C. This difference is most likely the influence of the binder present in that particular mix. Binder is stiffer at 40 °C than 50 °C; therefore, the mix will show less deformation at 40 °C than 50 °C. This observation is obvious in Figure 4.2 for average deformation of all passed samples. Similarly, the samples at 50 °C will fail in less number of passes than at 40 °C. Yet again, Figure 4.1 reflects this observation. These two figures reinforce our notion that the effect of test temperature is primarily due to the binder (asphalt). Since the different performance-graded binders are designed to perform at different temperatures, there might be an interaction present between binder type and test temperature.

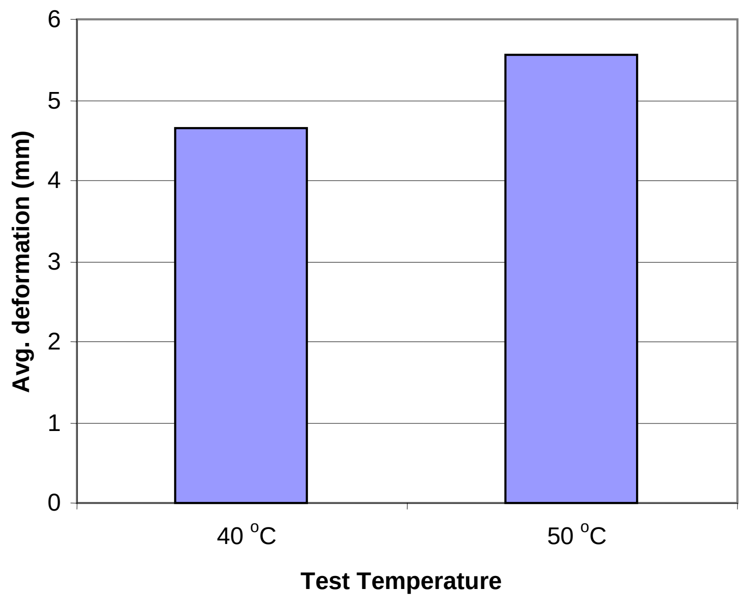


Figure 4.2. Average Deformation of Passed Samples at Different Test Temperatures.

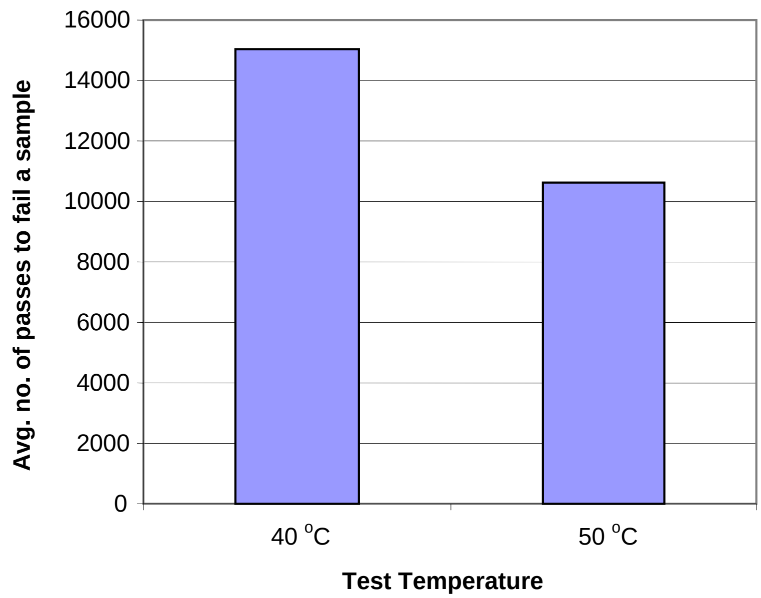


Figure 4.3. Average Number of Passes for Failed Samples at Different Test Temperatures.

A comparison of the effect of test temperature differential on test results performance for major factors clearly shows that all variable groups exhibit to some extent a fluctuation in performance due to temperature change. However, the sensitivity toward test temperature variation is only depicted for binder type and additive addition. When comparing the trend that tests performed at 40 ^{o}C show higher percent of passing than those performed at 50 ^{o}C, all variable groups showed a similar tendency. However, by comparing the test results (average deformation and number of passes) obtained for each category, each material parameter behaved differently except for two groups: the binder type and additive type. For example, for mix type category, a comparison of percentage of samples passed at 40 ^{o}C after ranking the results shows that type C has performed better than types B and D. A similar tendency is expected when comparing the test performance using average deformation; however, type D performed better than the two mix types with an average deformation of 3.96. Additionally, when comparing the average number of passes at failure, type B performed better than the other parameters with 19,900 passes. This comparison indicates that mix type variable is less sensitive to test temperature effect. Similarly, aggregate type also proves to be less sensitive to test temperature. Table 4.2 demonstrates the fluctuation in test performance of the major variable groups.

Table 4.2. Variation in Test Performance for Major Variables.

Value Range	Total Count	Pass				Fail			
		@ 40 ^oC		@ 50 ^oC		@ 40 ^oC		@ 50 ^oC	
		%	Avg. Def.	%	Avg. Def.	%	Avg. Wheel Passes	%	Avg. Wheel Passes
Mix Type									
Type B	66	93.3	4.67	48.1	5.73	6.7	19,900	51.9	10,886.7
Type C	296	93.9	4.87	70.4	5.86	6.1	18,500	29.6	11,664
Type D	225	92.6	3.96	57.1	5.43	7.4	18,050	42.9	10,123.7
Aggregate Type									
Gravel	183	100.0	6.14	85.2	5.4	0.0	---	14.8	11,938.3
Igneous	143	81.5	2.64	62.6	4.87	18.5	12,340	37.4	11,077.1
Limestone-Dolomite	389	89.5	4.89	57.2	5.94	10.5	16,750	42.8	10,061.5
Binder Type									
PG 64-22	179	80.8	5.96	34.6	8.25	19.2	16,440	65.4	8,498.7
PG 70-22	216	97.1	3.53	60.8	5.82	2.9	13,500	39.2	11,753.1
PG 76-22	315	100.0	3.1	83.1	4.85	0.0	---	16.9	13,698.9
Additive									
Lime	406	100.0	4.66	79.1	6.08	0.0	---	20.9	11,728
Liquid	201	89.7	4.37	55.0	5.12	10.3	18,850	45.0	10,091.5
None	200	84.1	4.81	48.7	6.28	15.9	14,642.9	51.3	10,373.9

The most significant effect of test temperature as demonstrated will be on the binder component of the asphalt concrete mix. The next section discusses a further investigation of the effect of test temperature on the binder type.

Interaction between Test Temperature and Binder Type

TxDOT predominantly uses three performance-graded binders for their mixes: PG 64-22, PG 70-22, and PG 76-22. These binders are rated to perform adequately for the specified temperature range, but rutting potentials were measured by the Hamburg wheel-tracking device at the same temperature for all three binders. This raises the question, "are all the PG binders being treated equally?" This issue will be investigated in this section.

All the mixes with these three binders are separated out from the TxDOT historical database. Table 4.3 gives a summary of the number of data points available in the database for each binder.

Table 4.3. Test Temperature Effect on Binder Type Performance.

	Number of Samples Tested at 40 °C					Number of Samples Tested at 50 °C				
		Passed		Failed			Passed		Failed	
	Total N	Freq	%	Freq	%	Total N	Freq	%	Freq	%
PG 64-22	69	54	78.2	15	21.7	101	33	32.7	68	67.3
PG 70-22	23	23	100	0	0.0	144	81	56.3	63	43.8
PG 76-22	6	6	100	0	0.0	182	150	82.4	32	17.6
Subtotal	98	83		15		427	264		163	

Figure 4.4 plots a relative comparison of the performance of these mixes. The performances at both test temperatures 40 °C and 50 °C are plotted in the same figure. The variable used to make the comparison is the percent of samples passing the test in each category. Figure 4.4 clearly shows that the higher the PG grade, the more samples pass the test, and this is true for both testing temperatures.

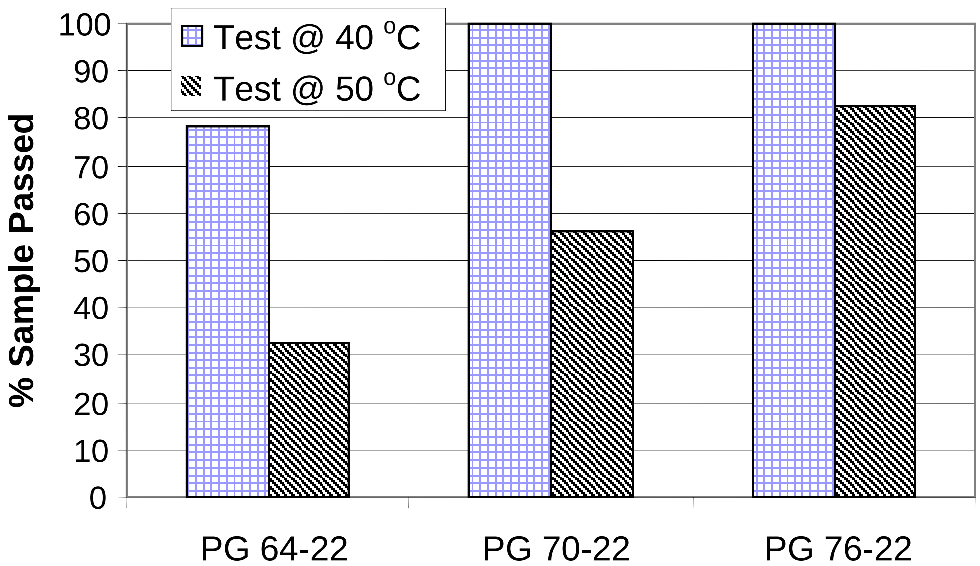


Figure 4.4. Effect of Test Temperature on Binder Type.

A similar trend is also obvious when plotting average deformation for samples that passed the test against binder type. As the test temperature increases, the average deformation increases accordingly. Figure 4.5 illustrates this trend. The plot also clearly shows that mixes with higher PG binders accumulated less deformation than those with lower grade binders, clearly indicating that there is a significant effect of test temperature and binder type on the Hamburg test results.

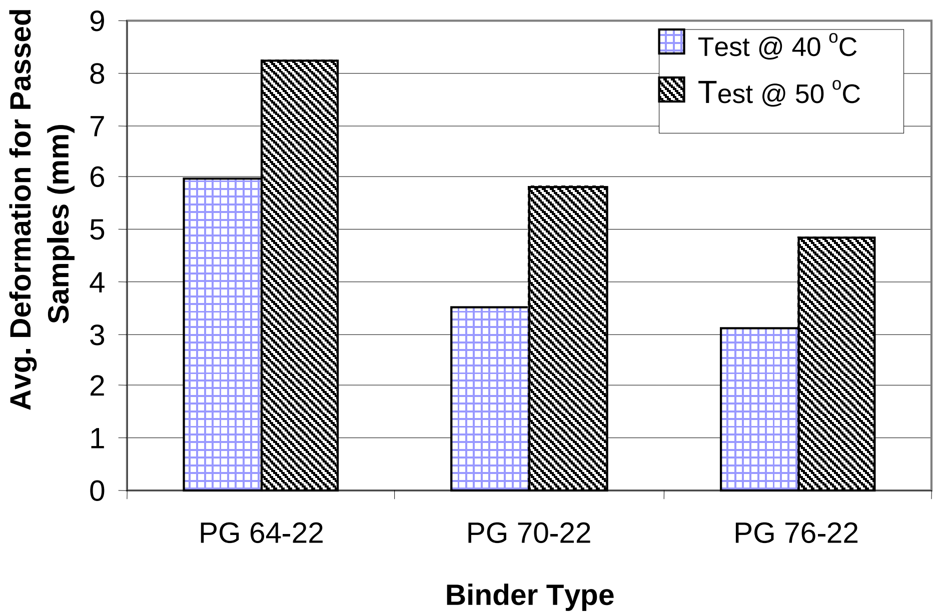


Figure 4.5. Test Temperature and Binder Type Effect on Average Deformation.

Test Temperature Effect on Additive-Binder Performance

This section shows how test temperatures influence test results and the combined interaction of binder and additive addition. The use of additive such as an anti-stripping agent to binder actually changes binder properties; in addition to the intended use, i.e., the additive provided resistance against moisture damage. It also affects the deformation characteristics of the binder. The two most common anti-stripping agents used by TxDOT are hydrated lime and liquid anti-stripping treatments. These agents are extensively used with all three PG graded binders (64-22, 70-22, and 76-22). Their performance is also affected by test temperatures. The performance of each additive treatment is plotted against binder type. First, the data were filtered for binders without any additive; second, with liquid additive, and finally, with lime additive. Table 4.4 summarizes the available data points after filtration.

Table 4.4. Summary Statistics for Available Data Points after Grouping Data Based on Binder and Additive Type.

Binder Type	Additive	Number of Samples Tested at 40 °C					Number of Samples Tested at 50 °C				
		Total	Passed		Failed		Total	Passed		Failed	
			Count	%	Count	%		Count	%	Count	%
PG 64-22	Lime	11	11	100.0	0	0	47	28	59.6	19	40.4
	Liquid	19	15	78.9	4	21.1	43	10	23.3	33	76.7
	None	22	16	72.7	6	27.3	36	6	16.7	30	83.3
	Subtotal	52	42	80.8	10	19.2	126	44	34.9	82	65.1
PG 70-22	Lime	17	17	100.0	0	0	99	73	73.7	26	26.3
	Liquid	8	8	100.0	0	0	37	16	43.2	20	54.1
	None	10	9	90.0	1	10	41	18	43.9	23	56.1
	Subtotal	35	34	97.1	1	2.9	177	107	60.5	70	39.5
PG 76-22	Lime	3	3	100.0	0	0	164	150	91.5	14	8.5
	Liquid	6	6	100.0	0	0	53	42	79.2	11	20.8
	None	9	9	100.0	0	0	65	44	67.7	21	32.3
	Subtotal	18	18	100.0	0	0	282	236	83.7	46	16.3

A relative comparison of anti-strip performance for all three binders is plotted in Figure 4.6. There is obviously a difference in performance (in terms of percent passing) between 40 °C and 50 °C testing temperatures for all three binders, whether with or without any additives. Mixes in general show better performance at 40 °C than 50 °C, and that is valid for all nine combinations shown in Figure 4.6. The mixes are more sensitive at 50 °C than 40 °C; this is especially true for higher PG grades. For example, consider PG 76-22, which has three categories:

- no additive,
- liquid additive, and
- lime additive.

Figure 4.6 shows all three binders have 100 percent of the samples that passed the test at 40 °C testing temperature, whereas at the 50 °C testing temperature, there is a difference in terms of percent passing. Lime performed better than liquid, and liquid performed better than binder without additive. A similar trend at 50 °C is also observed for the other two binders, as Figure 4.6 illustrates. Therefore, 50 °C testing temperature, compared to 40 °C, is more likely to pick up the difference in performance when additives are used, and the Hamburg test is sensitive to moisture damage.

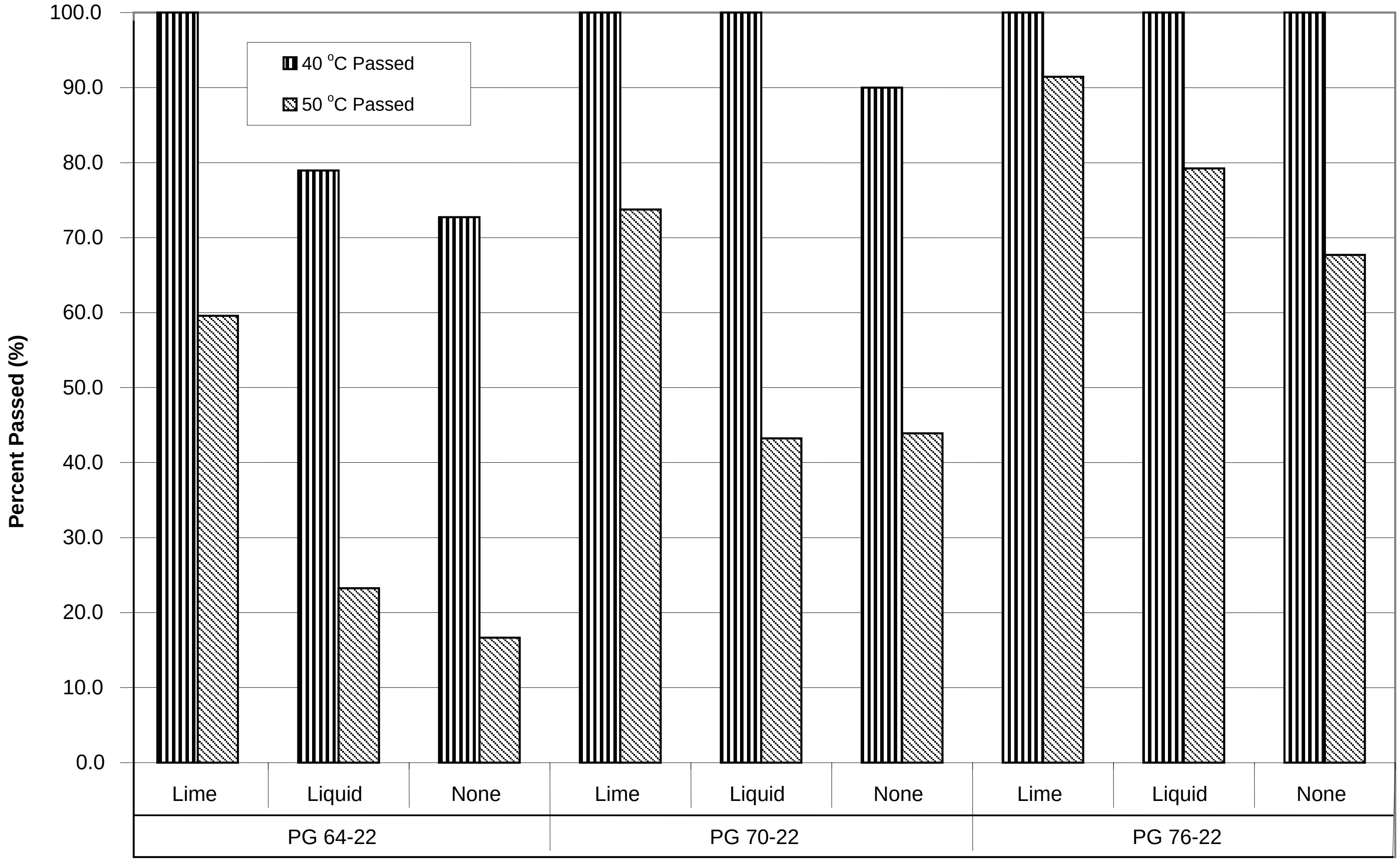


Figure 4.6. Effect of Test Temperature on Binder and Additive Performance.

Figure 4.7 shows a relative comparison of the performance of unmodified mixes (binder without additive). The performance at both test temperatures is plotted in the same figure. The variable used to make the comparison is percent of samples passing the test in each category. Figure 4.7 clearly shows that the higher the PG grade, the more samples pass the test; this is true for both testing temperatures. Therefore, using a specific temperature for all PG graded binder could be discriminating to lower graded binders. Other important observations from this plot follow.

The lines for 40 and 50 degrees are not parallel to each other. Therefore, there is an interaction present between test temperature and binder type.

The 50 °C line is steeper than the 40 °C line. This indicates that a higher testing temperature is more likely to show the differences in performance among different grades of asphalt than a low testing temperature. Figures 4.8 and 4.9, respectively, indicate that mixes with anti-stripping additive, i.e., lime or liquid, are also affected in similar ways as explained in Figure 4.7.

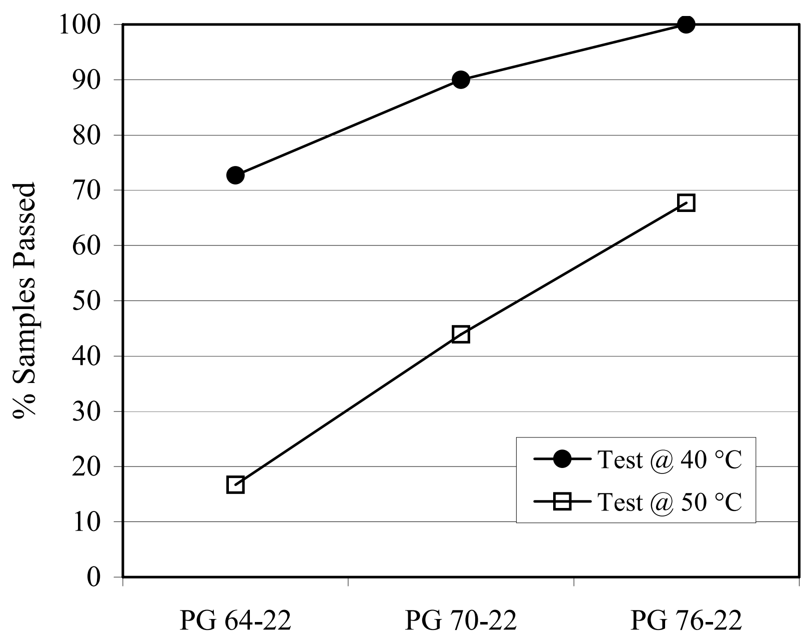


Figure 4.7. Effect of Test Temperature on Binder Type (without Any Additive).

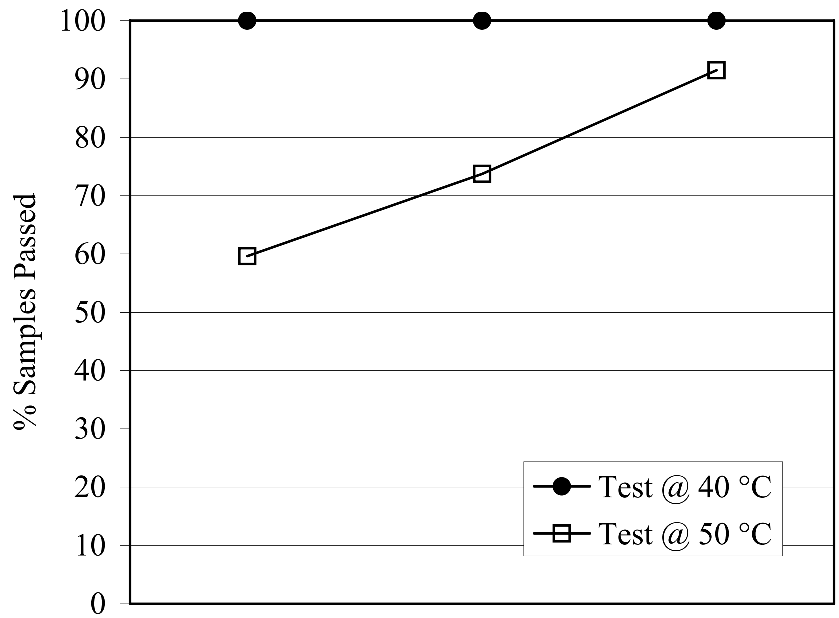


Figure 4.8. Effect of Test Temperature on Binder with Lime Additive.

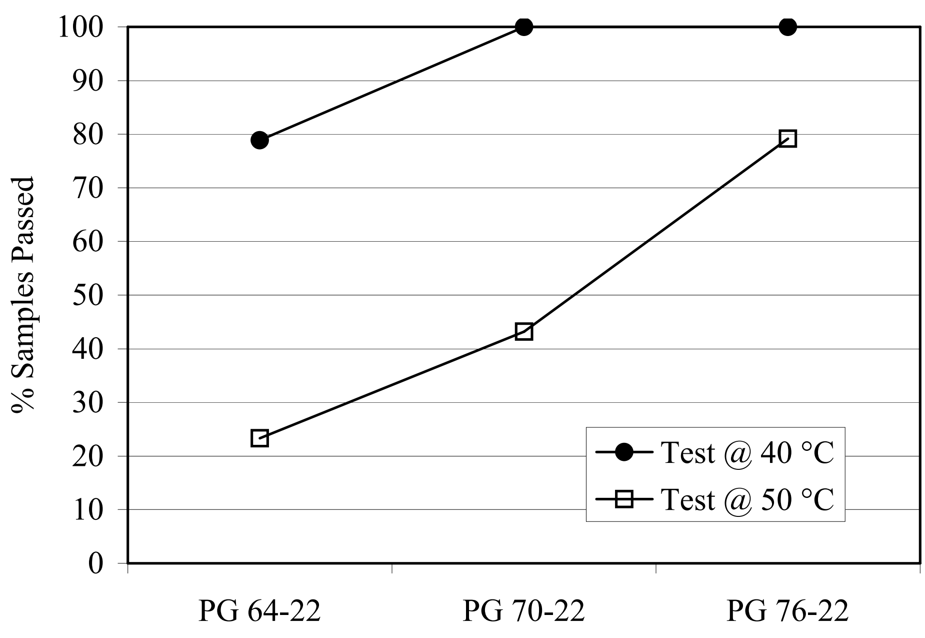


Figure 4.9. Effect of Test Temperature on Binder with Liquid Additive.

For further investigation of the effect of additives, the samples tested at 50 ^oC were considered. The average deformations of the passed samples were plotted against additive types for all three binders in Figure 4.10. Again, the lime has the lowest deformation, as expected, and the trend is the same as mentioned previously, that is the highest deformation for binders without any additive. Similarly, the average number of passes for failed samples is plotted in Figure 4.11. It is clear from the figure that the samples with lime additive need the highest number of passes to fail, and samples without any additive usually fail early. Table 4.5 shows the average deformation for samples that passed the Hamburg test at 50 ^oC.

Table 4.5. Average Deformation for Samples that Passed at 50 ^oC.

Binder Type	Additive	No. of Samples Tested	% Passed	Average Deformation (mm)	
				Mean	Std. Dev.*
PG 64-22	Lime	47	28	7.94	2.66
	Liquid	43	10	8.07	3.23
	None	36	6	10.02	2.2
	Subtotal	126	44		
PG 70-22	Lime	99	73	5.14	2.29
	Liquid	37	16	7.13	2.86
	None	41	18	6.74	2.36
	Subtotal	177	107		
PG 76-22	Lime	164	150	4.38	2.22
	Liquid	53	42	5.14	2.73
	None	65	44	5.8	2.72
	Subtotal	282	236		

* Std. Dev. = Standard Deviation

In Figure 4.10, the average deformations for PG 64s are highest and PG 76s are lowest. Similarly, in Figure 4.11, PG 76 shows the highest number of passes to fail and PG 64 shows the lowest. These results also indicate that the same testing temperature may be discriminating to the lower graded binders and less harsh to higher graded binders.

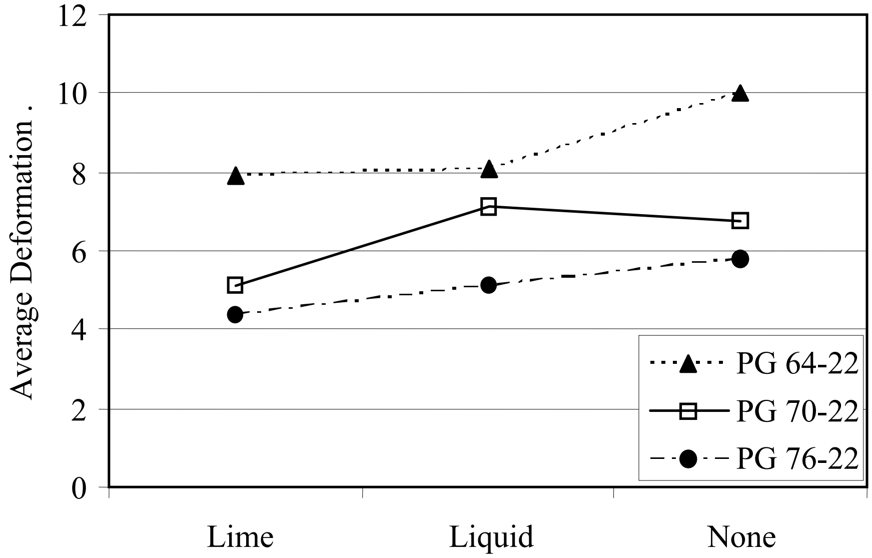


Figure 4.10. Effect of Binder and Additive on Average Deformation for Passed Samples.

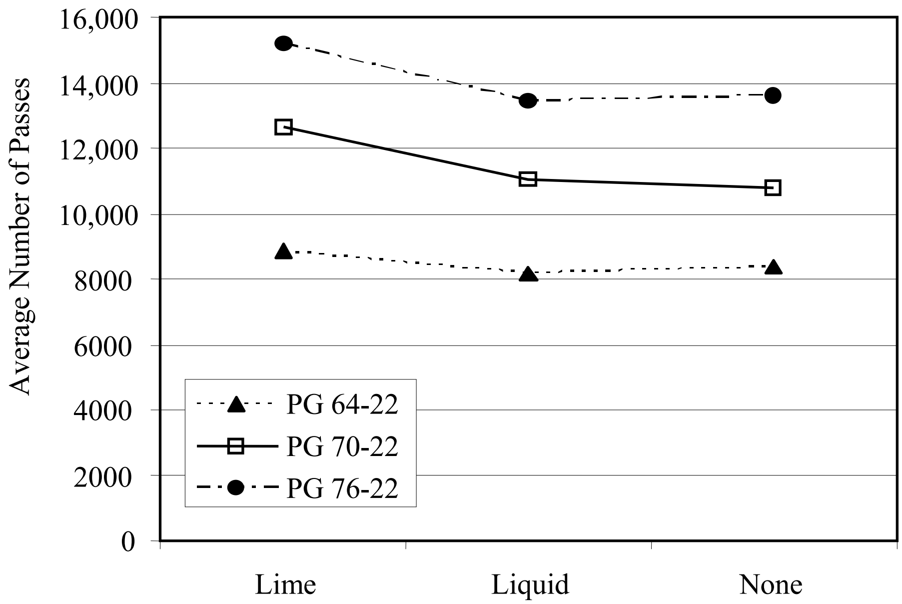


Figure 4.11. Effect of Binder and Additive on Average Number of Passes to Failure.

CHAPTER 5. EFFECT OF AGGREGATE PROPERTIES ON HAMBURG TEST RESULTS

It is obvious that aggregate has a significant influence on the performance of asphalt concrete since more than 90 percent of the materials are aggregate. Therefore, the objective of this section is to investigate the possible influence of aggregate properties on the performance of asphalt concrete in the laboratory performance test by the Hamburg wheel-tracking device. The available information regarding aggregate properties is very limited in the database. Only aggregate mineralogy and durability properties are readily available for further analysis. First, the effect of aggregate mineralogy as evident from aggregate type is investigated. Second, the durability aspect of aggregate is considered. In this approach, results from the Hamburg test were correlated with those obtained from soundness tests such as MSS and MD.

Several studies reported that aggregate type was a major factor influencing permanent deformation. Interactions of aggregate type with asphalt type, additive, and temperature were also indicated to be significant. Moreover, the aggregate properties such as particle shape, angularity, and surface texture are also predominant factors in rutting behavior of the mixes. Unfortunately, such information was not part of the Hamburg test database provided by TxDOT.

Based on the discussion in Chapter 4, there is an obvious effect of binder type, additive, and test temperature on the rutting performance of hot mix asphalt as measured by the Hamburg test in this database. The effect of aggregate properties on the rutting would be very difficult to quantify because most dominating aggregate properties such as aggregate size, gradation, aggregate particle shape, angularity, and surface texture information are not available in the database. Considering all these factors, aggregate durability properties (MSS and MD) alone were not expected to show a very high degree of correlation with rutting performance. However, the durability effects may show greater influence on the moisture susceptibility part of the Hamburg test results. Unfortunately, the database did not include such information. Despite all of these limitations, available aggregate properties showed appropriate trends with final Hamburg results (deformation or number of passes).

Effect of Aggregate Type

The influence of aggregate type on the performance of mixes in the Hamburg test was investigated. The data for the following three major types of aggregate considered were: Gravel, Igneous, and Limestone-Dolomite. To better expose the effect of aggregate type, tests performed at 50 °C are only used in the analysis. In fact, the higher the temperature, the less stiff the binder, allowing aggregate to carry out the load and degrade faster. This method will be used as a means to minimize the effect of binder and largely distinguish the aggregate characteristics. Table 5.1 shows the percent of samples passing or failing the Hamburg test at 50 °C in each category.

Table 5.1. Summary Statistics for Samples' Performance with Different Aggregate Types.

Aggregate Type	Total N	Passed Samples			Failed Samples		
		N	%	Avg. Deformation	N	%	Avg. Wheel Passes
				(mm)			
Igneous	122	104	85.2	4.87	18	14.8	11,938.3
Gravel	157	98	62.2	5.43	59	37.8	11,077.1
Limestone-Dolomite	313	179	57.2	5.9	134	42.8	9986.8

Figures 5.1 through 5.3 plot relative comparisons of the performance of these aggregates. The performances of each of the three aggregate types are plotted in the same figures. Again, three variables are used to make the comparison:

- percent of samples passing the test in each category,
- average deformation in millimeters for samples passing the test, and
- number of passes for samples failing the test.

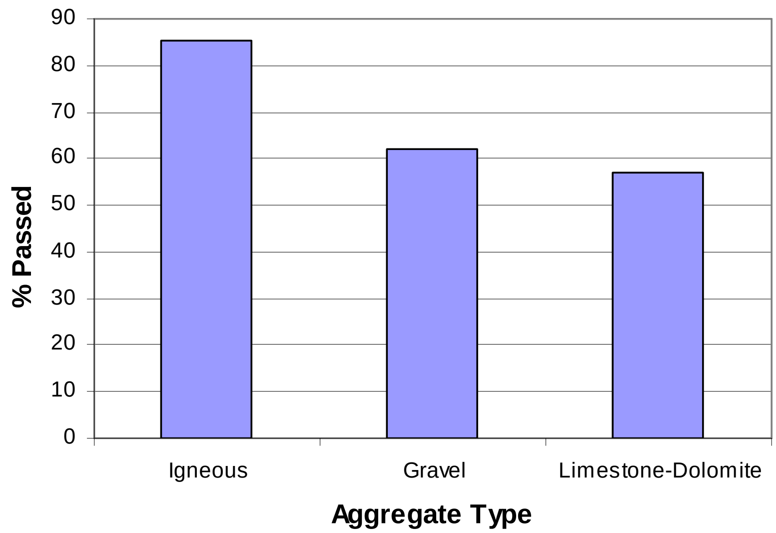


Figure 5.1. Effect of Aggregate Type on Hamburg Test Results.

Figure 5.1 clearly shows that samples with igneous aggregate have a higher percent of passing than samples with gravel or limestone-dolomite. Eighty-five percent of samples have the passing rate for igneous, whereas only 62 percent of the samples got passing rates for gravel, and 57 percent for limestone-dolomite.

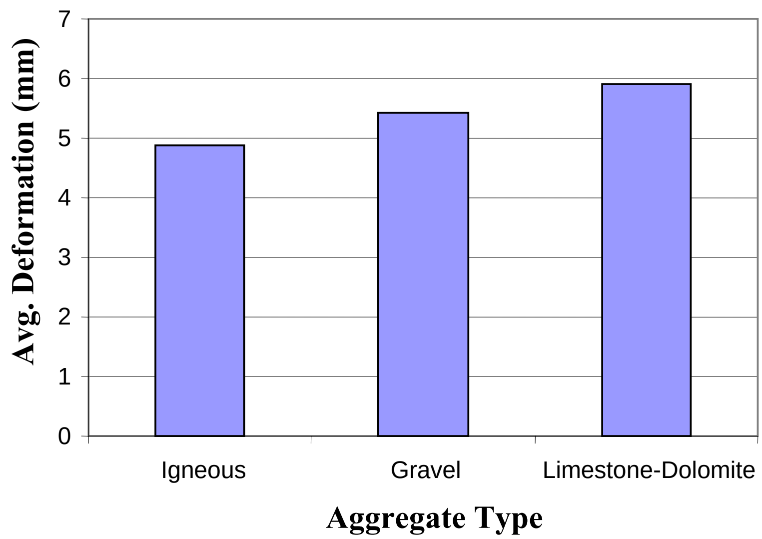


Figure 5.2. Average Deformation of Passed Samples.

A similar trend is also observed when relatively comparing the average deformation for the passed samples. Figure 5.2 shows that samples with igneous type aggregate have accumulated less rutting than samples with gravel or limestone-dolomite. Similarly, Figure 5.3 shows that samples with igneous aggregate fail at a higher number of passes (at approximately 12,000 passes), whereas samples with gravel fail at about 11,000 passes. Samples with limestone-dolomite, as expected, performed relatively poorly with less number of passes (about 10,000 passes).

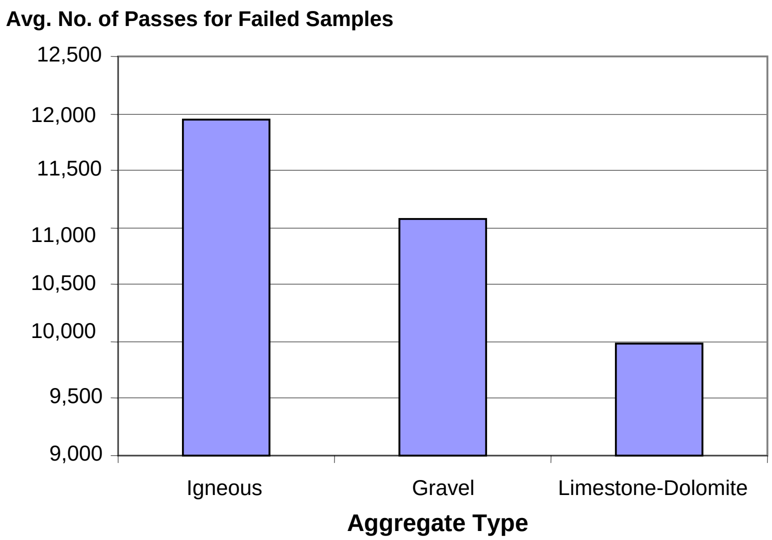


Figure 5.3. Average Number of Passes for Failed Samples.

Igneous type aggregate shows the best performance in the above figures, and limestone-dolomite is the worst performer. In general, limestone-dolomite type aggregate is less durable (i.e., has higher MSS or MD loss) than gravel or igneous type aggregate. Therefore, it might be an indication that the aggregate durability is contributing to such a performance in the Hamburg test. Further breakdown according to binder type also shows a similar trend.

To minimize the obvious effects of binder type and test temperature, the available data were grouped according to these factors. Table 5.2 summarizes the performance of samples in each category after grouping. Table 5.2 clearly shows similar trends after eliminating the effect of binder type and temperature. However, gravel type aggregate ranked second when comparing the percent passed, but it ranked third when comparing the average deformation. This could be the effect of further grouping the data, which led to fewer data available for analysis. Therefore, a further grouping of samples according to additive type is not expected to show much, especially with less available data. Figures 5.4 and 5.5 are graphical presentations of information presented in Table 5.2.

Table 5.2. Summary Statistics for Passed Samples Grouped by Binder Type.

Binder Type	Aggregate Type	Total N	Passed Samples		
			N	%	Avg. Deformation
PG 64-22	Igneous	20	9	45	7.2
	Gravel	23	10	43.5	8.99
	L.D.	64	19	29.7	8.27
PG 70-22	Igneous	35	32	91.4	4.68
	Gravel	36	24	66.7	6.53
	L.D.	86	38	44.2	5.93
PG 76-22	Igneous	61	58	95.1	4.59
	Gravel	67	52	77.6	3.81
	L.D.	112	87	77.7	5.51

* L.D. = Limestone-Dolomite

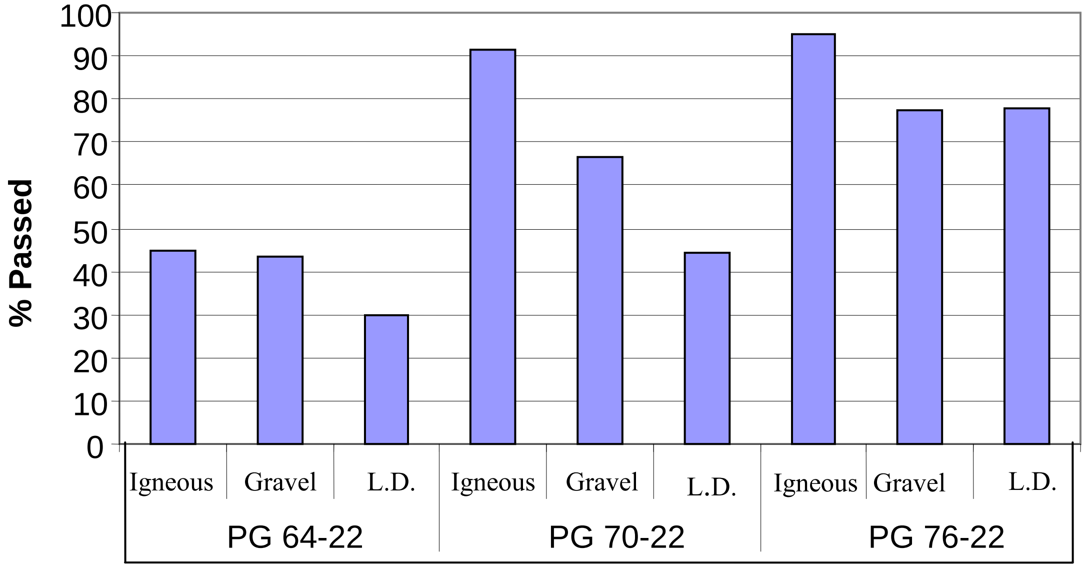


Figure 5.4. Percent of Samples Passed HWTD Test (Grouped Based on Binder and Aggregate Type).

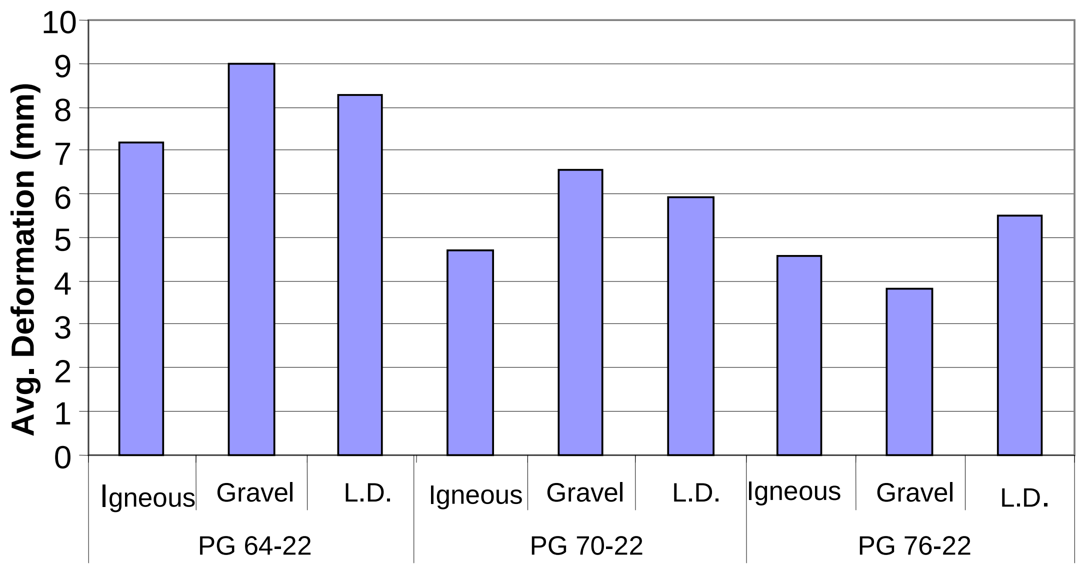


Figure 5.5. Average Deformation of Passed Samples after Grouping.

Effect of Aggregate Durability Based on Mineralogy

A previous study conducted at Texas Tech University investigated the relationship between aggregate mineralogy and durability as measured by magnesium sulfate soundness and Micro-Deval tests. The study reported that for an aggregate source grouped in mineralogical classifications, as used by TxDOT, in general, gravels and igneous rocks have lower MD and MSS loss than sandstone and limestone. Table 5.3 summarizes their findings. Average MD for gravel and igneous rock are 6.3 percent and 7.8 percent, respectively, whereas for limestone it varies from 10 to 20 percent depending on its absorption.

Table 5.3. MSS and MD Values for Different Types of Aggregate (*13*).

Aggregate Type	Micro-Deval (% Loss)		MS Soundness (% Loss)	
	Avg.	St. Dev.	Avg.	St. Dev.
Gravel	6.3	3.2	5.3	3.5
Igneous	7.8	2.1	6.0	4.3
Limestone	10.9 – 20.6	2.6 - 4.6	6.6 – 20.3	3.5 – 13.3

Similarly, in the HAP database, gravel and igneous aggregates have lower MD and MSS loss than limestone-dolomite. Table 5.4 shows that igneous in almost all cases has performed better and is accordingly ranked first. Gravel, on the other hand, has performed moderately and, therefore, is ranked second. Limestone-dolomite aggregate type has shown relatively poorer performance in comparison with the other two types and is ranked third. However, this observation is not obvious when relatively comparing results from the MD test. Overall, these results correlate well with the observation reported in the study previously mentioned although the MSS test has shown the capability of maintaining a trend similar to the Hamburg test.

Table 5.4. Average MD and MSS Values in HAP Database.

Aggregate Type	Total N	Avg. MSS	Avg. MD	Passed Samples			Failed Samples		
				N	Avg. MSS	Avg. MD	N	Avg. MSS	Avg. MD
		% Loss	% Loss		% Loss	% Loss		% Loss	% Loss
Igneous	84	3.4	6.6	73	3.4	6.5	11	3.3	7.4
Gravel	111	4.2	4.6	69	4.1	4.3	42	4.4	5.3
Limestone-Dolomite	164	13.2	17.5	83	12.4	17.0	80	14.2	18.2

Figures 5.6 through 5.8 graphically illustrate the information presented in Table 5.4. The trend discussed previously is clearly shown in all figures, whether plotting passed or failed samples. The only difference is the values; samples that passed the Hamburg test are characterized with relatively lower MSS and MD values than those that failed the test. Samples that passed the test have more durable aggregates than those that failed.

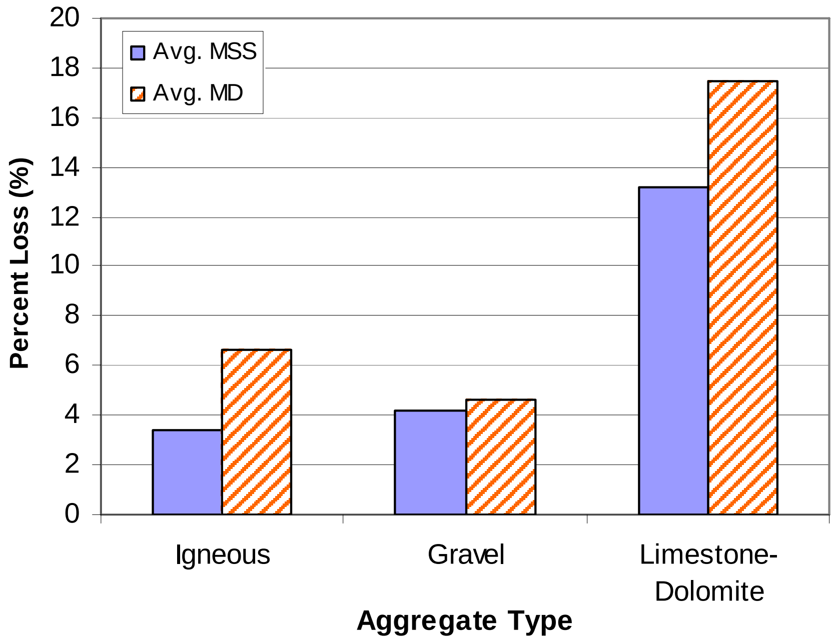


Figure 5.6. Average MSS and MD Values (% loss) for Different Aggregates in HAP Database.

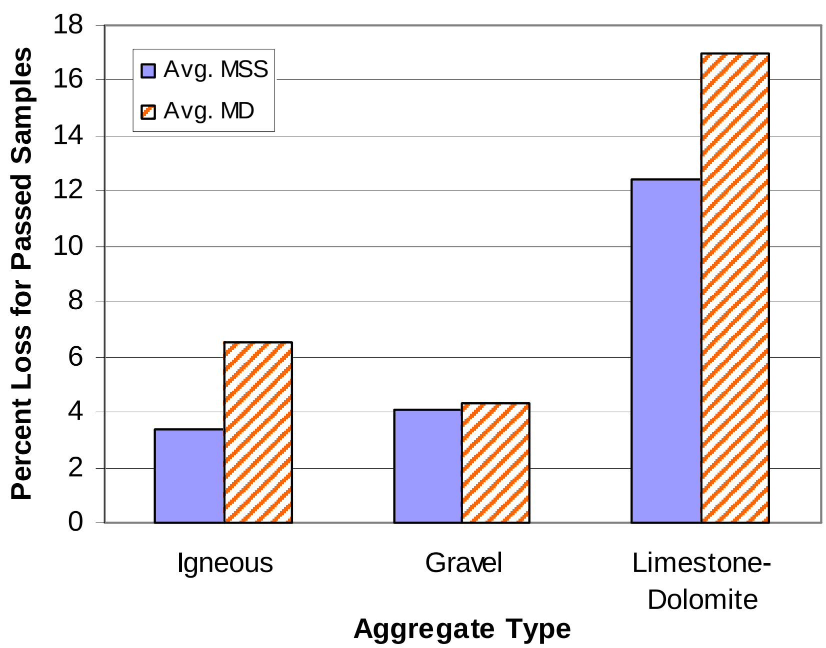


Figure 5.7. Average MSS and MD Values (% Loss) for Samples Passing the Hamburg Test.

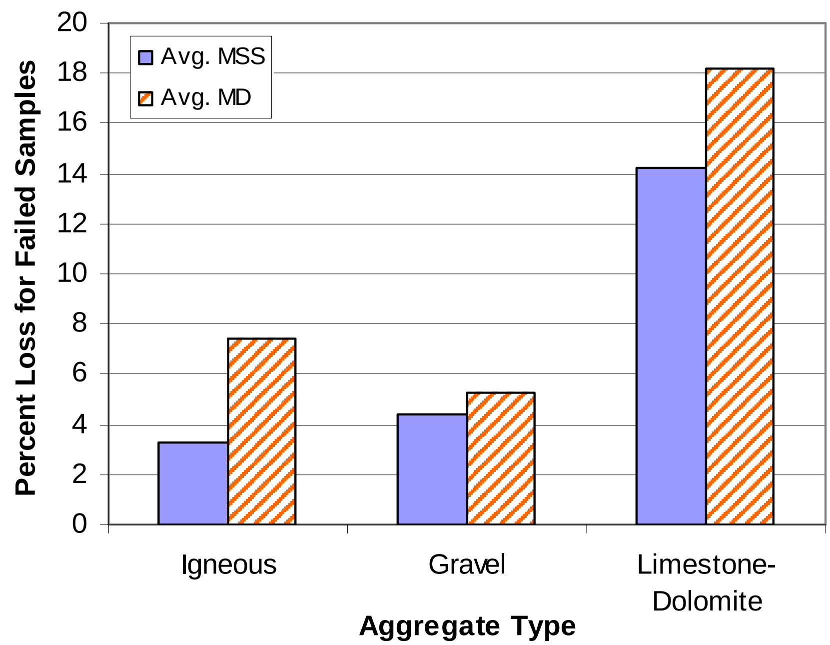


Figure 5.8. Average MSS and MD Values (% Loss) for Samples Failing the Hamburg Test.

Additional grouping of data according to binder type not only eliminates its effect, but it also shows the same trend as demonstrated earlier. The MSS test has preserved its capability to grade aggregates based on their performances. The MD test, on the other hand, shows the ability to distinguish gravel and igneous from limestone-dolomite. Table 5.5 summarizes the aggregates' durability as observed in the HAP database after grouping the data based on binder types for tests performed at 50 ^{o}C. Figures 5.9 through 5.11 graphically illustrate information presented in Table 5.5. For example, in Table 5.5, by comparing the percent loss of MSS and MD of igneous, gravel, and limestone-dolomite for the binder type "PG 64-22," both igneous and gravel aggregate types are characterized with relatively lower loss values than limestone-dolomite. This finding meets our expectation in which limestone-dolomite is known to be relatively less durable than igneous and gravel. By further assembling the data based on fail/pass criteria, a similar trend is observed. Again, gravel and igneous have lower loss values, and limestone-dolomite has the higher loss value.

Table 5.5. Aggregate Durability after Grouping Data Based on Binder Type.

Binder Type	Aggregate Type	Total N	Avg. MSS	Avg. MD	Passed Samples			Failed Samples		
					N	Avg. MSS	Avg. MD	N	Avg. MSS	Avg. MD
PG 64-22	Igneous	12	2.9	5.7	8	2.8	5.4	4	3.1	6.4
	Gravel	11	3.8	5.0	4	4.3	5.1	7	3.6	4.9
	Limestone-dolomite	44	17.0	19.8	12	18.1	20.3	32	16.6	19.7
PG 70-22	Igneous	26	3.5	6.7	23	3.5	6.6	3	3.3	7.5
	Gravel	30	3.7	3.7	20	3.7	3.5	10	3.7	3.9
	Limestone-dolomite	47	12.4	16.5	19	13.0	17.6	27	12.2	16.0
PG 76-22	Igneous	43	3.5	6.4	40	3.5	6.3	3	3.7	4.5
	Gravel	50	3.9	4.2	40	4.0	4.2	10	3.7	7.0
	Limestone-dolomite	50	11.5	16.5	38	10.9	16.1	12	13.1	17.7

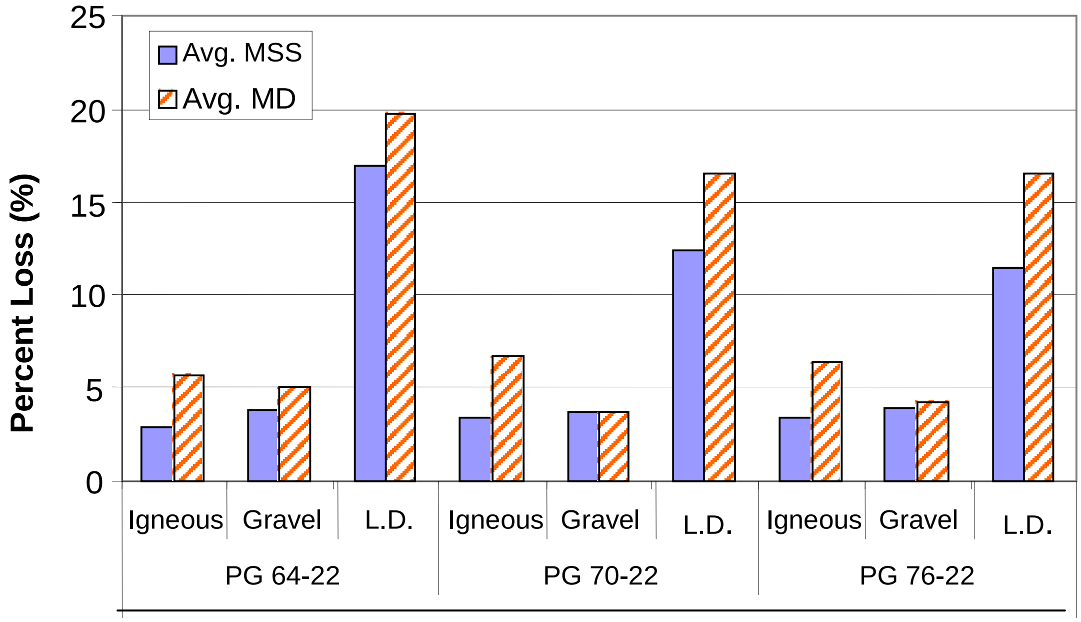


Figure 5.9. MSS and MD Loss after Grouping Data Based on Binder Type.

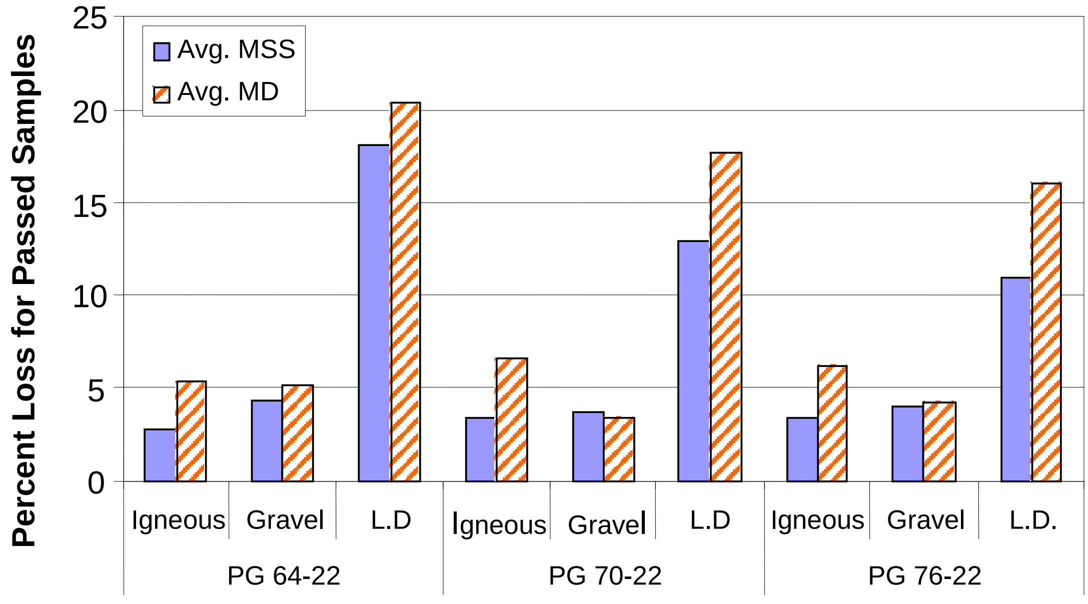


Figure 5.10. MSS and MD Loss for Passed Samples (Data Grouped Based on Binder Type).

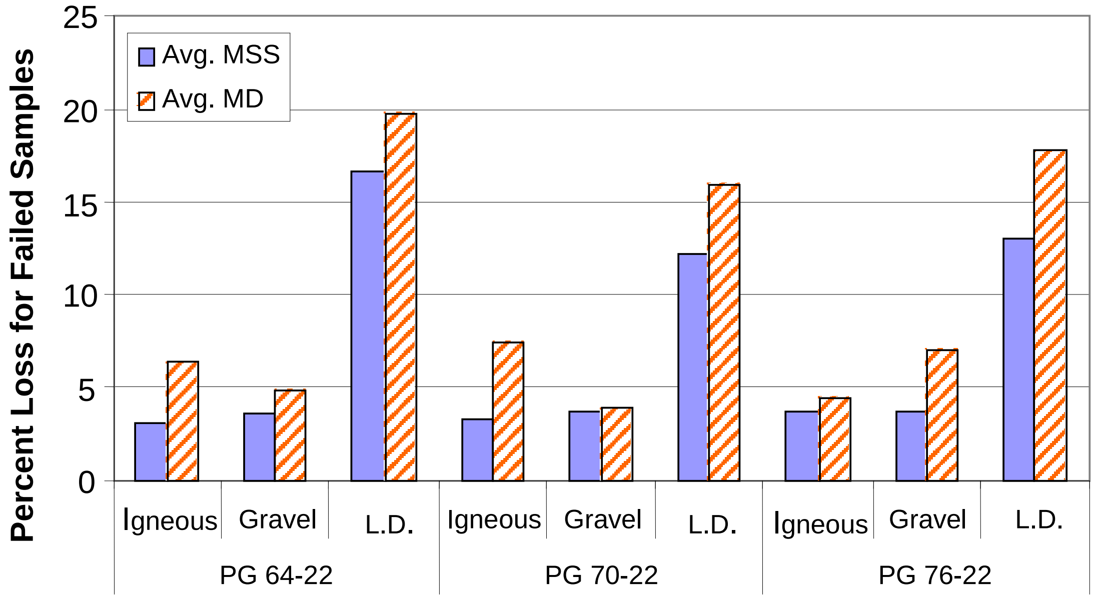


Figure 5.11. MSS and MD Loss for Failed Samples (Data Grouped Based on Binder Type).

Influence of Aggregate Durability Properties on Hamburg Results

The durability of different types of aggregate, in general, shows some influence on the Hamburg wheel-tracking results in the previous section. To further investigate this influence, MSS and MD loss values were used as the direct measure of aggregate durability irrespective of the aggregate mineralogy. The data were grouped into two categories for further analysis: samples that passed the Hamburg test and samples that failed. Each of the passed samples has an average deformation corresponding to 20,000 wheel passes. On the other hand, the failed sample has the number of passes to reach 12.5 mm deformation (rut). To investigate the trends of Hamburg wheel-tracking results against the MSS and MD loss values, scatter plots were used. First, the average deformations for the passed samples were plotted against MSS and MD values in Figures 5.12 and 5.13, respectively. Both regression lines have positive slopes, as expected, indicating higher deformation for higher MSS or MD. Similarly, average numbers of passes for failed samples were plotted in Figures 5.14 and 5.15. Again, the trend of the higher the MSS or MD loss, the lower the number of passes required to achieve 12.5 mm rut is also expected. The strength of correlations (R^2) in Figures 5.12 through 5.15 is very low. This is not surprising because, as mentioned previously, the aggregate durability effects would be masked by the more dominant variables such as binder type, test temperature, and aggregate particle shape, angularity, and surface texture. There is very little difference between the strength of correlation for MSS and MD, but MD is always stronger in both cases. In addition, the strength of correlation is higher for the failed samples than that of passed samples. This is also expected because non-durable aggregates are most likely to fail in a condition similar to the Hamburg wheel-tracking test. The durability effects may be more visible in the failed samples than passed samples.

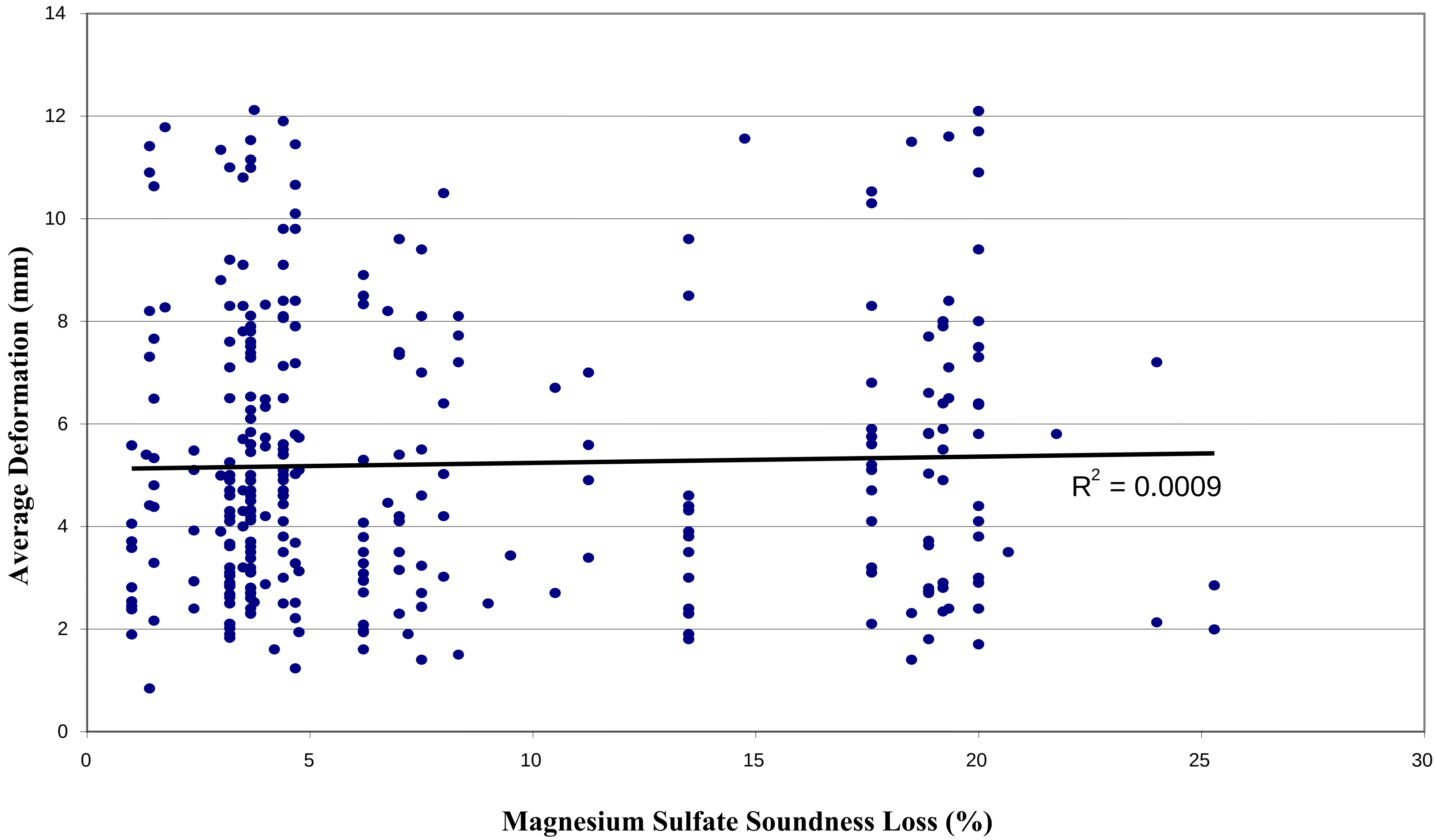


Figure 5.12. Average Deformation vs. Magnesium Sulfate Soundness Loss for Passed Samples.

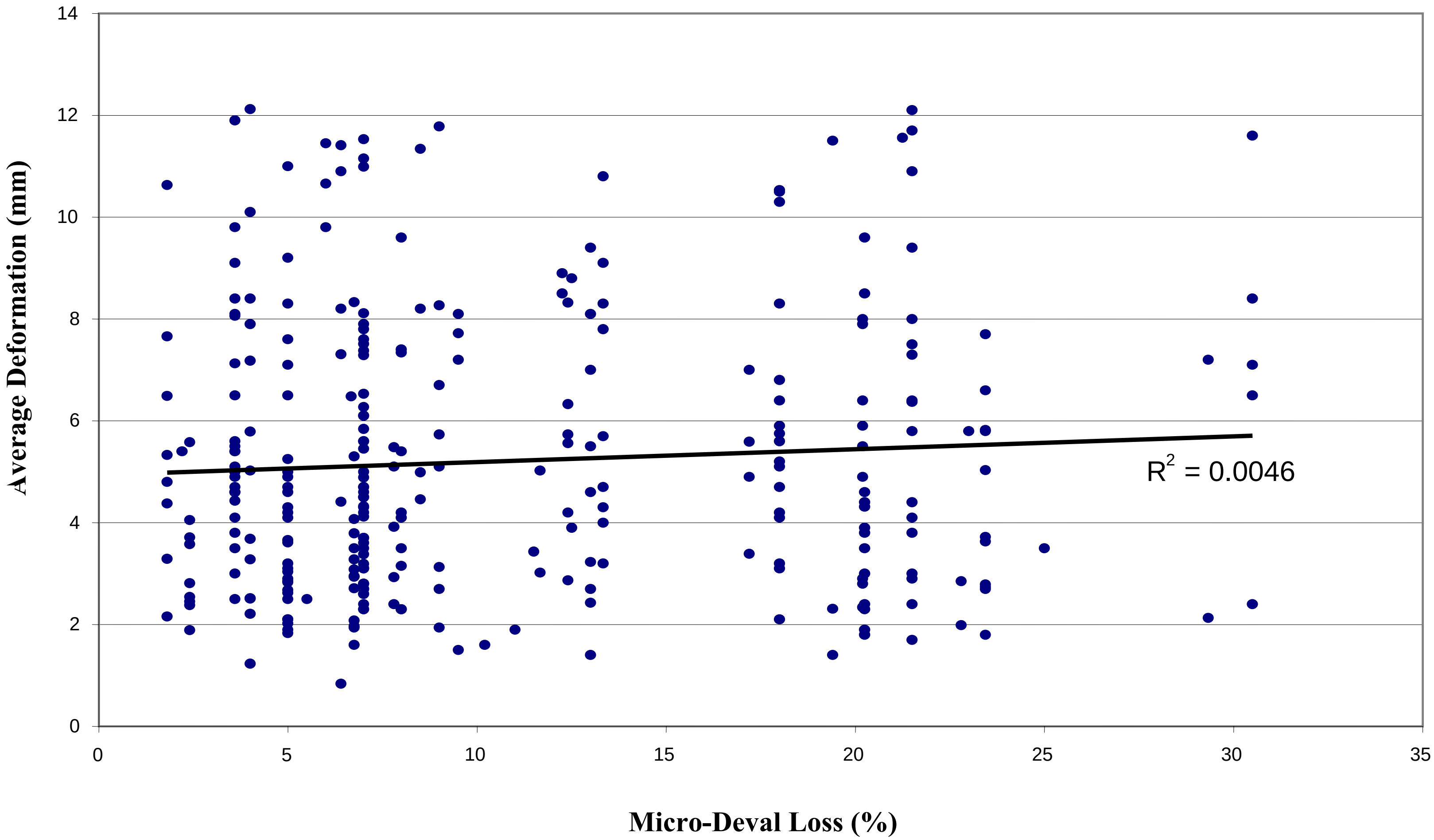


Figure 5.13. Average Deformation vs. Micro-Deval Loss for Passed Samples.

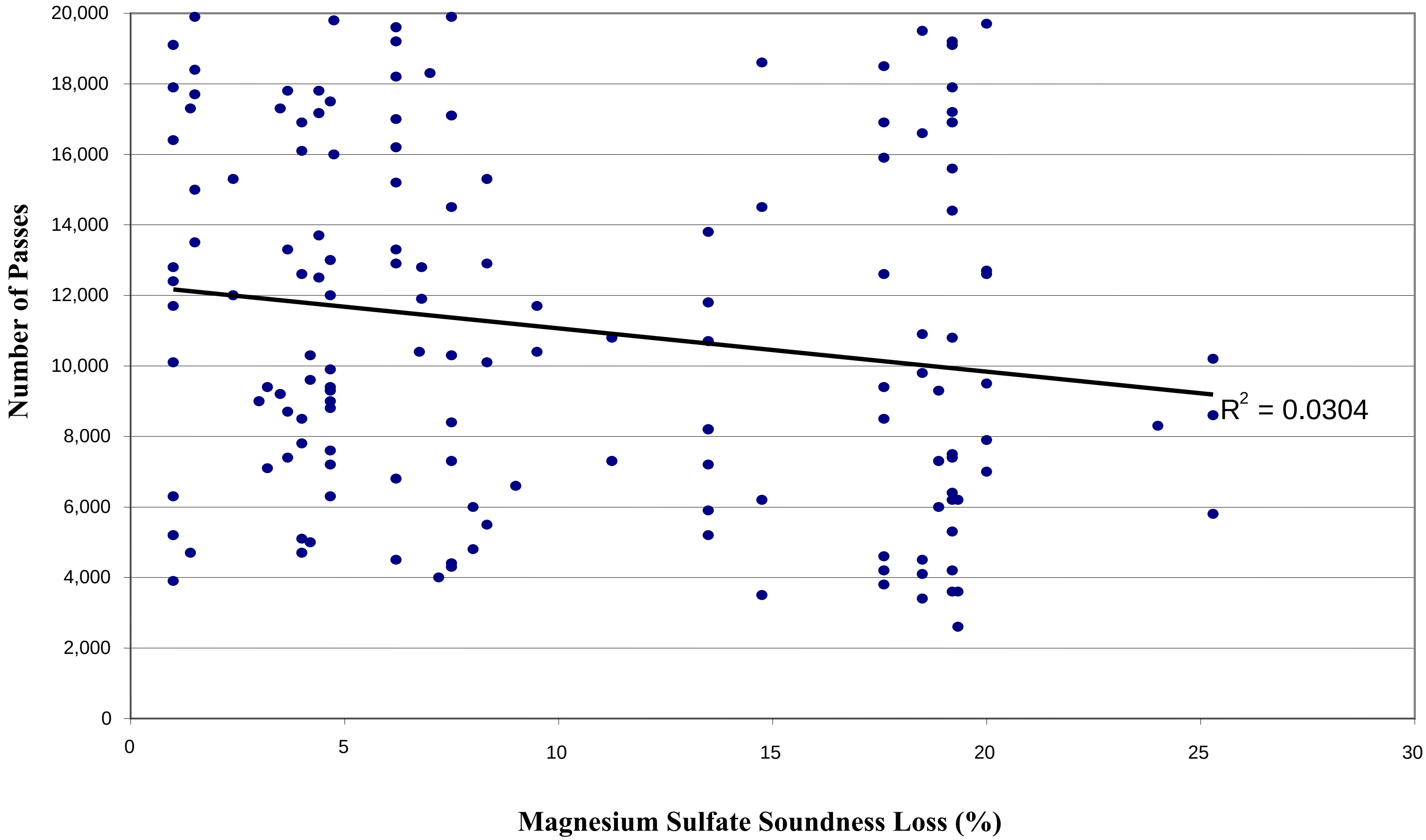


Figure 5.14. Number of Passes vs. Magnesium Sulfate Soundness Loss for Failed Samples.

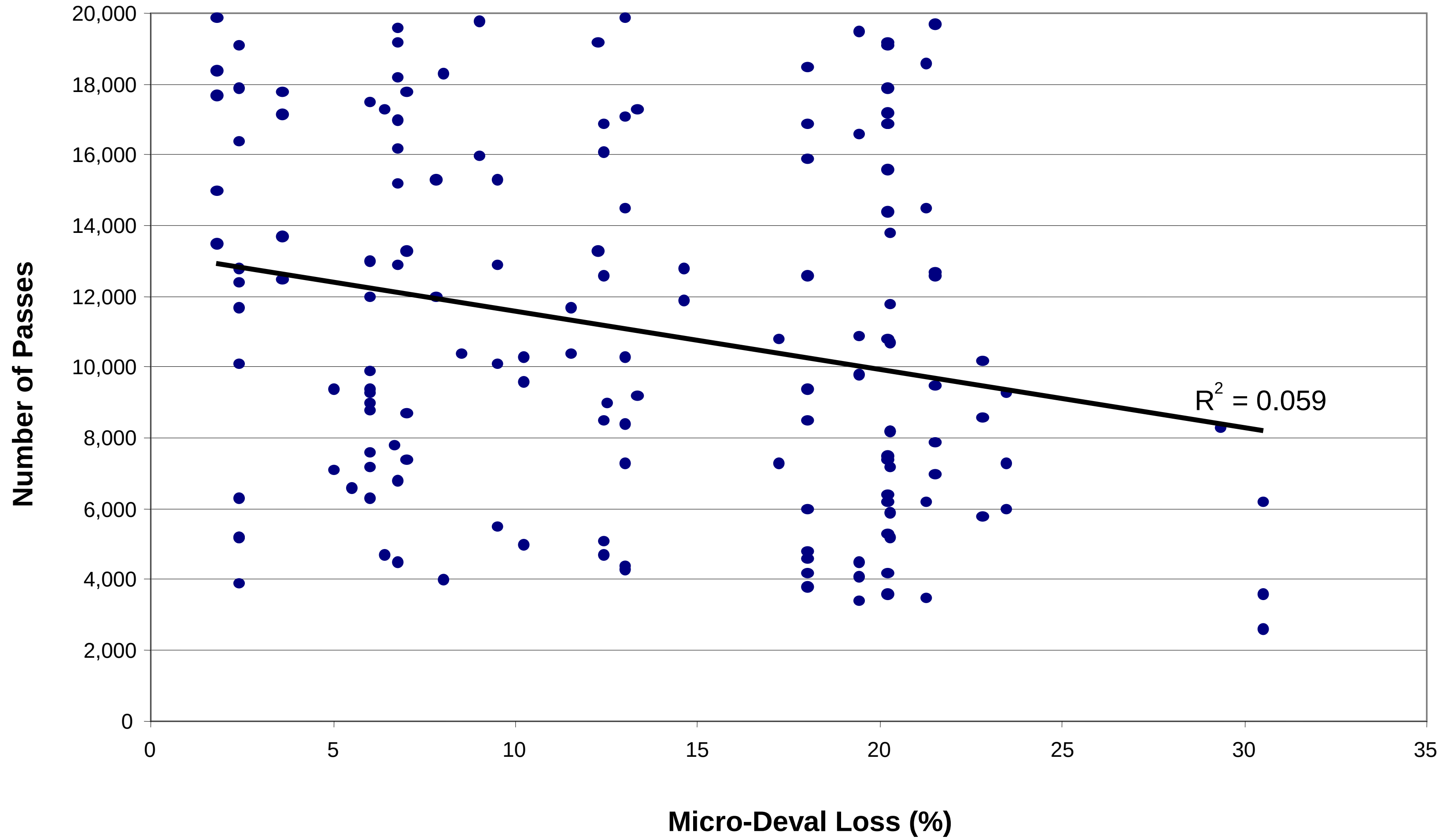


Figure 5.15. Number of Passes vs. Micro-Deval Loss for Failed Samples.

To reduce the effect of test temperature and binder type in the above correlation, the data were further grouped according to these two variables. However, such grouping did not show any significant improvement of correlation strength. In contrast, the opposite correlation did show in a few cases as in Figures 5.17 and 5.19. This result might have occurred due to the fact that some of these groups have a very limited number of data points available for the analysis. The very poor correlation of the data indicates that there is no apparent pattern or tendency in the Hamburg test results with respect to magnesium sulfate soundness or Micro-Deval loss in the current database. It is obvious that other factors have masked any expected influences of the aggregate durability properties. Therefore, further assembling of data by aggregate type, as expected, will not show any significant improvement of the relationship. Figures A.1 through A.18 in Appendix A are plots that illustrate the advance grouping. To perform a meaningful analysis of this nature, the data have to be collected through a controlled experiment based on proper statistical procedure. The dominant factors such as binder type, testing temperature, aggregate size and gradation, and aggregate particle shape, angularity, and surface texture as well as hot mix asphalt mixture design have to be controlled in the experimental program.

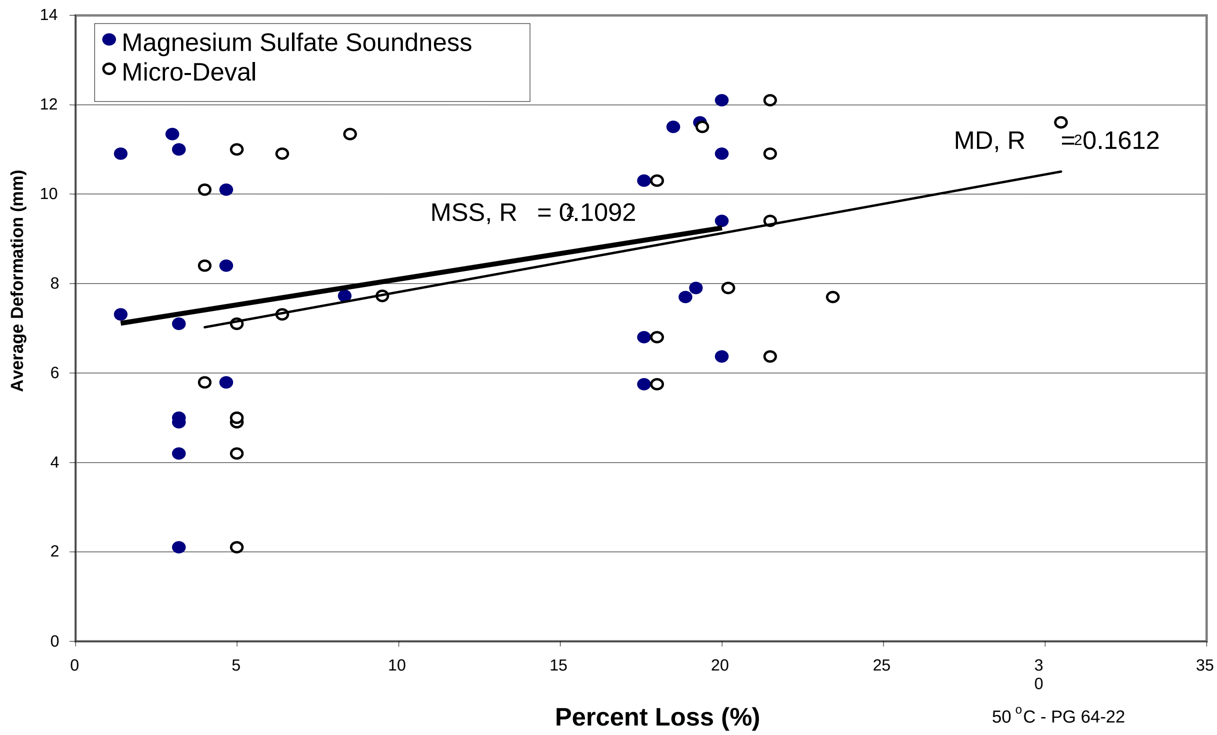


Figure 5.16. Average Deformation vs. MSS and MD Loss for Passed Samples (PG 64-22).

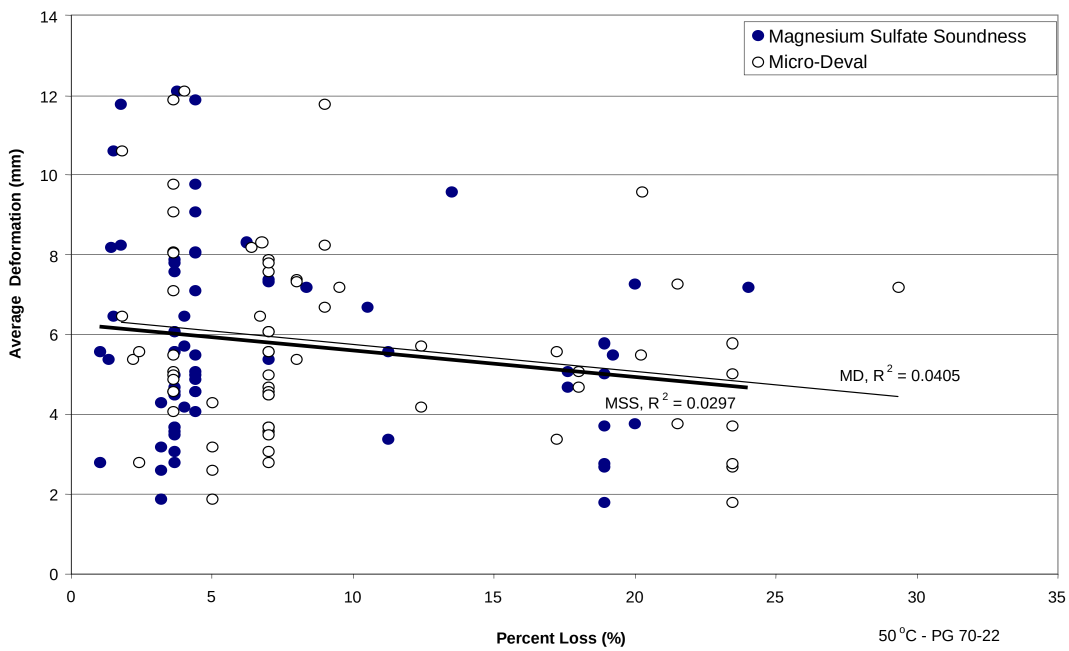


Figure 5.17. Average Deformation vs. MSS and MD Loss for Passed Samples (PG 70-22).

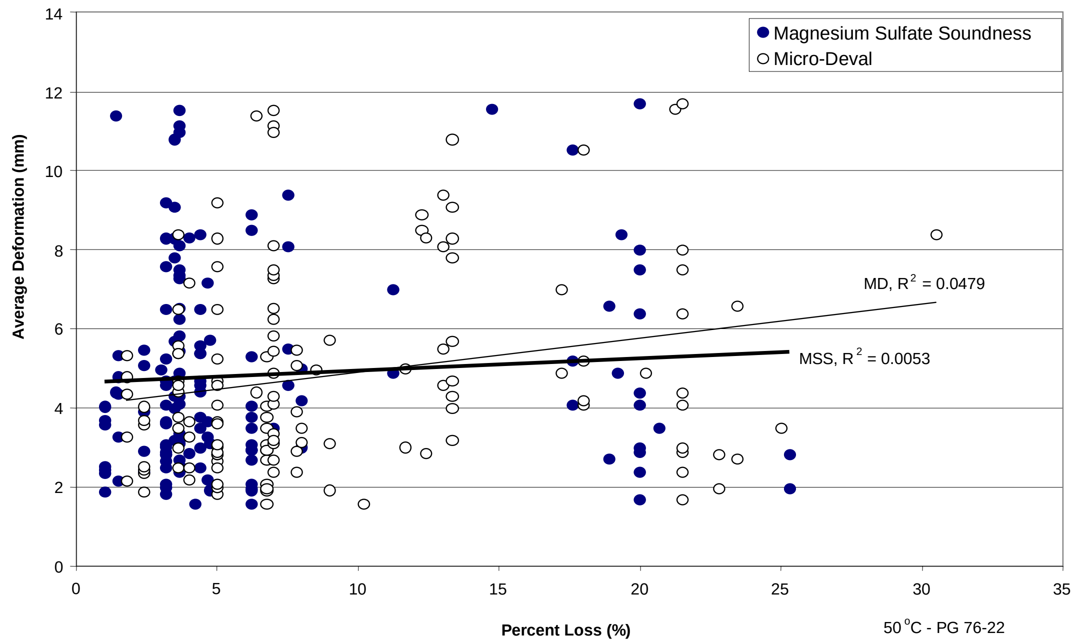


Figure 5.18. Average Deformation vs. MSS and MD Loss for Passed Samples (PG 76-22).

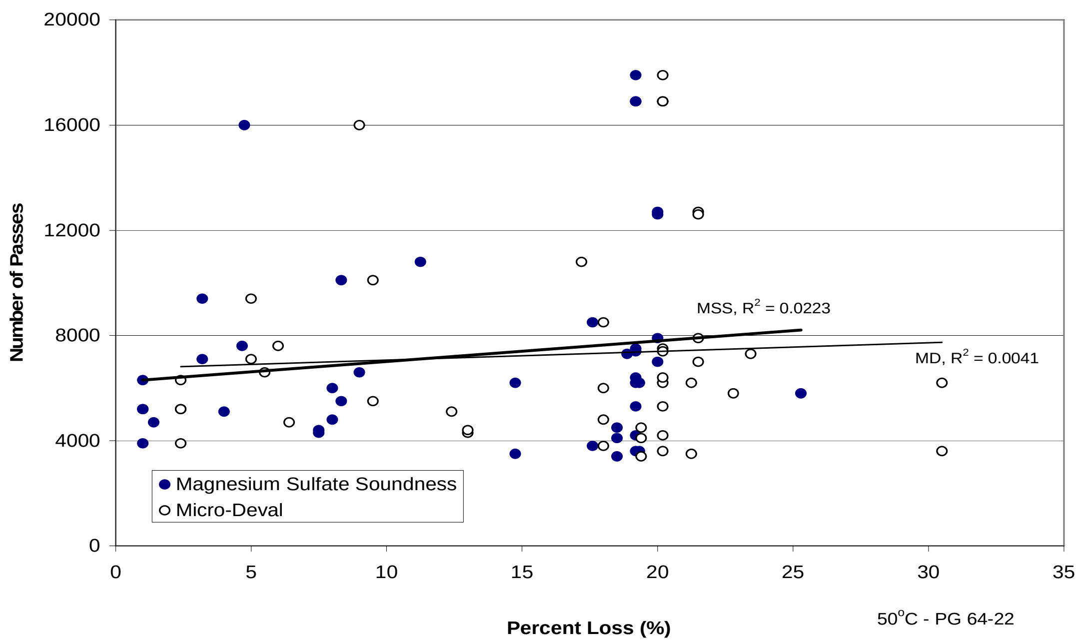


Figure 5.19. Number of Passes vs. MSS and MD Loss for Failed Samples (PG 64-22).

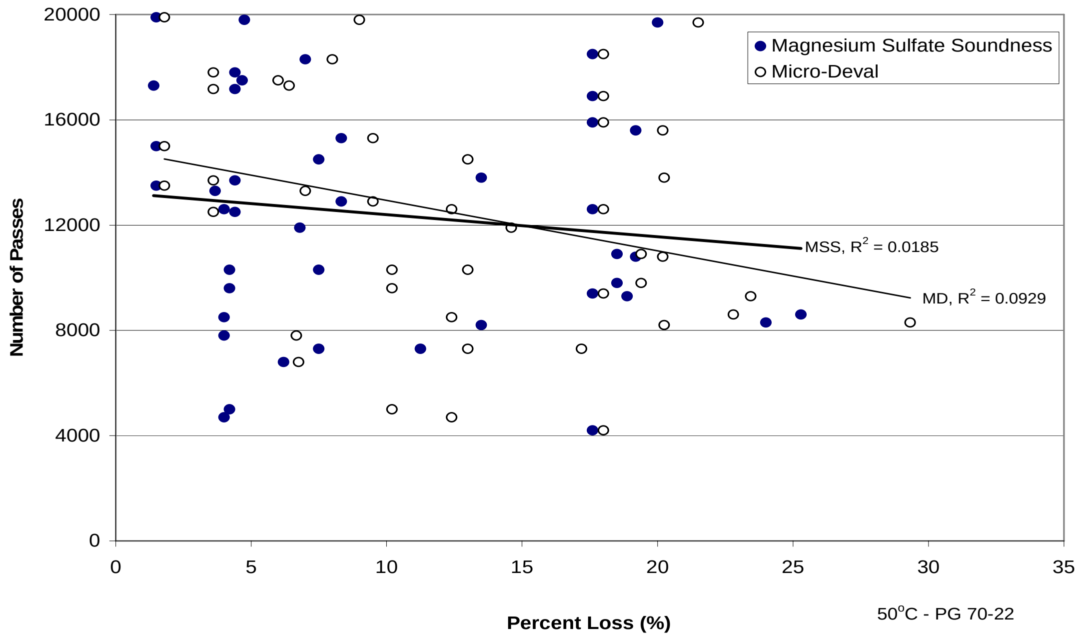


Figure 5.20. Number of Passes vs. MSS and MD Loss for Failed Samples (PG 70-22).

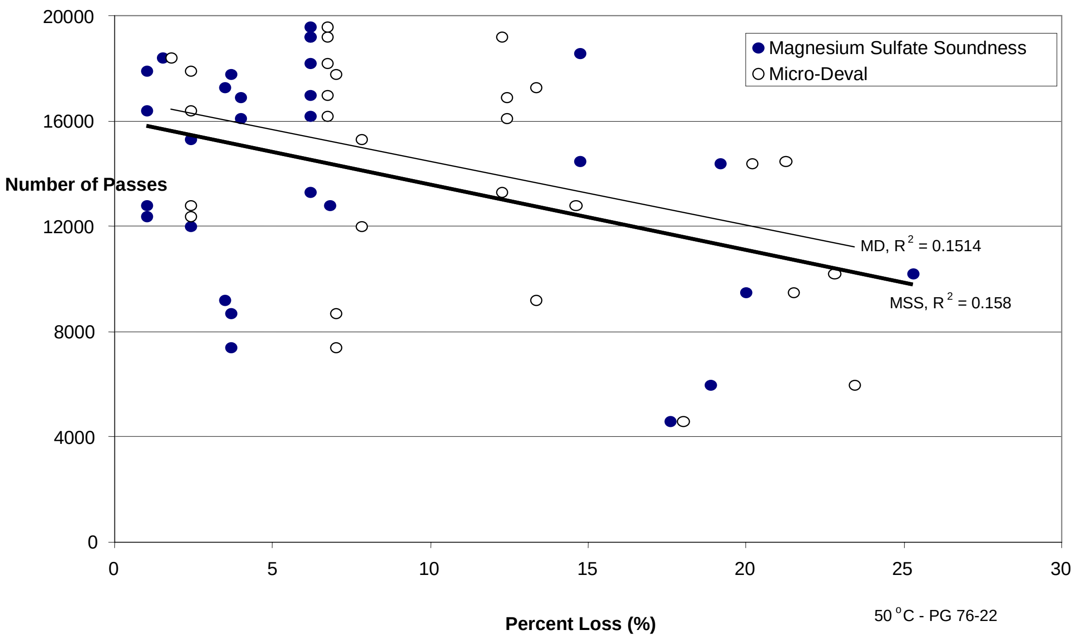


Figure 5.21. Number of Passes vs. MSS and MD Loss for Failed Samples (PG 76-22).

Relative Ranking of Aggregate Quality

The durability property of aggregates shows an appropriate trend with final Hamburg results in terms of central tendency. This trend suggests that there is an obvious effect of aggregate durability on Hamburg test results. However, the one-by-one relationship as illustrated by scattergrams showed either very weak tendencies or no pattern in the Hamburg test with respect to magnesium sulfate soundness or the Micro-Deval test results. The relatively flat regression line and very low R^2 value indicate that aggregate durability does not correlate well with the results obtained from the Hamburg test. Therefore, another way to investigate the effect of durability is to compare the performance of two extreme groups. The first group will consist of good performing aggregate with MSS and MD percent loss of less than or equal to 4 percent. The other group will consist of bad performing aggregate with MSS and MD loss greater than or equal to 20 percent.

MSS and MD loss of less than 4 percent represents good aggregate and is expected to perform adequately better than those with loss values greater than 20 percent, which are considered to have poor aggregate quality. Such grouping is expected to be effective in separating good and poor aggregates and, therefore, it would facilitate identifying any distinct difference between the two groups.

Figure 5.22 is a plot of asphalt performance based on average deformation versus aggregate type at MSS loss less than or equal to 4 percent. The plot shows only the samples that passed the test at 50 ^{o}C. The vertical axis on the left side shows the Hamburg final test results — average deformation in millimeters — whereas the horizontal axis shows the types of aggregate falling in this specific extreme group. The right axis, on the other hand, shows the MSS values for each aggregate type and is used as a means to correlate Hamburg test results with aggregate durability results. The regression line with the R^2 value shows the direction and strength of the relationship between Hamburg test results and the variation in aggregate types with respect to their durability properties.

Figure 5.22 suggests that at this range of durability, gravel appears to be more dominant with lower rut depth and lower MSS value. Igneous, on the other hand, seems to be the next best performer with a relatively higher average deformation and MSS value. Limestone-dolomite, as expected, came last with the highest average deformation and MSS value. This confirms the trend observed previously; the lower the MSS loss the lower the corresponding deformation. However, the strength of correlation between average deformation and aggregate type is very weak, suggesting that aggregate type may not be the major variable influencing the Hamburg test results. The plot also indicates that at this specific range of MSS values, the Hamburg test, to some extent, is capable of segregating aggregates similar to their field performance history. However, relative comparisons as presented in Figures 5.22 through 5.29 show that MD is better in depicting the trend in which the higher the MD loss, the higher the corresponding deformation.

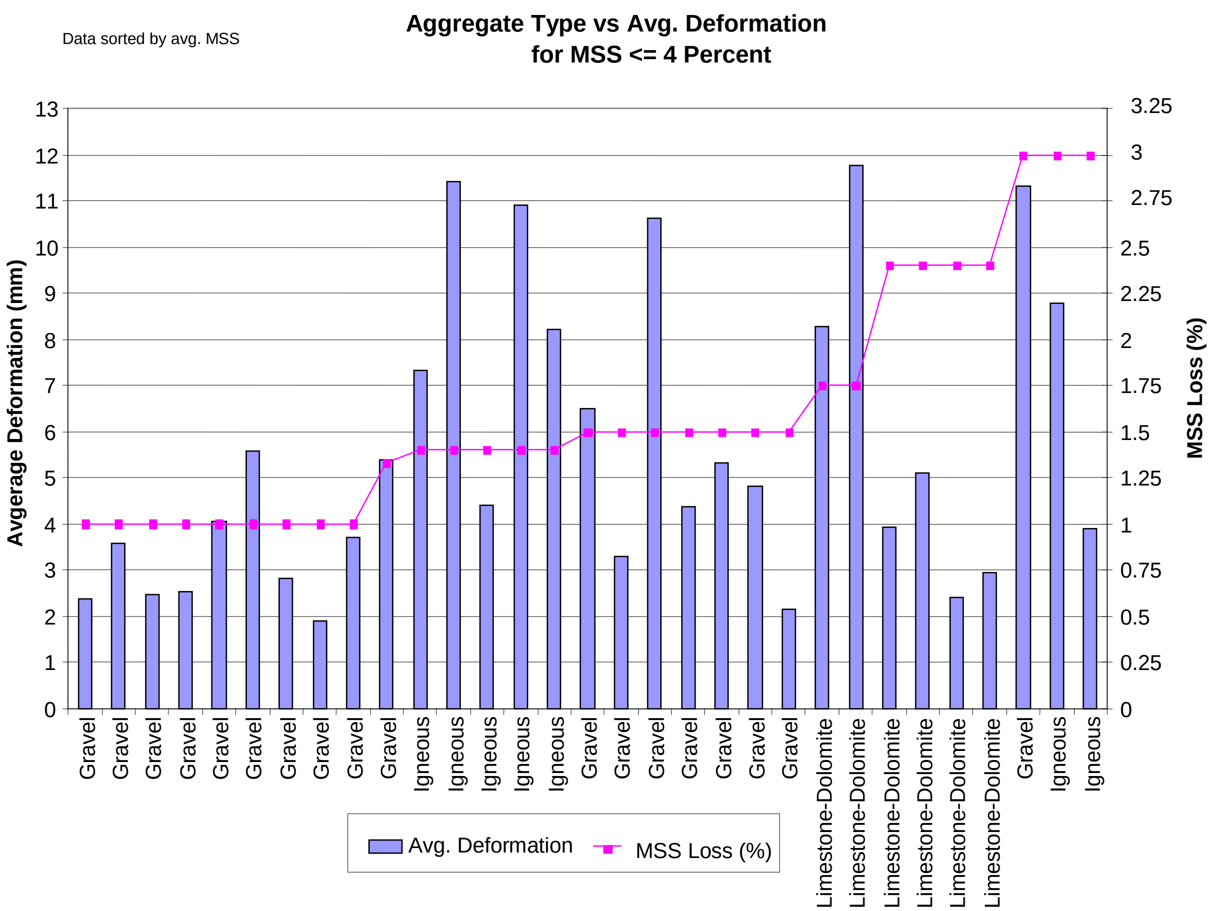


Figure 5.22. Average Deformation for Passed Samples vs. Aggregate Type at MSS ≤ 4 Percent.

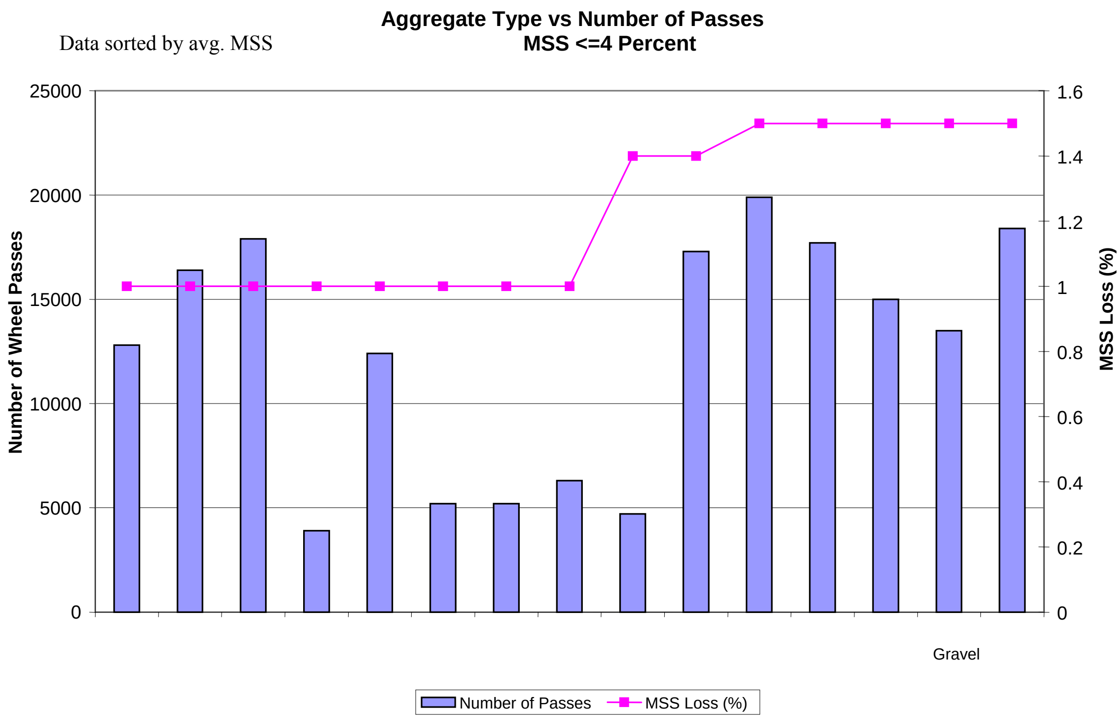


Figure 5.23. Number of Wheel Passes for Failed Samples vs. Aggregate Type at MSS ≤ 4 Percent.

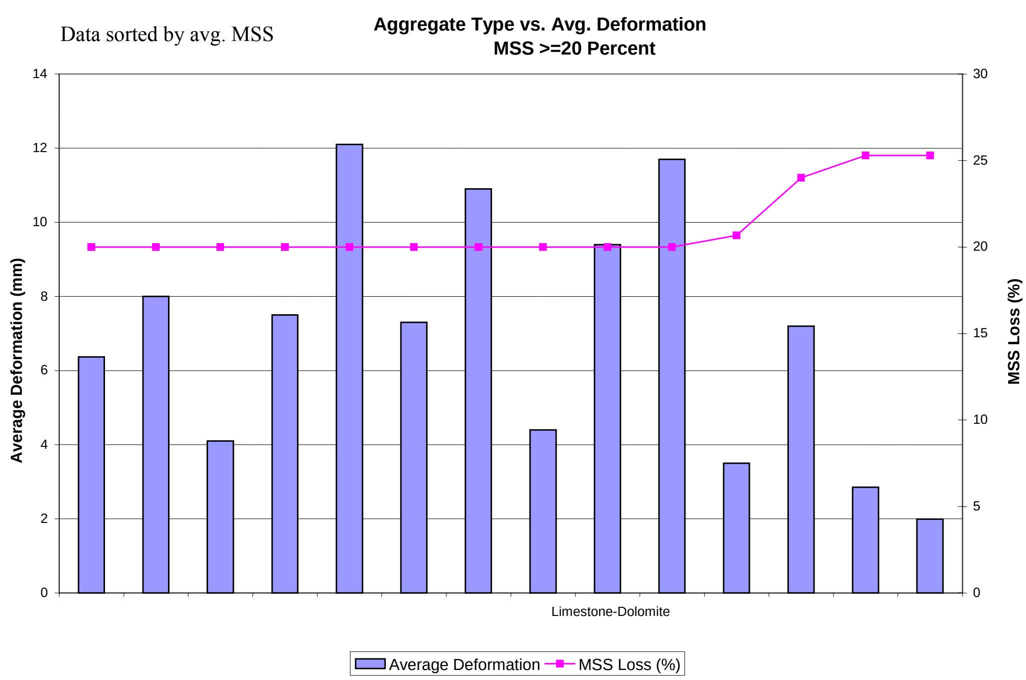


Figure 5.24. Average Deformation for Passed Samples vs. Aggregate Type at MSS ≥ 20 Percent.

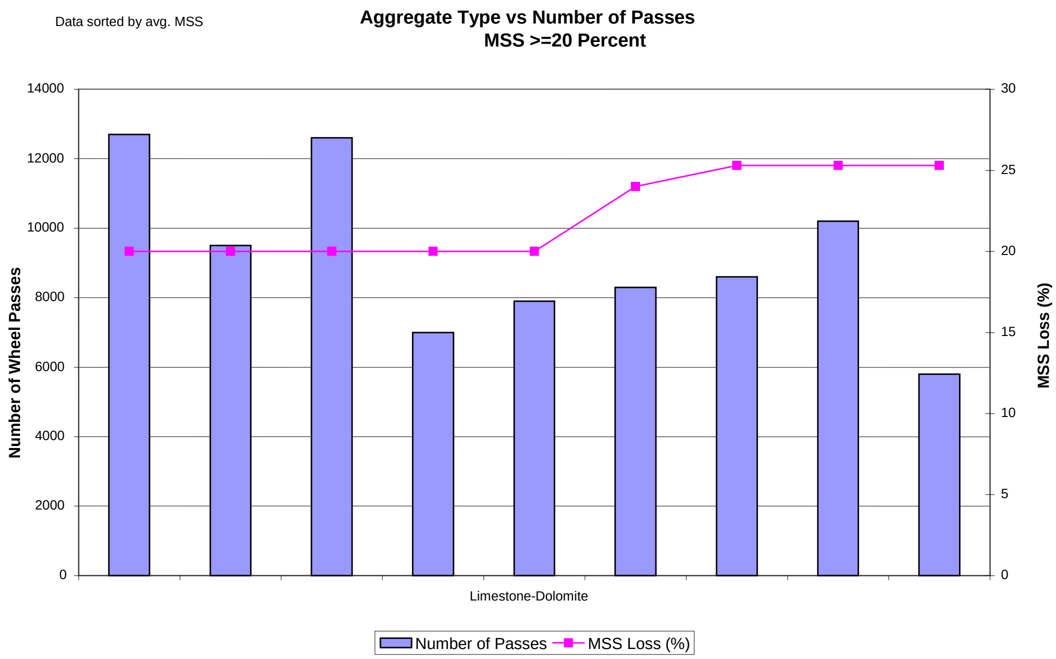


Figure 5.25. Number of Wheel Passes for Failed Samples vs. Aggregate Type at MSS ≥ 20 Percent.

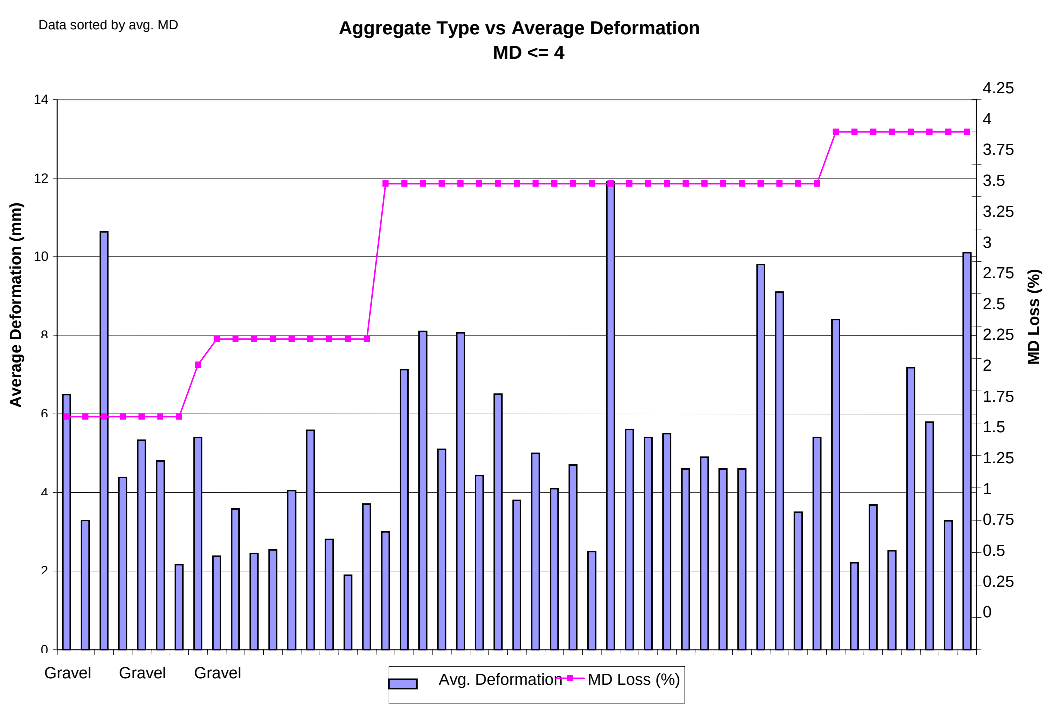


Figure 5.26. Average Deformation for Passed Samples vs. Aggregate Type at MD ≤ 4 Percent.

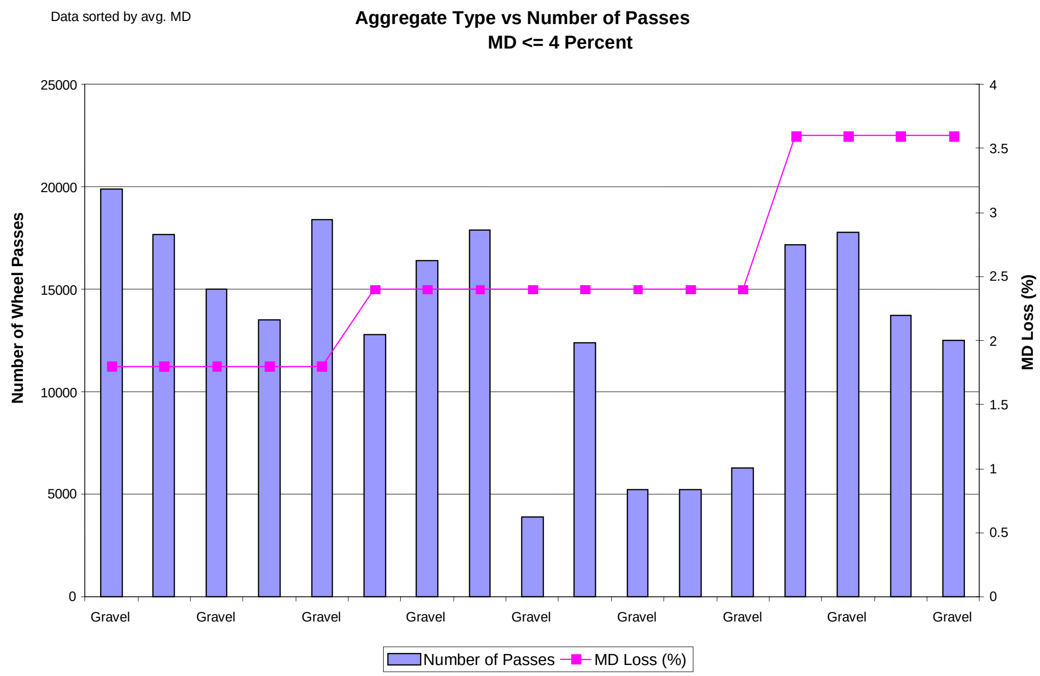


Figure 5.27. Number of Wheel Passes for Failed Samples vs. Aggregate Type at MD ≤ 4 Percent.

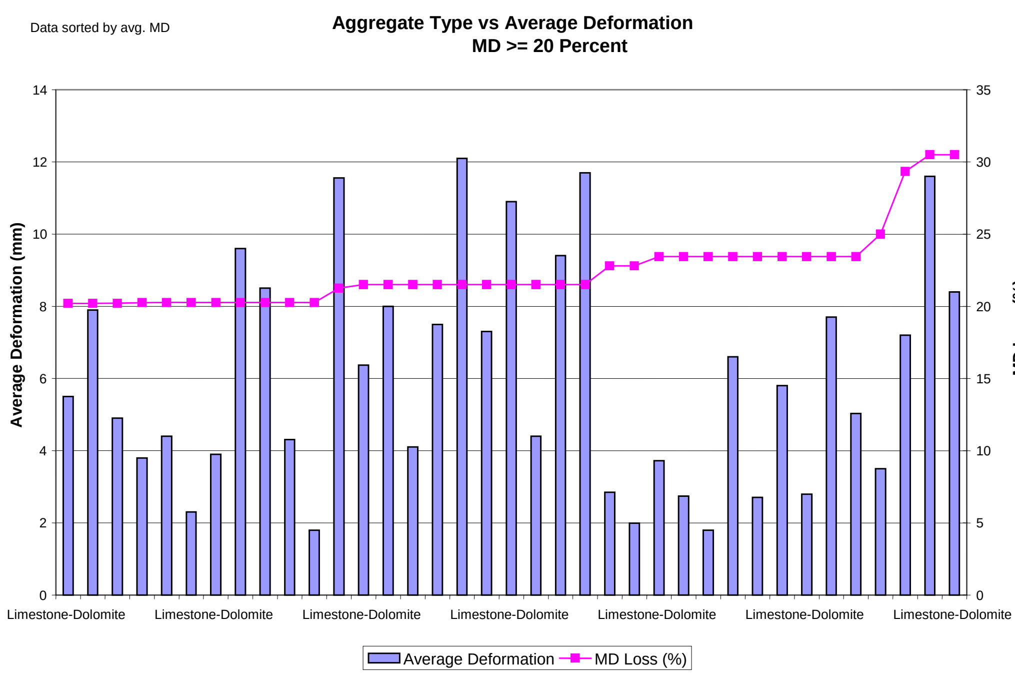


Figure 5.28. Average Deformation for Passed Samples vs. Aggregate Type at MD ≥ 20 Percent.

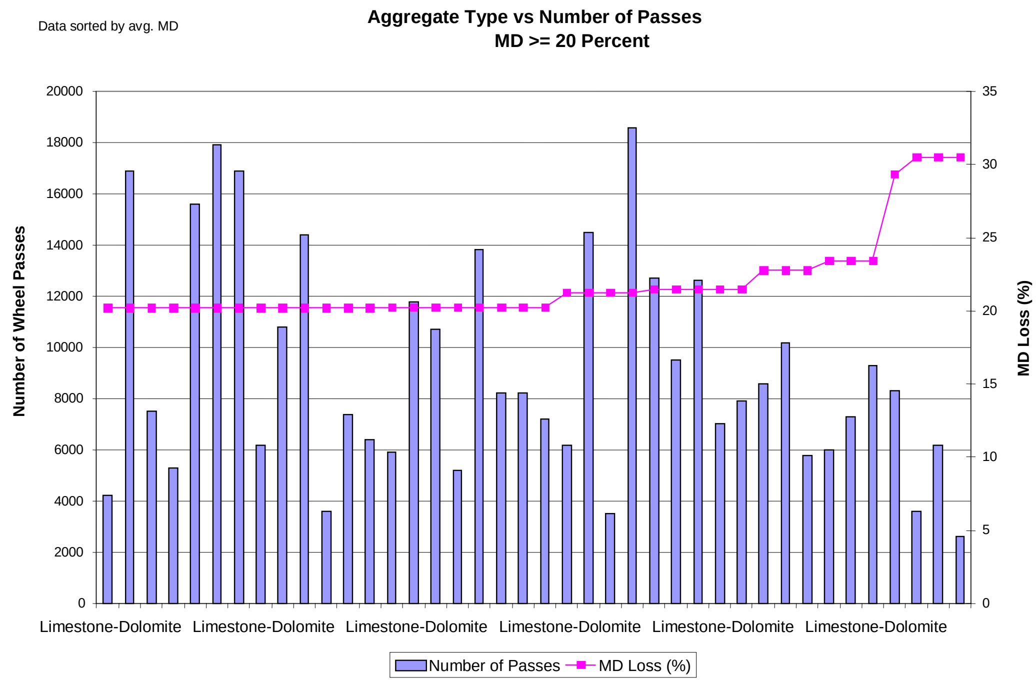


Figure 5.29. Number of Wheel Passes for Failed Samples vs. Aggregate Type at MD ≥ 20 Percent.

Table 5.6 summarizes the information presented in the previous figures. The table shows the percent of passed and failed samples within each extreme group. No apparent trend is obvious, which may be due to limited data availability. However, it is clear that for MSS and MD less than or equal to 4 percent, the predominant aggregates are either gravel or igneous, whereas in the other extreme group when MSS and MD are larger than or equal to 20 percent, the only aggregate shown in this group was the limestone-dolomite. This again confirms our notion that gravel and igneous are durable aggregates while limestone-dolomite is less durable and, accordingly, falls within the group with MSS and MD loss greater than 20 percent.

Table 5.6. Aggregate Durability for Extreme MSS and MD Groups.

Aggregate Type	MSS <= 4 @ 50 ^oC						MSS >= 20 @ 50 ^oC					
	Passed Samples			Failed Samples			Passed Samples			Failed Samples		
	N	%	Avg. Def.	N	%	No. of Passes	N	%	Avg. Def.	N	%	No. of Passes
Igneous	70	88.6	5.22	9	11.4	10522.2	0	---	---	0	---	---
Gravel	20	58.8	4.59	14	41.2	12314.3	0	---	---	0	---	---
Limestone-dolomite	17	73.9	5.88	6	26.1	10650	14	60.9	6.95	9	39.1	9177.8

Aggregate Type	MD <= 4 @ 50 ^oC						MD >= 20 @ 50 ^oC					
	Passed Samples			Failed Samples			Passed Samples			Failed Samples		
	N	%	Avg. Def.	N	%	No. of Passes	N	%	Avg. Def.	N	%	No. of Passes
Igneous	0	---	---	0	---	---	0	--	--	0	---	----
Gravel	49	74.2	5.14	17	25.8	13280.6	0	--	--	0	---	----
Limestone-dolomite	0	--	--	0	---	----	6	85.7	3.67	1	14.3	19700

In general, this grouping approach helps categorize good and poor aggregates. Gravel and Igneous, as expected, are good performing aggregates and therefore had MD and MSS values below 4 percent loss; whereas limestone-dolomite aggregate is a poorer performing aggregate and hence has MD and MSS values in excess of 20 percent loss. This suggests that critical MD and MSS test values of 10 percent loss would identify good performing aggregates, whereas values ranging from 10–20 percent loss are appropriate to identify fair performing aggregates. MD and MSS values of 20 percent loss, on the other hand, are appropriate to exclude the aggregates identified as poorer performers. Tables 5.7 and 5.8 show the passed and failed samples categorized based on MSS and MD values and their corresponding Hamburg test results. Figures 5.30 through 5.32 are graphical presentations of information presented in Tables 5.7 and 5.8.

Table 5.7. Passed Samples Categorized Based on MSS and MD Values.

	Passed Samples					
	MSS			MD		
Category	N	%	Avg. Deformation	N	%	Avg. Deformation
0-5	176	56.7	5.28	86	27.7	4.96
5-10	49	15.8	4.75	105	33.9	5.17
10-15	20	6.5	4.79	33	10.7	5.47
15-20	59	19.0	5.67	24	7.7	5.75
20-25	4	1.3	4.66	55	17.7	5.14
25-30	2	0.7	2.42	2	0.7	4.67
30-35	0	0	---	5	1.6	7.20
Total	310	100		310		

Table 5.8. Failed Samples Categorized Based on MSS and MD Values.

	Failed Samples					
	MSS			MD		
Category	N	%	Avg. Wheel Passes	N	%	Avg. Wheel Passes
0-5	56	37.1	11,742.3	22	15.0	12,871.4
5-10	33	21.9	11,797.9	39	26.5	11,866.7
10-15	14	9.2	9421.4	26	17.7	11,146.2
15-20	44	29.1	10,386.2	20	13.6	9605.0
20-25	1	0.7	8300	40	27.2	10,475.0
25-30	3	2.0	8200	1	0.7	8300.0
30-35	0	0	---	3	2.0	4133.3
Total	151			151		

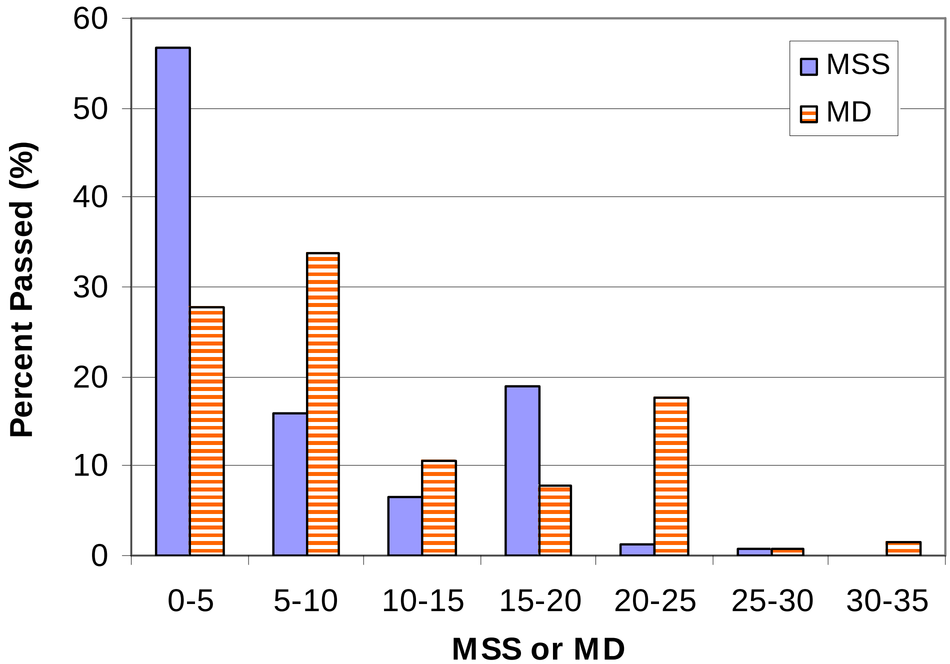


Figure 5.30. Percent Passed in Each MSS and MD Category.

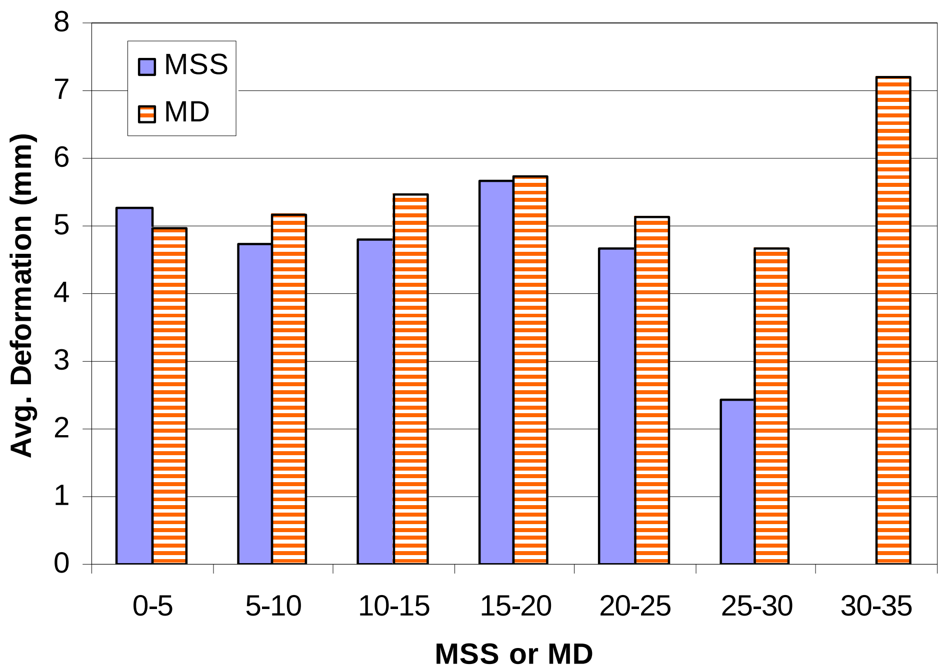


Figure 5.31. Average Deformation for Passed Samples Classified by MSS and MD.

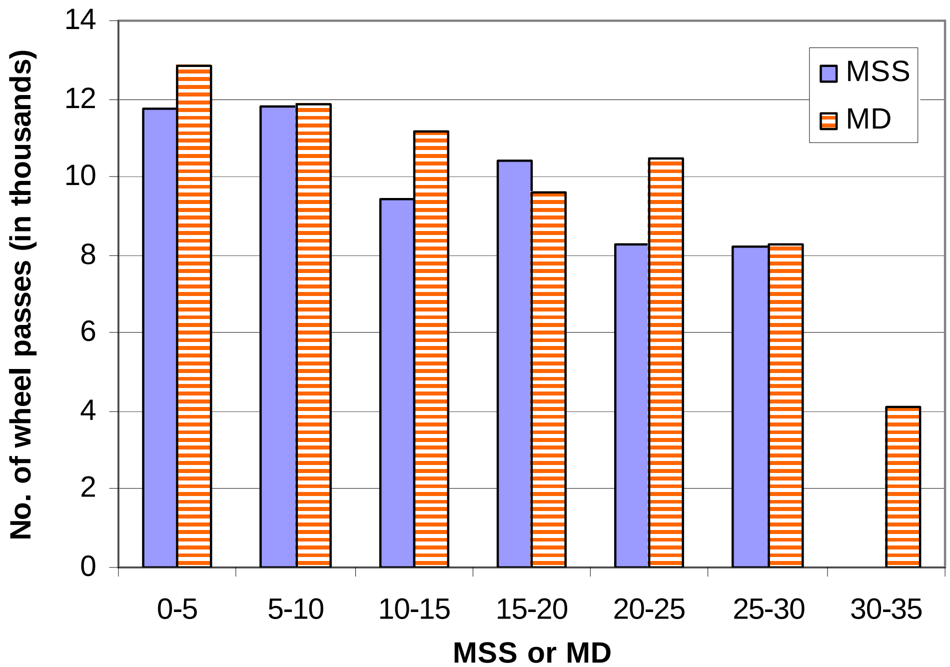


Figure 5.32. Number of Wheel Passes for Failed Samples Classified by MSS and MD.

Specification for Aggregate Quality Selection

Results from the Hamburg test show, to some extent, compatibility with durability test results as presented by MSS and MD values. Relative comparisons of central tendency as measured by the mean show that the Hamburg test is capable of identifying aggregates with different durability levels. The ability of the Hamburg test to categorize aggregate quality, in particular the durability characteristics similar to MSS and MD, suggests that a ranking system may be developed for the Hamburg test. The ranking system suggested consists of four different rates: very good, good, fair, and poor. Table 5.9 shows the ranking system specifications for both the passed and failed samples. The average deformation can be used to further classify samples that passed the test. For example, a sample that "passed" is rated "very good" because it achieved 20,000 wheel passes. However, to further rank all samples that passed the test, these samples have to be segregated based on their corresponding deformations. Hence, if the corresponding deformation is between 0 and 7.5 mm, the aggregate is considered "very good." If the average deformation is between 10 and 12.5 mm, the aggregate quality is considered "fair" even though it passed the Hamburg test. In other words, a sample could pass the test and can still be ranked.

Table 5.9. Ranking Specifications for Categorizing Aggregate Types.

Ranking Rates	Ranking Range	
	Number of Wheel Passes	Average Deformation (mm)
Very Good	20,000	0 – 7.5
Good	18,500 – 20,000	7.5 - 10
Fair	12,500 – 18,500	10 – 12.5
Poor	0 – 12,500	12.5

Tables 5.10 and 5.11 show the Hamburg database categorized based on the suggested ranking system. There are 310 samples that passed the test and 152 samples that failed that test. Among the samples that failed the test, only 7.9 percent ranked as "good," 31.8 percent ranked "fair," and 60.3 percent ranked as poor; whereas, for the passed samples, only 7.7 percent ranked "fair," 13.5 percent ranked "good," and 78.7 percent ranked "very good."

Table 5.10. Evaluation of Aggregate Performance Based on Number of Wheel Passes.

No. of Wheel Passes	Pass/Fail Criteria	Performance Rate Based on Avg. Deformation	Freq.	(%)
= 20,000	Passed	Very Good	310	100
< 20,000	Failed	Good	12	7.9
		Fair	48	31.8
		Poor	91	60.3
		Total	152	100

Table 5.11. Evaluation of Aggregate Performance Based on Average Deformation.

Average Deformation	Pass/Fail Criteria	Performance Rate Based on Avg. Deformation	Freq.	(%)
= 12.5	Failed	Poor	151	100
< 12.5	Passed	Very Good	244	78.7
		Good	42	13.5
		Fair	24	7.7
		Total	310	100

CHAPTER 6. INFLUENCE OF DIFFERENT FACTORS ON HWTD PERFORMANCE

This chapter outlines statistical analyses performed to investigate whether the Hamburg wheel-tracking device can be used to evaluate the influence of asphalt concrete mixture aggregate types on Hamburg rutting performance. Currently, specific results from HWTD tests are recorded in a database maintained by TxDOT. A perceived shortcoming of this database is that the performance-related data are a single result obtained from Hamburg tests, which may not accentuate the influence of aggregate types on performance. It is possible that different parameters obtained from Hamburg test rutting curves may better describe the influence of aggregate type on performance. This chapter briefly outlines the content of the HWTD database and reports analyses performed to investigate HWTD rutting curve parameters toward identifying the influence of aggregate type on Hamburg rutting performance.

Statistical Analysis

A perceived shortcoming of the HWTD database is that it records limited performance-related data. Only the maximum rutting after the application of 20,000 load cycles or the number of cycles until failure of the tested specimens is routinely recorded. To better evaluate the influence of aggregate type on Hamburg rutting performance, a statistical analysis was done on data collected from available Hamburg rutting curves, such as the example shown in Figure 6.1.

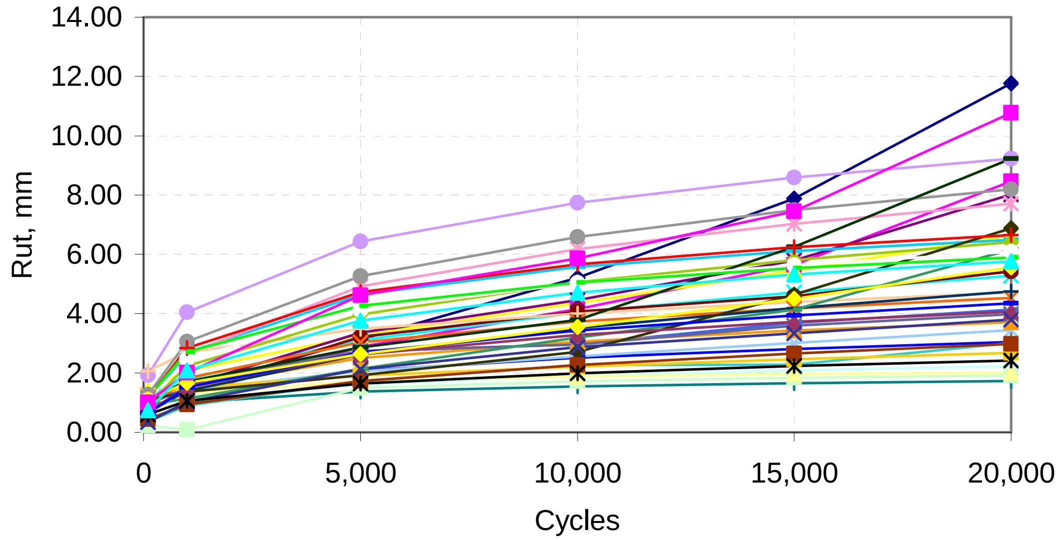


Figure 6.1. Hamburg Rutting Results of Specimens that Passed.

In the analysis, it was deemed necessary to group the available data in terms of mixture type, binder grade, aggregate type, and additive. Each of these variables has an influence on Hamburg rutting performance, and it is necessary to isolate the groupings to distinguish the influence of aggregate type. Experience with Hamburg testing indicates that the influence of the different mix related variables is related to the degree with which these tend to stiffen the mix. In general, the greater the stiffening effect, the better the Hamburg performance of the mix.

Binder grade is the dominant factor influencing the Hamburg performance of asphalt concrete mixes. The stiffer the binder grade, the stiffer the mix. Stiffer materials are generally more resistant to rutting and less susceptible to moisture damage. Additives, particularly lime, increase the stiffness of asphalt mixes; mixes with lime additives generally perform well in the Hamburg test, often regardless of mix type or aggregate type. Asphalt mixes used in Texas are generally dense graded or have stone skeleton structures. These mixes provide added resistance to rutting to the extent that it is difficult to distinguish the relative Hamburg rutting performance of different asphalt mix types. The influence of aggregate type on Hamburg rutting performance, however, is discernible, particularly when used with mixes having less stiff binders.

The influence of aggregate type on Hamburg rutting performance may be related to the interaction between the aggregate and the asphalt binder in the mix. Additives such as lime strengthen the physical-chemical bond between aggregates and binders and enhance the resistance of the mix to the stripping influence of water. Aggregate hardness, surface texture, and shape influence the inter-particle friction characteristics and hence the rutting resistance of asphalt mixes.

Hamburg Rutting Curve Data

The Hamburg test records used for the statistical analyses were obtained from TxDOT-archived computer files. The rutting curve records are usually not filed since the only performance data recorded as part of the HWTD database are the maximum rutting after the application of 20,000 cycles or the number of cycles until failure of the specimens. The available data are, therefore, limited, and the records are not necessarily representative. A total of 57 rutting curve records were salvaged, comprising data from a variety of aggregate types (AGG), mix types (MIX), binder grade types (PG), and additive types (ADD). Table 6.1 summarizes the available data and the number of records available for each of these factors. The records are of Hamburg tests done at a temperature of 50 °C.

Table 6.1. Available Records and Factor Counts.

AGG	Count	MIX	Count	PG	Count	ADD	Count
Granite	3	CMHB-C	4	PG 70-22	22	Lime	42
Gravel	13	Superpave	8	PG 76-22	35	Liquid	15
Igneous	6	Type-B	3				
Limestone	25	Type-C	12				
Quartzite	5	Type-D	30				
Sandstone	5						

The available records do not allow for a balanced analysis of variance (ANOVA). For this reason, it is not possible to evaluate interactions among the different factors. A full or fractional factorial experiment would be necessary for this evaluation. Given the restrictive scope, the analyses focused on investigating whether different responses based on Hamburg rutting curve parameters could be used to better investigate the influence of aggregate type on rutting performance.

The parameters investigated include:

- rutting at specific cycles (100, 1000, 10,000, 15,000, and 20,000),
- slope of the rutting curve at these cycles, and
- area beneath the rutting curve at these cycles.

These responses are termed R1, R2, R3, R4, and R5 for the ruts at 100, 1000, 10,000, 15,000, and 20,000 cycles, respectively; S1, S2, S3, S4, and S5 for the slopes; and A1, A2, A3, A4, and A5 areas at the cycle counts.

Appendix A contains the response data collected from the available records. Figures 6.1 and 6.2 show the Hamburg rutting curves of the tested specimens that passed, i.e., rutting less than 12.5 mm after 20,000 cycles, and those that failed, respectively. The latter is based on data extrapolated based on best-fit trends to allow responses to be determined up to 20,000 cycles. Table 6.2 summarizes these response data. Units for the different response variables are mm (rutting), mm/cycle (slope) and mm cycle (area).

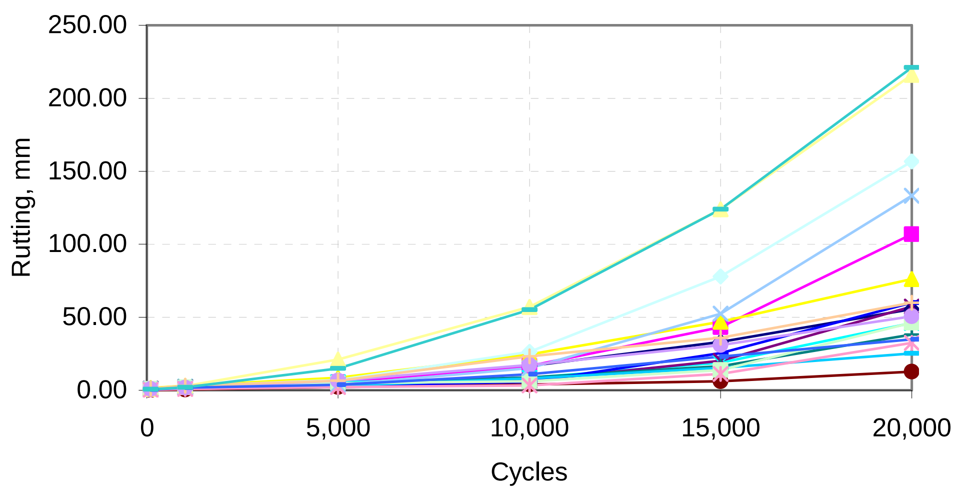


Figure 6.2. Hamburg Rutting Results of Specimens that Failed.

Table 6.2. Summary of Response Data.

Variable	N	Mean	Median	Std	Minimum	Maximum	Q1	Q3
R1	57	0.8867	0.916	0.3721	0.04	2.06	0.6685	1.098
R2	57	1.7863	1.616	0.7481	0.087	4.05	1.315	2.325
R3	57	4.041	3.218	3.165	1.374	21.06	2.235	4.684
R4	57	8.1	4.36	10.84	1.55	57	3.01	7.16
R5	57	15.72	5.64	25.59	1.65	124	3.71	15.96
R6	57	28.76	6.65	48.95	1.73	221	4.1	36.64
S1	57	0.00205	0.00163	0.00157	0.00017	0.0066	0.00079	0.00281
S2	57	0.00069	0.00061	0.00036	0.00004	0.00155	0.00037	0.00098
S3	57	0.00068	0.00025	0.0017	0	0.012	0.00013	0.00043
S4	57	0.0011	0.00018	0.00229	0.00001	0.011	0.0001	0.00099
S5	57	0.00201	0.00016	0.0038	0.00001	0.016	0.00008	0.00257
S6	57	0.00354	0.00014	0.00653	0	0.0244	0.00006	0.00464
A1	57	75.65	75.9	33.65	2.11	189	50	98.2
A2	57	1328.3	1255	561.4	14.5	3079	1007.5	1665
A3	57	12,949	11,067	6019	5469	35,199	8336	16,216
A4	57	41,875	31,289	36,230	13,111	208,287	21,254	45,638
A5	57	99,144	56,295	123,217	21,125	651,400	40,459	97,598
A6	57	204,343	90,787	298,123	66	1,490,000	61,013	228,607

Results of ANOVA

Appendix B contains the results of an ANOVA to investigate the significance of the different factors on the response variables. The following is a summary of the pertinent findings, discussed by response parameter.

Rutting

Given the extreme variation in the rutting results, the ANOVA indicates rutting data with large standardized residuals. These data are not considered outliers and describe the very variable nature of Hamburg test results. An analysis of the rutting results at the different cycle levels indicates that PG grade and additive type are significant factors (at the 95 percent confidence level) influencing rutting after 20,000 cycles (R6). Rutting after 5000; 10,000; and 15,000 cycles appears to be significantly influenced by additive type only. Figure 6.3 shows the main effects plot for response variable R6.

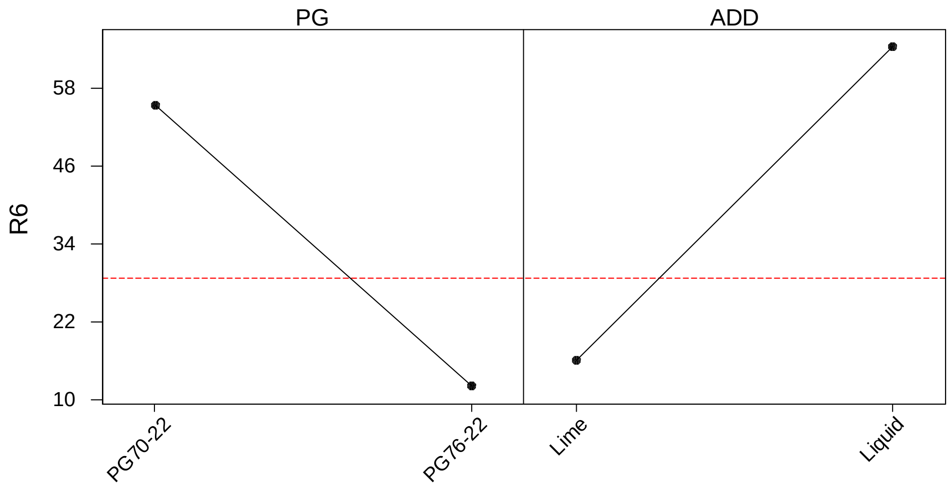


Figure 6.3. Main Effects Plot for R6.

Slope

Based on the ANOVA of the slope responses at the different cycle levels, the significant factors influencing the responses varied considerably. Aggregate and mix type were significant factors at S1; PG grade was significant at S2; additive type was significant at S3 and S4; and PG grade and additive type were significant factors at S6. Figure 6.4 shows the main effects plot of the S1 response variable as influenced by the significant aggregate- and mix-type factors. S1 represents the slope after 100 Hamburg cycles. Unfortunately, this response variable is not a good indicator of rutting performance since it is too early in the test to effectively predict rutting behavior as indicated in Figure 6.5, which shows that there is no relationship between S1 and R6, the rutting after 20,000 cycles.

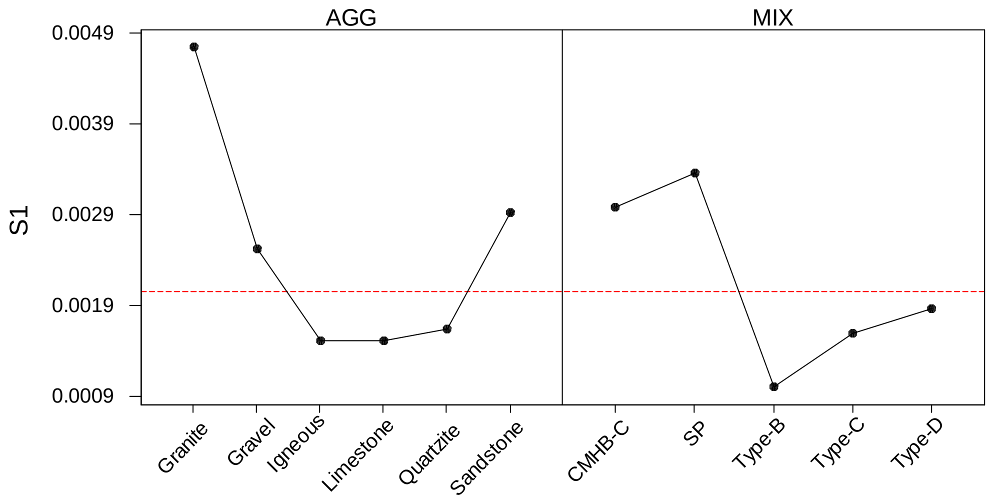


Figure 6.4. Main Effects Plot for S1.

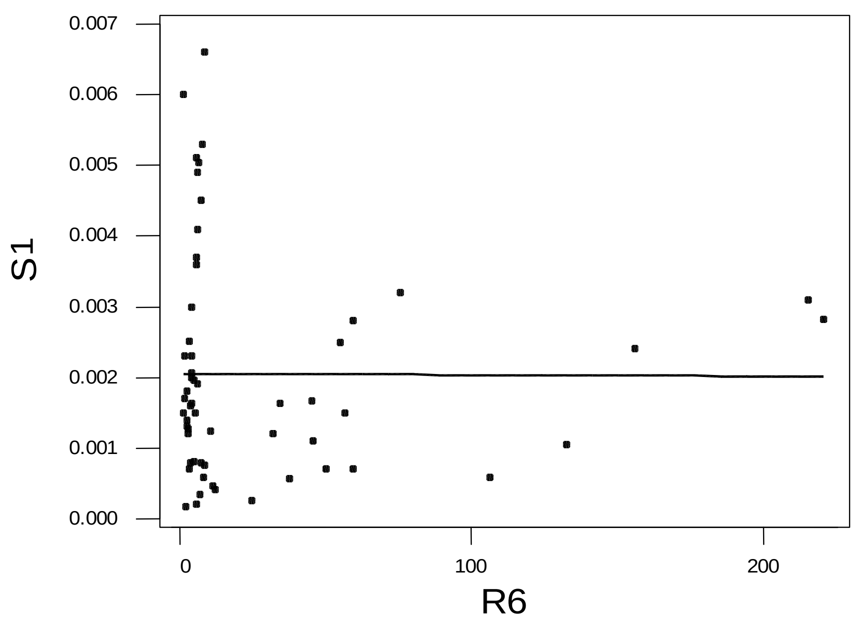


Figure 6.5. Relationship between S1 and R6.

Area

Contrary to expectations, the area responses at the different cycle levels indicated fewer significant factors than the rutting and slope responses. Aggregate type was found to be a significant factor for the A1 response, but as with S1, the response is too early in the test to effectively predict performance. Additive type was significant at A4, A5, and A6.

Discussion

Table 6.3 summarizes the significant factors found based on the ANOVA for the different response variables evaluated. In general, it may be concluded that the two factors predominantly influencing the Hamburg performance of asphalt mixes are PG grade and additive type. Hamburg performance is better at the stiffer PG grades and with the use of lime as an additive. Both of these factors would tend to stiffen the asphalt mixture. Aggregate and mix type were not found to significantly influence Hamburg performance. This finding may suggest that the Hamburg test cannot be used to effectively investigate the influence of aggregate types for asphalt mixes. It appears that the TxDOT procedure of measuring and recording rutting after 20,000 cycles alone is adequate to characterize the Hamburg rutting performance of asphalt mixes. Analyses using data relating to PG 70-22 binder and liquid additive only were considered to negate the dominant stiffening influences of PG grade and lime additives, but insufficient data were available to investigate this.

Table 6.3. Significant Factors for the Different Response Variables.

	R1	R2	R3	R4	R5	R6	S1	S2	S3	S4	S5	S6	A1	A2	A3	A4	A5	A6
PG						x		x			x	x						
AGG							x						x					
MIX							x											
ADD			x	x	x	x			x	x	x					x	x	x

In this project the effects of aggregate, binder grade, mix type, and additive on HWTD results were evaluated. The HWTD test parameters investigated included rutting, slope of the rutting curve, and the area beneath the rutting curve at specific cycles. HWTD data were obtained from TxDOT-archived computer files. Unfortunately, the available data for specific aggregate, mix type, PG grade, and additive groups were limited. Based on the results of the analysis, researchers concluded that the dominant factors influencing Hamburg test performance are those that stiffen the mix, particularly stiffer PG grades and additives such as lime. Based on the limited data, no significant effect of aggregates on HWTD test results was observed.

CHAPTER 7. CONCLUSIONS

The objective of this project was to examine the possibility of using the Hamburg wheel-tracking device to validate durability tests, such as the magnesium sulfate soundness and Micro-Deval tests. In order to accomplish this objective, two TxDOT databases were investigated: the TxDOT Hamburg test database and the aggregate properties database. The two databases were manipulated and merged together for the project analysis.

The results of this study suggest that Micro-Deval and magnesium sulfate soundness test results do not correlate well with Hamburg test results. The correlation between them was very weak, indicating that the current database does not show a pattern in the Hamburg test results in regards to MSS or MD loss. This lack of agreement may be explained in two ways. First, the effect of more dominant variables, such as binder type and test temperature, may be masking the effect of aggregate durability. Second, other variables, like aggregate angularity, aggregate particle shape, and surface texture, that are not included in the database may also have significant influence.

Due to the lack of correlation between the test results, this topic should be further researched, as the low correlation could be due to factors outside of those considered in this study. Therefore, further investigation should be performed in a controlled experiment where binder type and test temperature are kept constant, other important aggregate parameters such as aggregate angularity, shape and texture are quantified, and other Hamburg test parameters such as creep slope, stripping slope and stripping inflection point are recorded.

In the last part of this project, researchers evaluated the effects of aggregate, binder grade, mix type, and additive on HWTD results. The HWTD test parameters investigated included rutting, slope of the rutting curve, and the area beneath the rutting curve at specific cycles. HWTD data were obtained from TxDOT archived computer files. Unfortunately, the available data for specific aggregate, mix type, PG grade, and additive groups were limited. Therefore, a statistical analysis was performed to ensure an accurate evaluation of the influence of aggregate type on Hamburg rutting performance. From the results of this analysis, it may be concluded that the two factors that mainly influence the Hamburg performance of asphalt mixes are additive type and PG grade. Hamburg performance is generally better at stiffer PG grades and with an additive that stiffens the asphalt mixture. The research suggests that the affect of aggregate type on Hamburg rutting performance could be related to the interaction between the aggregate and the asphalt binder in the mix. Aggregate and mix type were not found to significantly affect Hamburg performance. This result could indicate that the Hamburg test cannot be used to effectively study the influence of aggregate types on asphalt mixes.

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APPENDIX A:
ANALYSIS OF MS AND MD VALUES

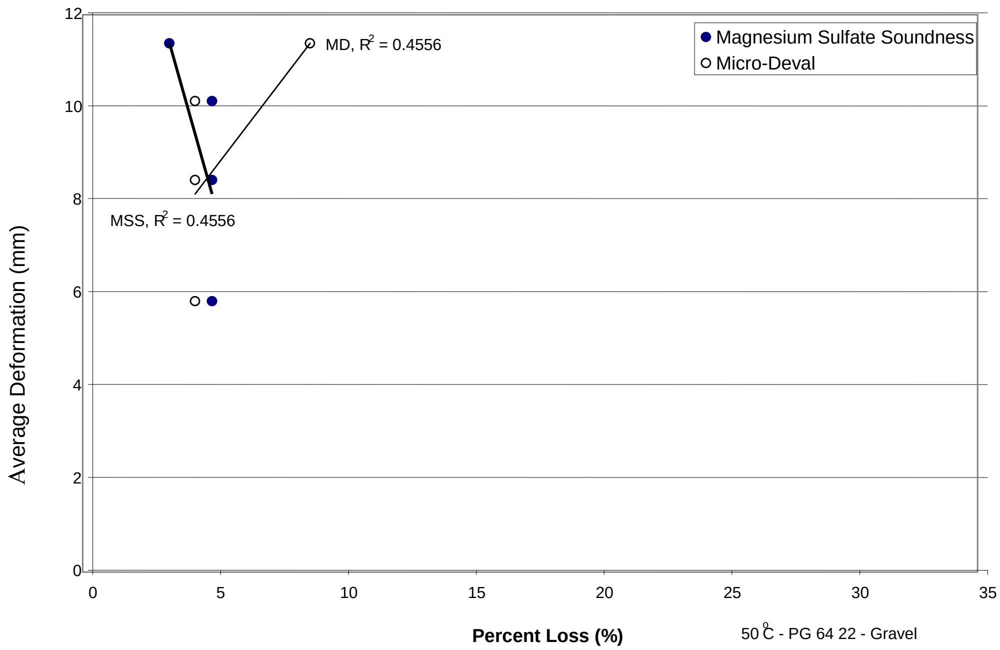

Figure A-1. Average Deformation vs. Percent Loss for Passed Samples - Gravel.

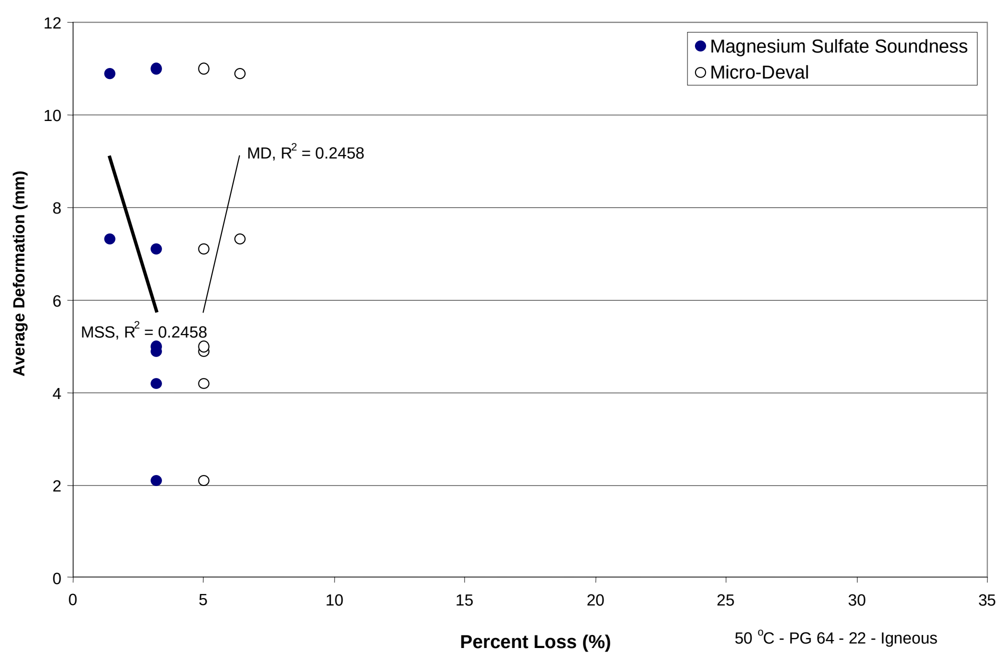

Figure A-2. Average Deformation vs. Percent Loss for Passed Samples - Igneous.

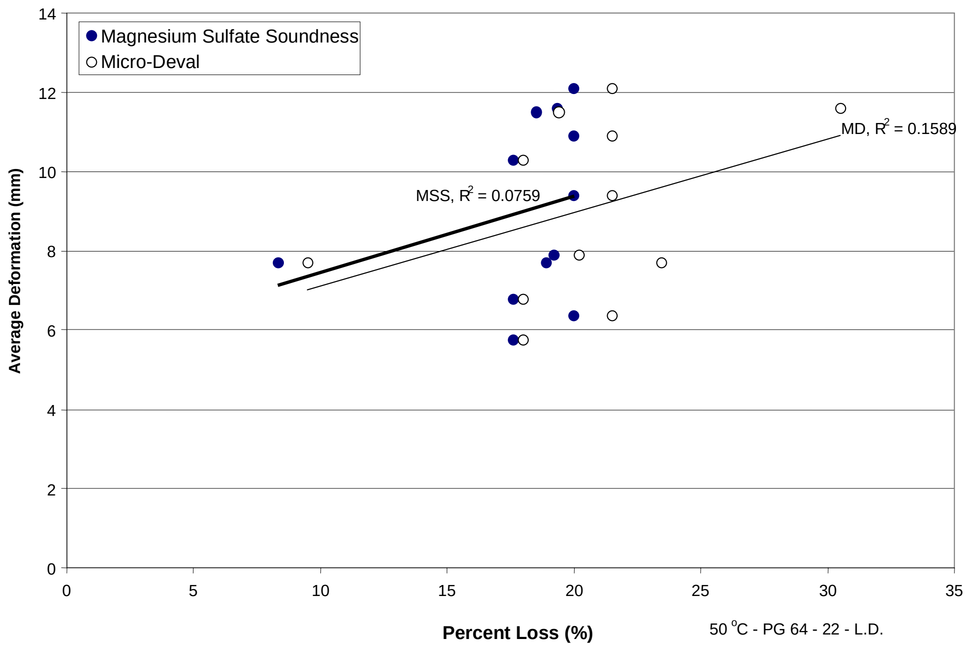

Figure A-3. Average Deformation vs. Percent Loss for Passed Samples - L.D.

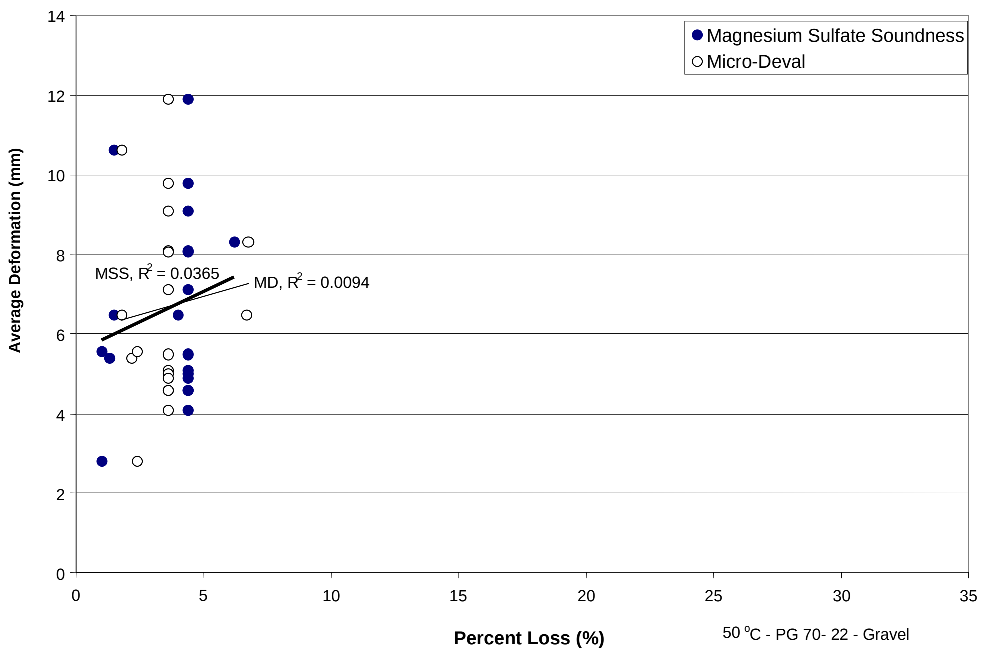

Figure A-4. Average Deformation vs. Percent Loss for Passed Samples - Gravel.

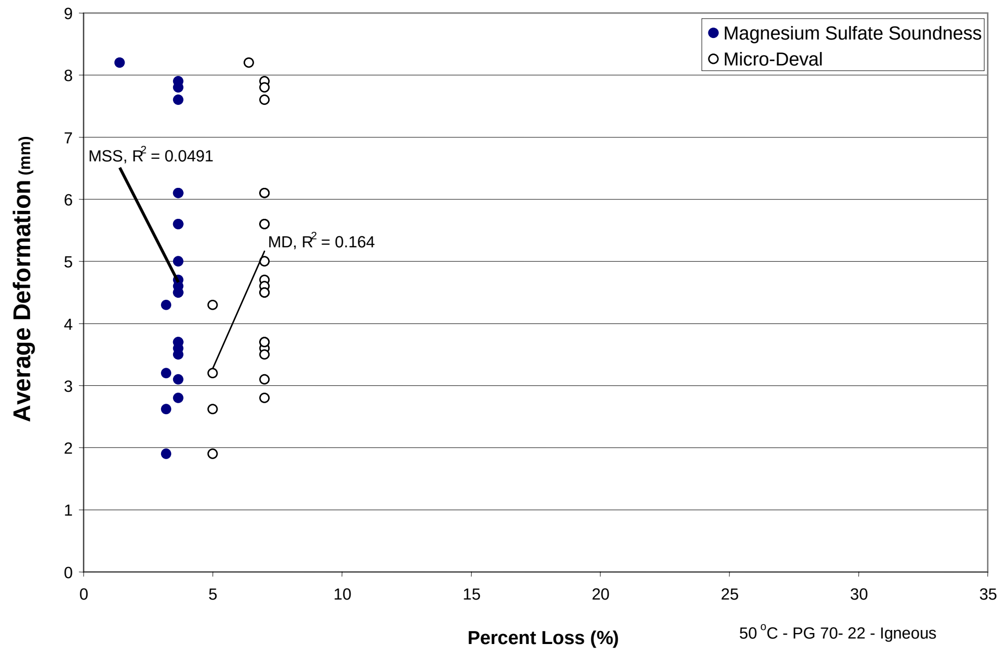

Figure A-5. Average Deformation vs. Percent Loss for Passed Samples - Igneous.

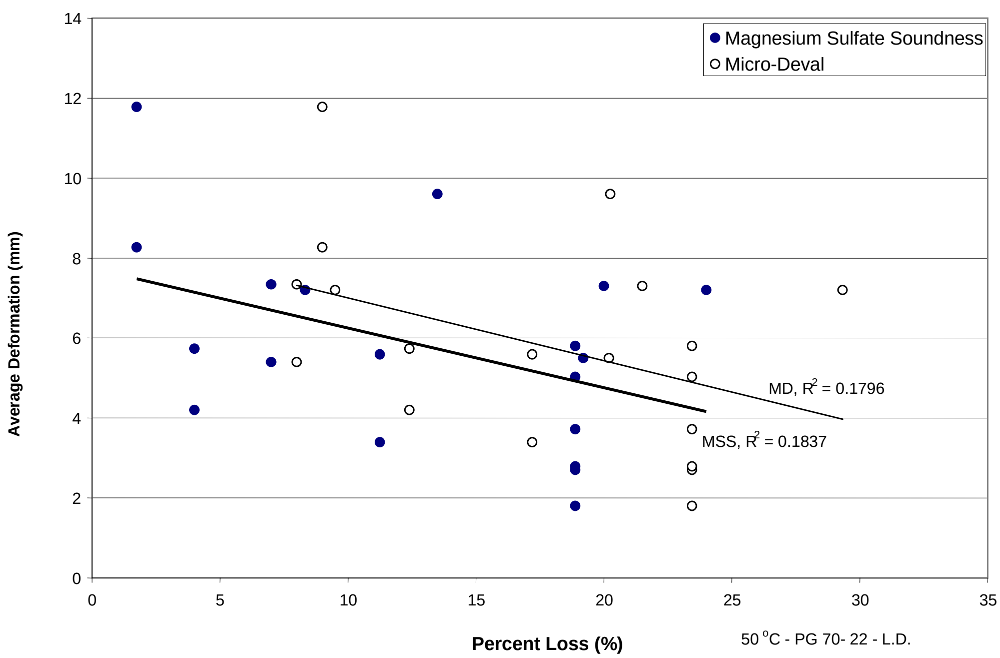

Figure A-6. Average Deformation vs. Percent Loss for Passed Samples - L.D.

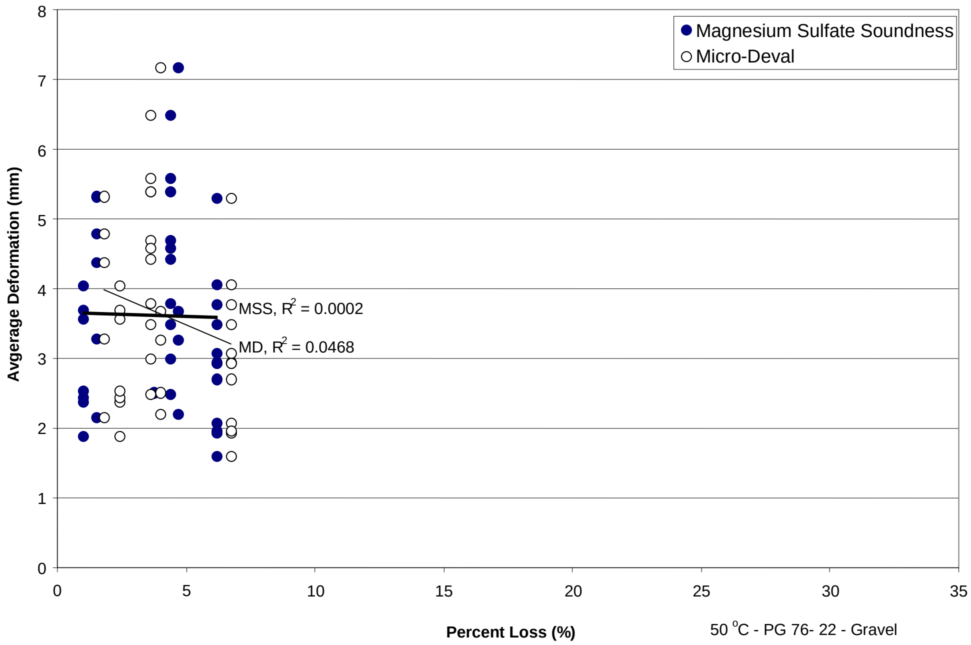

Figure A-7. Average Deformation vs. Percent Loss for Passed Samples - Gravel.

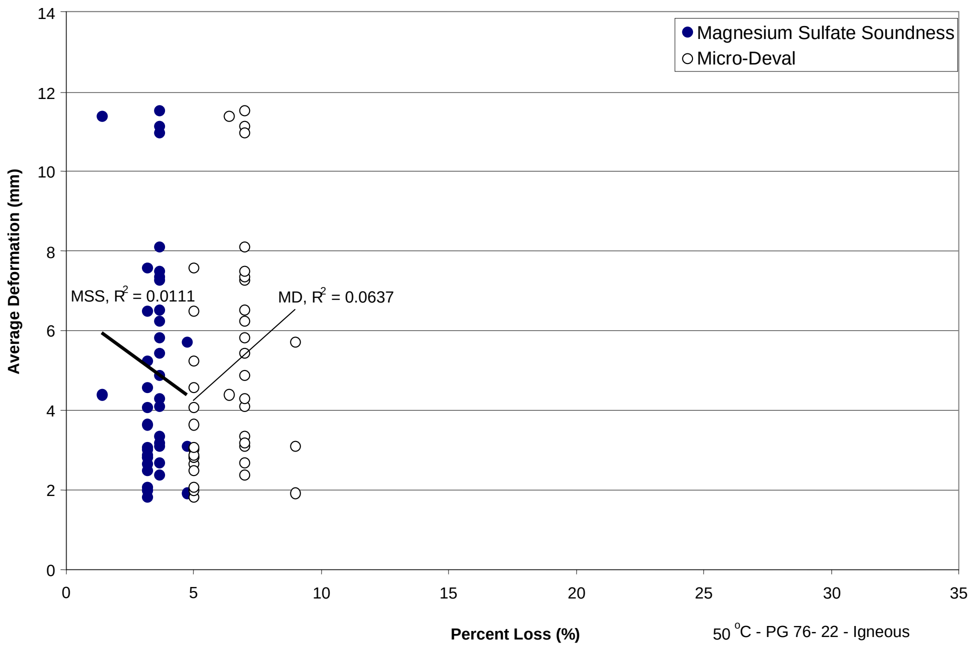

Figure A-8. Average Deformation vs. Percent Loss for Passed Samples - Igneous.

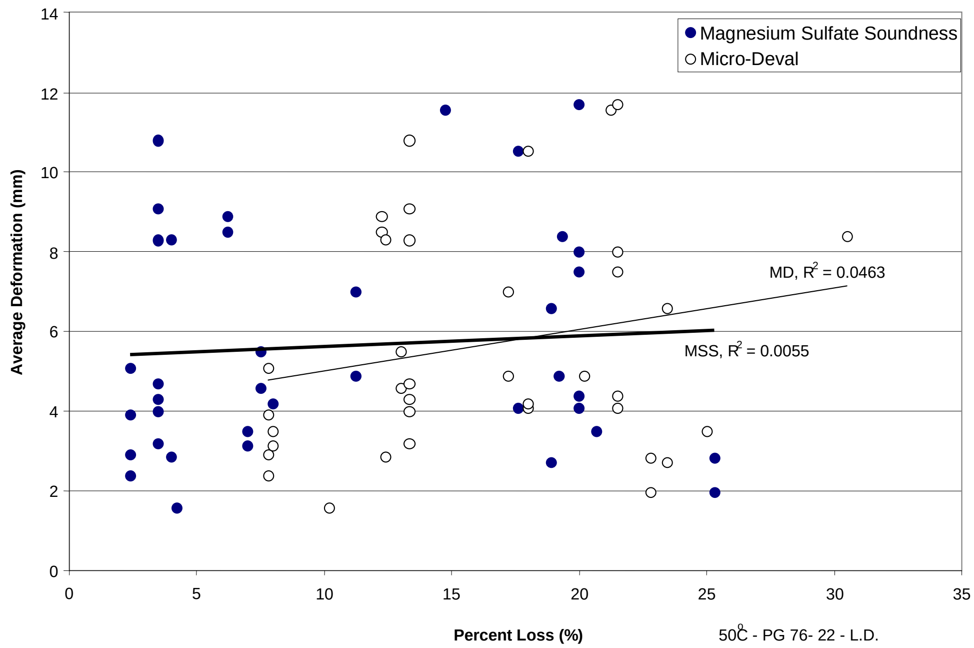

Figure A-9. Average Deformation vs. Percent Loss for Passed Samples – L.D.

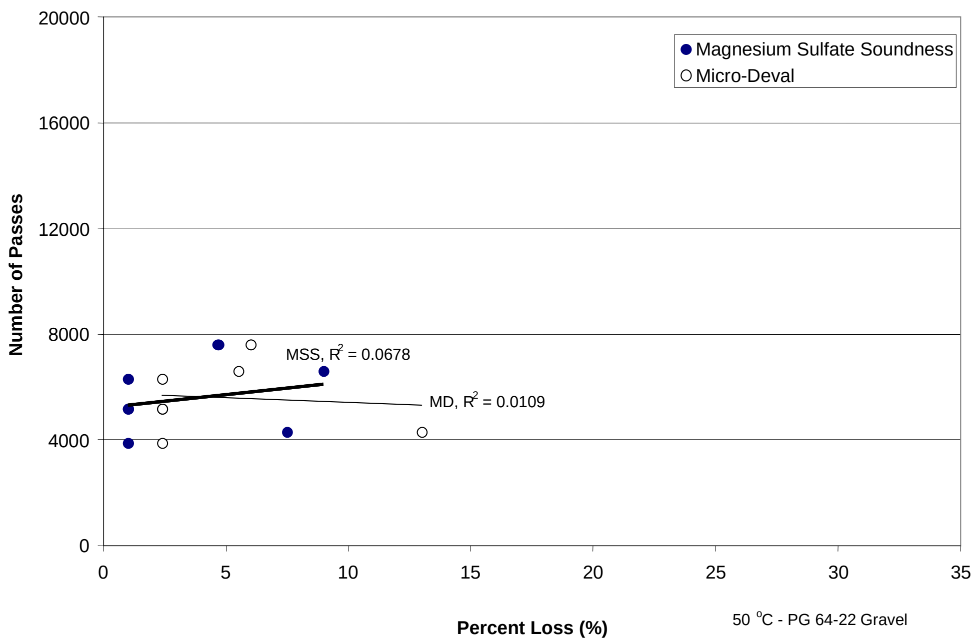

Figure A-10. Number of Passes vs. MSS and MD Loss for Failed Samples - Gravel.

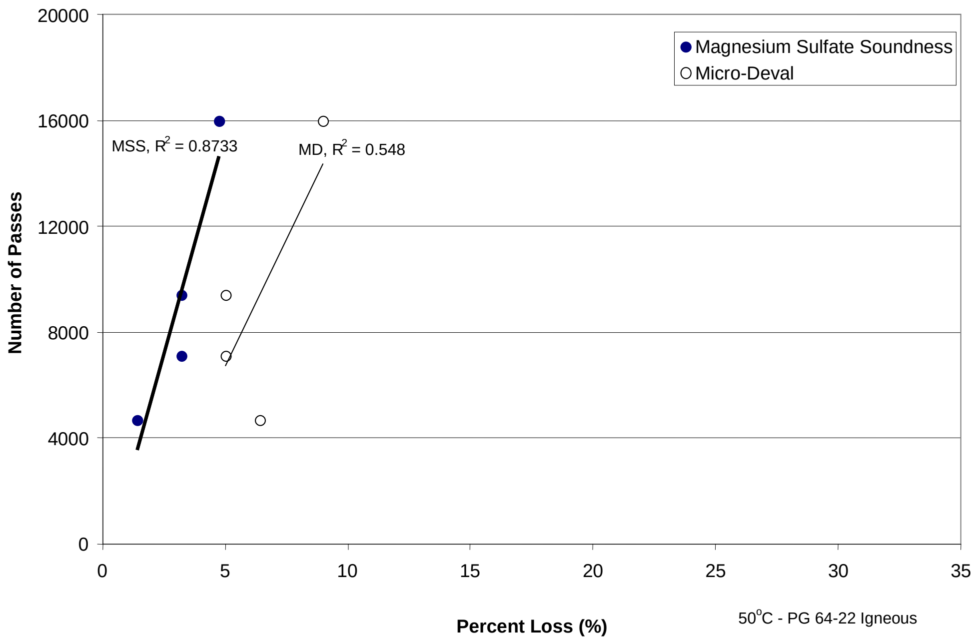

Figure A-11. Number of Passes vs. MSS and MD Loss for Failed Samples - Igneous.

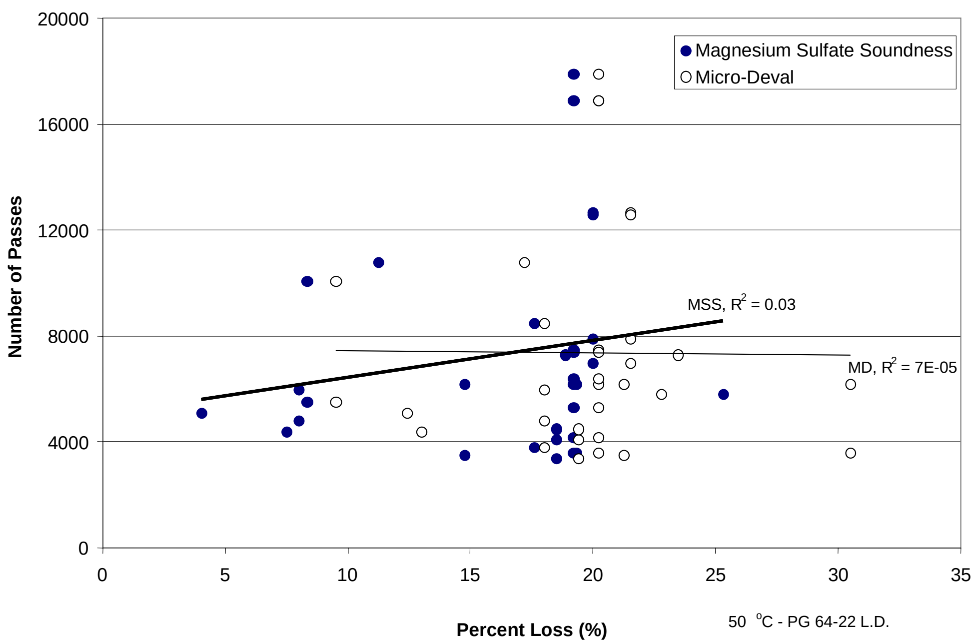

Figure A-12. Number of Passes vs. MSS and MD Loss for Failed Samples – L.D.

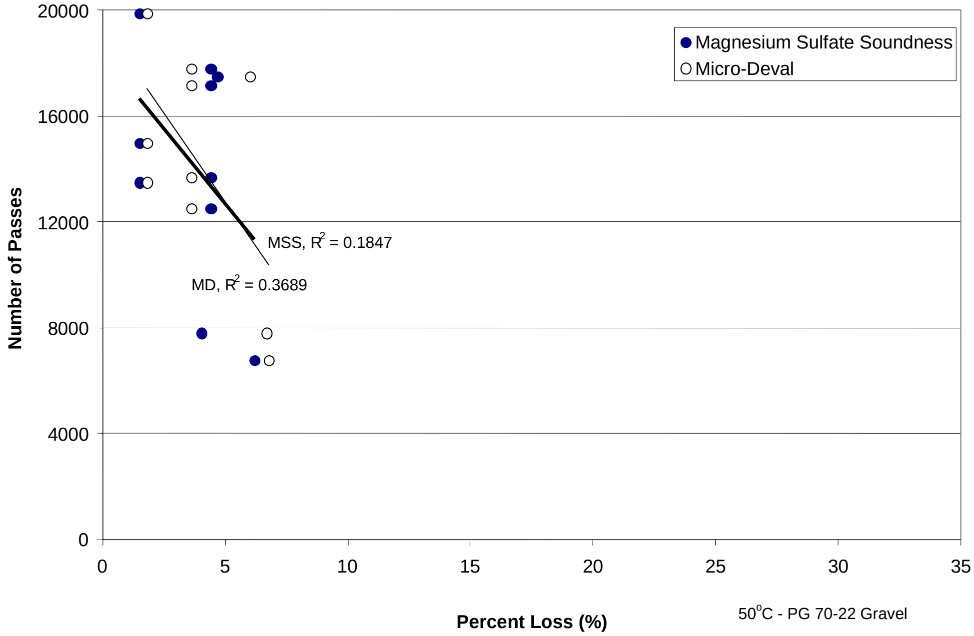

Figure A-13. Number of Passes vs. MSS and MD Loss for Failed Samples - Gravel.

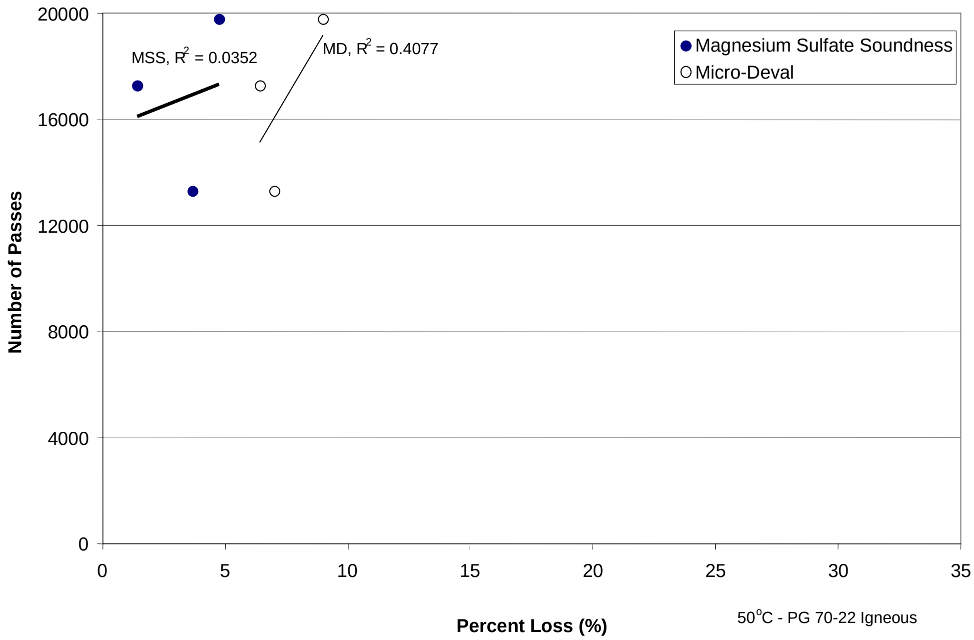

Figure A-14. Number of Passes vs. MSS and MD Loss for Failed Samples – Igneous.

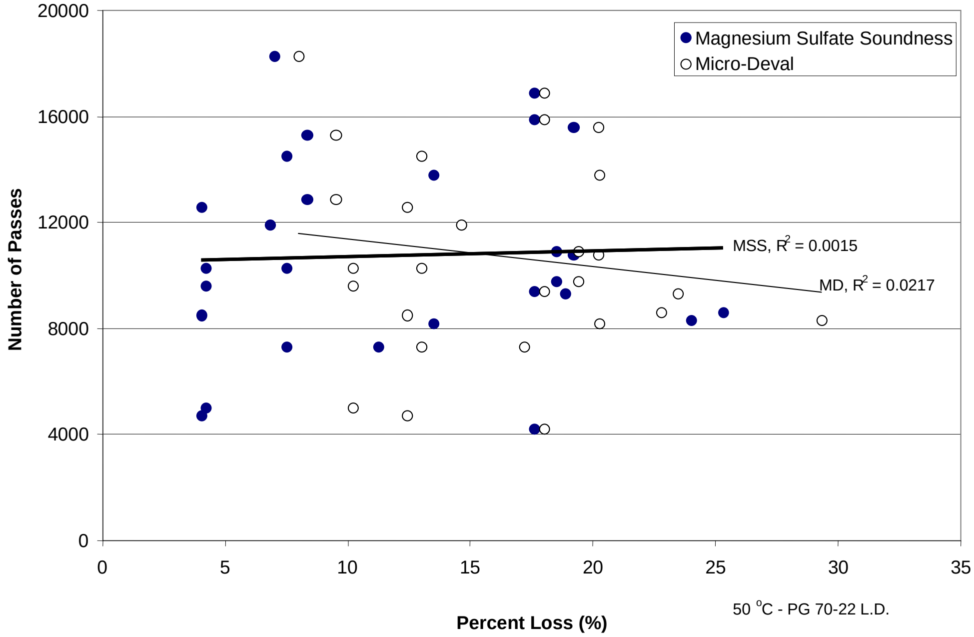

Figure A-15. Number of Passes vs. MSS and MD Loss for Failed Samples - L.D.

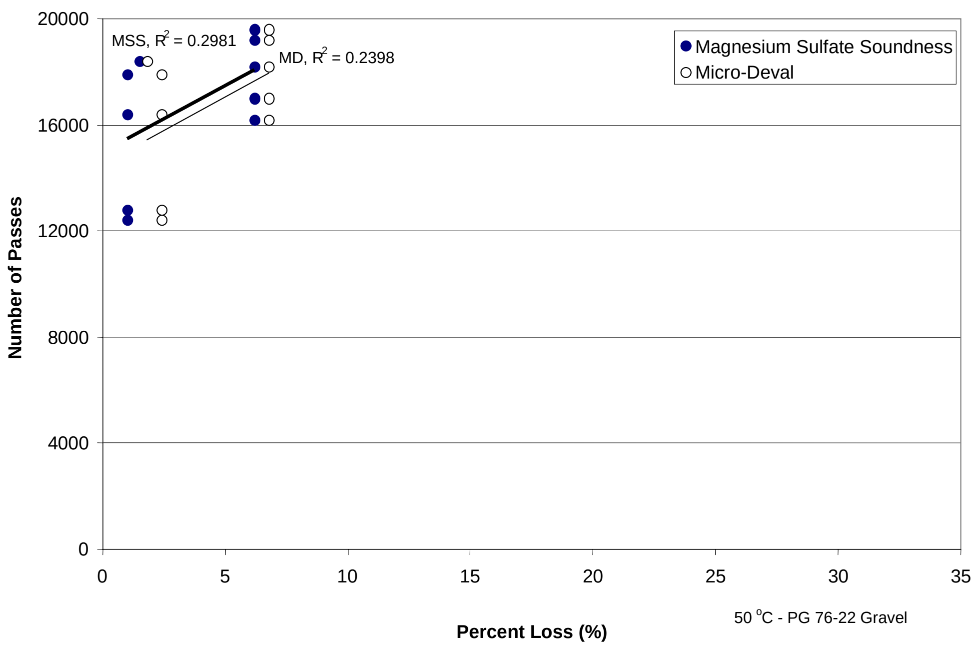

Figure A-16. Number of Passes vs. MSS and MD Loss for Failed Samples - Gravel.

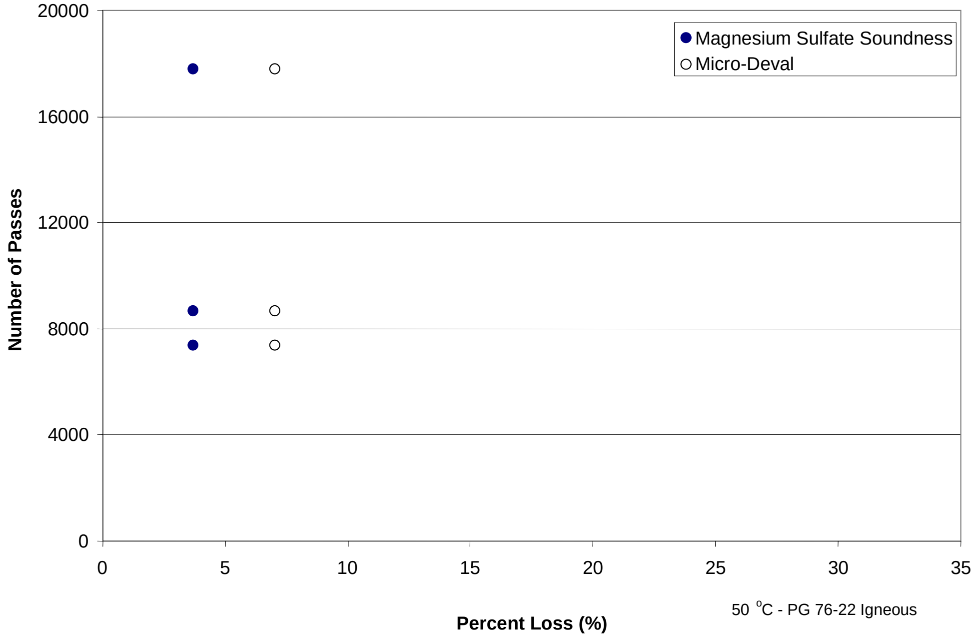

Figure A-17. Number of Passes vs. MSS and MD Loss for Failed Samples - Igneous.

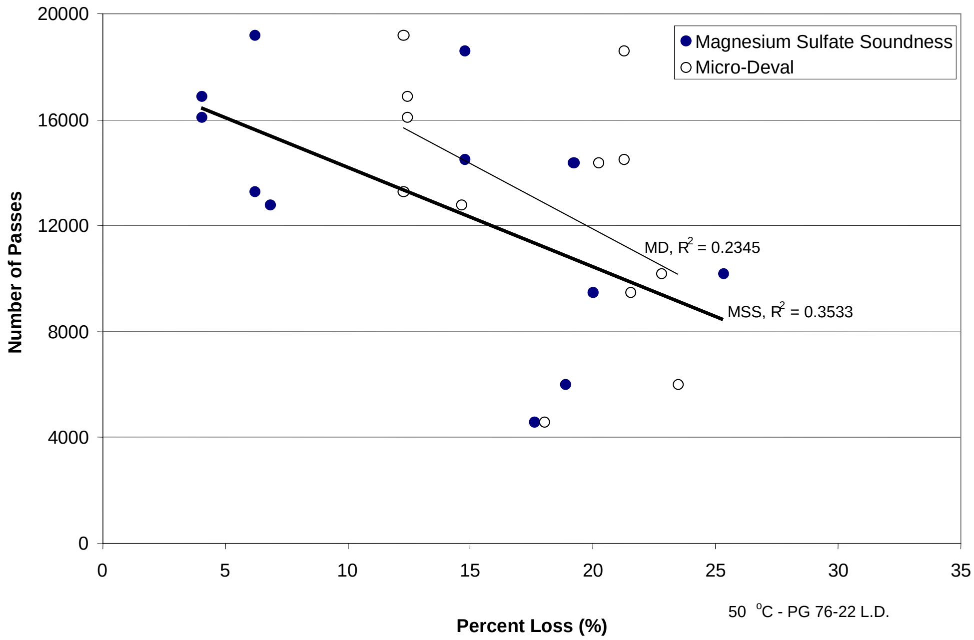

Figure A-18. Number of Passes vs. MSS and MD Loss for Failed Samples - L.D.

APPENDIX B:

FREQUENCY TABLES FOR KEY VARIABLE GROUPS FOR TXDOT HAMBURG WHEEL-TRACKING TEST

Variables Frequencies for Hamburg Data

Table B-1. Mix Type.

Mix Type	Frequency	Percent
	11.0	0.9
" B " Valero	1.0	0.1
(Blank)	61.0	5.0
1/2 HDSMA	1.0	0.1
1/2 Superpave	4.0	0.3
1/2 Superpave / No Rap	1.0	0.1
3/4 HDSMA	1.0	0.1
3/4 SFHMACP	5.0	0.4
3/4 Stone Filled	1.0	0.1
A	10.0	0.8
A w/RAP	2.0	0.2
Asphalt stabilized base	5.0	0.4
B	88.0	7.3
C	390.0	32.2
C Class A	2.0	0.2
C class B 5/8 "	1.0	0.1
C w/RAP	2.0	0.2
CMHB-C	96.0	7.9
CMHB-F	7.0	0.6
CRM	13.0	1.1
Crm HMA Mod.	2.0	0.2
D	286.0	23.6
D (Class A)	1.0	0.1
F	8.0	0.7
GGCRM	4.0	0.3
GR 4	1.0	0.1
HDSMA-2	8.0	0.7
HDSMA-3	1.0	0.1
PEM	1.0	0.1
PFC	2.0	0.2
Plastasphalt	7.0	0.6
RAP	5.0	0.4
SF-2	26.0	2.1
SF-3	19.0	1.6
SF-4	33.0	2.7
SMA-C	5.0	0.4
SMA	5.0	0.4
SP-2	23.0	1.9
SP-3	16.0	1.3
SP-4	54.0	4.5
SP	1.0	0.1
Strata	3.0	0.2
Total	**1213.0**	**100.0**

Table B-2. Aggregate Type.

Aggregate Type	Frequency	Percent
	30.0	2.5
(Blank)	222.0	18.3
A	1.0	0.1
B,C,D,F,Manuf.Sand,LmstnScrns,Lime	2.0	0.2
Bay Sweet 16 Gravels	1.0	0.1
C,D,F	1.0	0.1
Crush Granite	4.0	0.3
Crush Gravel	2.0	0.2
Crush Limestone	1.0	0.1
Crush Sand & Gravel	1.0	0.1
Gravel	215.0	17.7
Gravel, concrete sand, Lmstn.	1.0	0.1
Gravel, Crush screenings, Fibers	1.0	0.1
Gravel+Limestone Blend	10.0	0.8
Igneous	162.0	13.4
Igneous+Limestone Blend	8.0	0.7
Limestone-Dolomite	438.0	36.1
Limestone-Granite	3.0	0.2
Limestone-Traprock	5.0	0.4
Limestone	57.0	4.7
Monterrey Limestone Screenings	1.0	0.1
Other	4.0	0.3
S & G Base	1.0	0.1
Sandstone	28.0	2.3
Sandstone+Limestone Blend	12.0	1.0
Thrasher D rock, Brwn. Scrn	1.0	0.1
Traprock	1.0	0.1
Total	**1213.0**	**100.0**

Table B-3. AC Grades.

Grade	Frequency	Percent
	14.0	1.2
(Blank)	110.0	9.1
AC 10	14.0	1.2
AC 10w/ Crm.Rub	1.0	0.1
AC 20	40.0	3.3
AC 30	1.0	0.1
AC 40	2.0	0.2
PG 58-22	4.0	0.3
PG 64-22	232.0	19.1
PG 64-22S	1.0	0.1
PG 64-28	34.0	2.8
PG 64-28S	1.0	0.1
PG 70-16	8.0	0.7
PG 70-22	247.0	20.4
PG 70-22S	21.0	1.7
PG 70-28	21.0	1.7
PG 70-28S	2.0	0.2
PG 76-16	11.0	0.9
PG 76-22-L	19.0	1.6
PG 76-22	414.0	34.1
PG 76-22S	10.0	0.8
PG 76-22TR	1.0	0.1
PG 76-28	3.0	0.2
Strata Binder III	2.0	0.2
Total	**1213.0**	**100.0**

Table B-4. Modifier Types.

Modifier	Frequency	Percent
	1079.0	89.0
Latex (SBR)	23.0	1.9
SBS	89.0	7.3
TR (Tire rubber)	16.0	1.3
Unknown	6.0	0.5
Total	**1213.0**	**100.0**

Table B-5. Additive Types.

Additive	Frequency	Percent
	24.0	2.0
(Blank)	383.0	31.6
Crm Rubber	24.0	2.0
Elvaloy	2.0	0.2
Hydrated Lime	2.0	0.2
Latex	3.0	0.2
Lime	467.0	38.5
Lime & Arrmaz	7.0	0.6
Lime & Liquid Anti-Strip	2.0	0.2
Lime, HP Plus	3.0	0.2
Liquid	257.0	21.2
Liquid Anti-Strip	1.0	0.1
None	31.0	2.6
Rohm & Hass (Morlife 5000)	1.0	0.1
San Antonio Lime	1.0	0.1
See Comments	5.0	0.4
Total	**1213.0**	**100.0**

Table B-6. Type of Specimens.

Specimen Type	Frequency	Percent
	9.0	0.7
(Blank)	13.0	1.1
Laboratory mix	290.0	23.9
Plant mix	802.0	66.1
Road core	97.0	8.0
Slab	2.0	0.2
Total	**1213.0**	**100.0**

Table B-7. Test Types.

Test Type	Frequency	Percent
	10.0	0.8
(Blank)	14.0	1.2
Design	159.0	13.1
Forensic	66.0	5.4
Other	714.0	58.9
Pilot Project	17.0	1.4
QCQA	61.0	5.0
Research	172.0	14.2
Total	**1213.0**	**100.0**

Table B-8. Test Temperatures.

Test Temp	Frequency	Percent
	4.0	0.3
40 °C	186.0	15.3
50 °C	1023.0	84.3
Total	**1213.0**	**100.0**

TABLE B-9: VARIABLE CONSIDERED IN "OTHER" CATEGORY OF TABLE 3.6

Mix Type	No.
1/2 Superpave Count	3
1/2 Superpave / No Rap Count	1
3/4 SFHMACP Count	3
3/4 Stone Filled Count	1
A Count	6
A w/RAP Count	1
Asphalt stabilized base Count	3
B Count	66
C Count	296
C Class A Count	2

C w/RAP Count	1
CMHB-C Count	59
CMHB-F Count	1
CRM Count	9
D Count	225
D (Class A) Count	1
F Count	3
GR 4 Count	1
HDSMA-2 Count	8
HDSMA-3 Count	1
RAP Count	1
SF-2 Count	22
SF-3 Count	15
SF-4 Count	31
SMA Count	2
SMA-C Count	3
SP Count	1
SP-2 Count	19
SP-3 Count	13
SP-4 Count	41
Strata Count	1
Grand Count	840

Aggregate Type	No.
A Count	1
B,C,D,F,Manuf.Sand,LmstnScrns,Lime Count	2
Bay Sweet 16 Gravels Count	1
C,D,F Count	1
Crush Granite Count	4
Crush Gravel Count	2
Crush Limestone Count	1
Crush Sand & Gravel Count	1
Gravel Count	183
Gravel,concrete sand, Lmstn. Count	1
Gravel+Limestone Blend Count	10
Igneous Count	143
Igneous+Limestone Blend Count	8
Limestone Count	51
Limestone-Dolomite Count	389
Limestone-Granite Count	2
Limestone-Traprock Count	2
Monterrey Limestone Screenings Count	1
Other Count	3
Sandstone Count	24
Sandstone+Limestone Blend Count	8
Thrasher D rock,Brwn. Scrn Count	1

Traprock Count	1
Grand Count	840

Grade	No.
AC 10 Count	10
AC 20 Count	17
AC 30 Count	1
AC 40 Count	1
PG 64-22 Count	179
PG 64-28 Count	31
PG 70-16 Count	6
PG 70-22 Count	216
PG 70-22S Count	15
PG 70-28 Count	18
PG 70-28S Count	2
PG 76-16 Count	4
PG 76-22 Count	315
PG 76-22-L Count	17
PG 76-22S Count	5
PG 76-22TR Count	1
PG 76-28 Count	2
Grand Count	840

Additive	No.
(Blank) Count	169
Crm Rubber Count	11
Elvaloy Count	1
Hydrated Lime Count	2
Latex Count	2
Lime Count	406
Lime & Arrmaz Count	6
Lime & Liquid Anti-Strip Count	2
Lime , HP Plus Count	2
Liquid Count	201
None Count	31
Rohm & Hass (Morlife 5000) Count	1
San Antonio Lime Count	1
See Comments Count	5
Grand Count	840

TABLE B-10. VARIABLES CONSIDERED IN "OTHERS" OF TABLE 3.11

1.

	Aggregate Type
Gravel Count	124
Gravel+Limestone Blend Count	3
Igneous Count	98
Igneous+Limestone Blend Count	6
Limestone Count	16
Limestone-Dolomite Count	207
Sandstone Count	5
Sandstone+Limestone Blend Count	3
Grand Count	462

	Mix Type
Strata Count	1
SP-4 Count	22
SP-3 Count	12
SP-2 Count	7
SMA-C Count	1
SMA Count	1
SF-4 Count	26
SF-3 Count	13
SF-2 Count	19
RAP Count	1
HDSMA-3 Count	1
HDSMA-2 Count	6
D Count	127
CRM Count	6
CMHB-F Count	1
CMHB-C Count	35
C Count	134
B Count	45
A Count	3
1/2 Superpave Count	1
Grand Count	462

	Grade
AC 10 Count	7
AC 20 Count	2
PG 64-22 Count	105
PG 64-28 Count	26
PG 70-16 Count	6
PG 70-22 Count	131
PG 70-28 Count	12
PG 76-16 Count	1
PG 76-22 Count	170
PG 76-28 Count	2
Grand Count	462

	Additive
(Blank) Count	100
Crm Rubber Count	6
Lime Count	244
Liquid Count	104
None Count	5
See Comments Count	3
Grand Count	462

APPENDIX C:

GENERAL STATISTICS FOR TXDOT'S HAMBURG DATABASE AFTER CLEAN UP TOTAL DATA POINTS 840

Table C-1a. Database Classification Based on Number of Cycles (total data points 840).

	Mix Type			Aggregate Type			Grade			Temperature		Additive		
Cycles	B	C	D	Gravel	Igneous		PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
0-5000	4	9	14	7	2	22	22	4	1	0	33	6	16	9
5000 -15000	18	39	53	40	10	88	50	49	27	6	148	47	39	58
15000 - 20000	5	28	21	17	6	32	21	19	23	7	61	22	23	20
20000	38	220	137	119	125	246	86	143	265	120	464	331	123	113
Sub total	65	296	225	183	143	388	179	215	316	133	706	406	201	200
Total	586			714			710			839		807		

Table C-1b. Percent Occurrence for Predominant Parameters.

Cycles	B	C	D	Gravel	Igneous		PG 64-22	PG 70-22	PG 76-22	40° C	50 °C	Lime	Liquid	None
	%	%	%	%	%	%	%	%	%	%	%	%	%	%
0-5000	6.2	3.0	6.2	3.8	1.4	5.7	12.3	1.9	0.3	0.0	4.7	1.5	8.0	4.5
5000 -15000	27.7	13.2	23.6	21.9	7.0	22.7	27.9	22.8	8.5	4.5	21.0	11.6	19.4	29.0
15000 - 20000	7.7	9.5	9.3	9.3	4.2	8.2	11.7	8.8	7.3	5.3	8.6	5.4	11.4	10.0
20000	58.5	74.3	60.9	65.0	87.4	63.4	48.0	66.5	83.9	90.2	65.7	81.5	61.2	56.5
% out of same category	11.1	50.5	38.4	25.6	20.0	54.3	25.2	30.3	44.5	15.9	84.1	50.3	24.9	24.8
% out of total dataset	7.7	35.2	26.8	21.8	17.0	46.2	21.3	25.6	37.6	15.8	84.0	48.3	23.9	23.8
% Data considered	69.8			85.0			84.5			99.9		96.1		

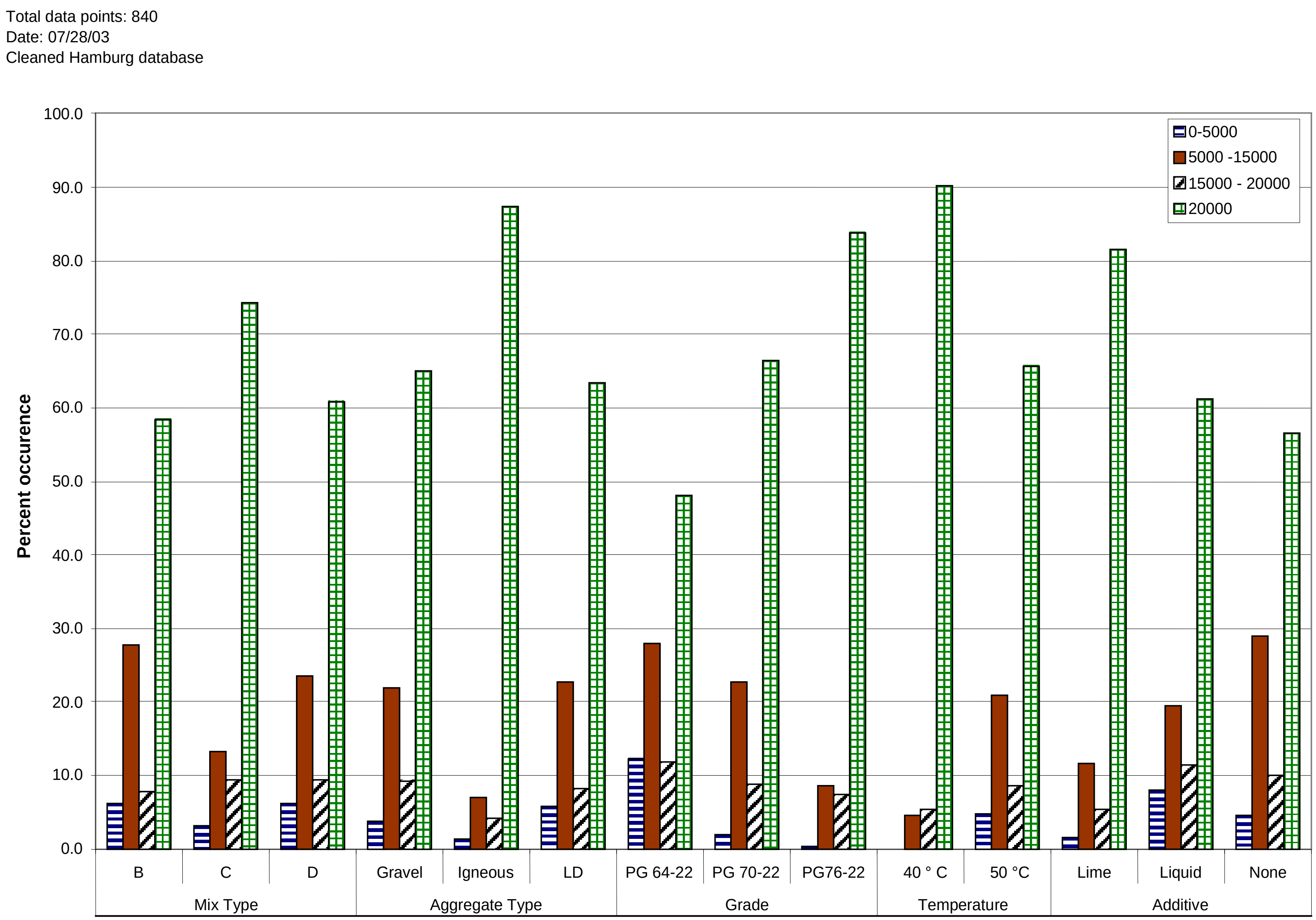

Figure C-1. Hamburg Database Classification Based on Number of Passes after Discarding Missing Data and Outliers.

Table C-2a. Database Classification Based on Average Deformation (total data points 840).

	Mix Type			Aggregate Type			Grade			Temperature		Additive		
Avg. Deformation (mm)	B	C	D	Gravel	Igneous	L.D.	PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
0 -5	22	102	80	60	87	117	19	75	166	74	233	194	57	51
5 - 10	14	94	45	49	29	105	49	61	82	39	188	120	49	49
10 – 12.5	2	24	14	11	9	25	18	8	17	7	45	17	19	13
12.5	28	76	86	63	18	142	93	72	50	13	241	75	76	87
Sub Total	66	296	225	183	143	389	179	216	315	133	707	406	201	200
Total	587			715			710			840		807		

Table C-2b. Percent Occurrence for Predominant Parameters.

Avg. Deformation (mm)	B	C	D	Gravel	Igneous	L.D.	PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
	%	%	%	%	%	%	%	%	%	%	%	%	%	%
0 -5	33.3	34.5	35.6	32.8	60.8	30.1	10.6	34.7	52.7	55.6	33.0	47.8	28.4	25.5
5 - 10	21.2	31.8	20.0	26.8	20.3	27.0	27.4	28.2	26.0	29.3	26.6	29.6	24.4	24.5
10 – 12.5	3.0	8.1	6.2	6.0	6.3	6.4	10.1	3.7	5.4	5.3	6.4	4.2	9.5	6.5
12.5	42.4	25.7	38.2	34.4	12.6	36.5	52.0	33.3	15.9	9.8	34.1	18.5	37.8	43.5
% out of same category	11.2	50.4	38.3	25.6	20.0	54.4	25.2	30.4	44.4	15.8	84.2	50.3	24.9	24.8
% out of total dataset	7.9	35.2	26.8	21.8	17.0	46.3	21.3	25.7	37.5	15.8	84.2	48.3	23.9	23.8
% Data considered	69.9			85.1			84.5			100		96.1		

Total data points: 840
Date: 07/28/03
Cleaned Hamburg database

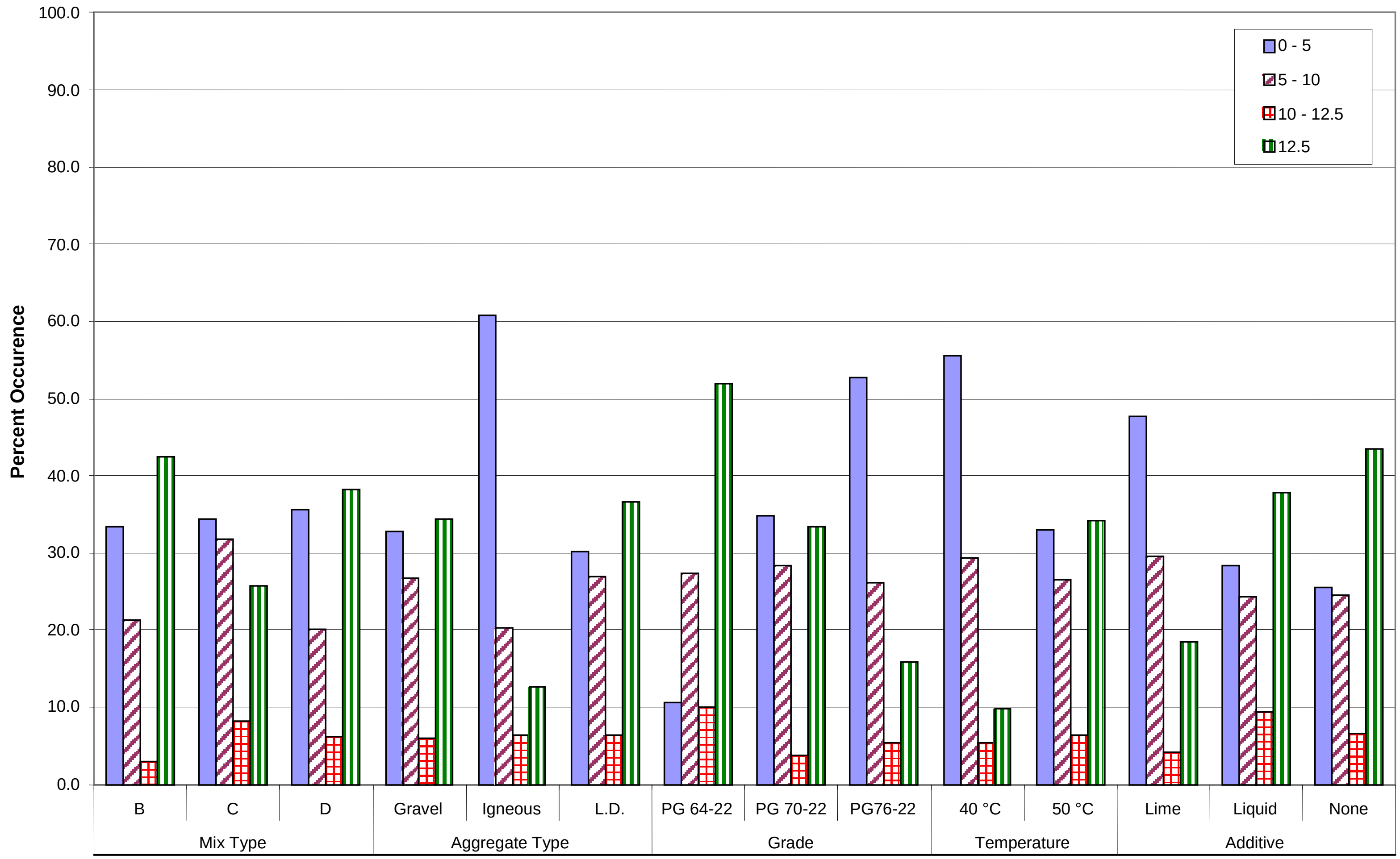

Figure C-2. Hamburg Database Classification Based on Average Deformation after Discarding Missing Data and Outliers.

APPENDIX D:

GENERAL STATISTICS FOR HAMBURG-AGGREGATE DATABASE TOTAL DATA POINTS 462

Table D-1a. HAP Database Classification Based on Number of Cycles (total data points 462).

	Mix Type			Aggregate Type			Grade			Temperature		Additive		
Passes to fail samples	B	C	D	Gravel	Igneous	L.D.	PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
0-5000	3	6	9	4	1	16	13	4	1	0	21	2	11	8
5000 -15000	10	22	25	28	6	52	29	27	13	4	85	32	22	29
15000 - 20000	3	20	11	15	4	19	11	13	15	7	35	15	12	14
20000	29	86	82	77	87	120	52	87	141	60	250	195	59	54
Sub Total	45	134	127	124	98	207	105	131	170	71	391	244	104	105
Total	306			429			406			462		453		

Table D-1b. Percent Occurrence for Predominant Parameters.

Passes to fail samples	B	C	D	Gravel	Igneous	L.D.	PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
	%	%	%	%	%	%	%	%	%	%	%	%	%	%
0-5000	6.7	4.5	7.1	3.2	1.0	7.7	12.4	3.1	0.6	0.0	5.4	0.8	10.6	7.6
5000 -15000	22.2	16.4	19.7	22.6	6.1	25.1	27.6	20.6	7.6	5.6	21.7	13.1	21.2	27.6
15000 - 20000	6.7	14.9	8.7	12.1	4.1	9.2	10.5	9.9	8.8	9.9	9.0	6.1	11.5	13.3
20000	64.4	64.2	64.6	62.1	88.8	58.0	49.5	66.4	82.9	84.5	63.9	79.9	56.7	51.4
% out of same category	14.7	43.8	41.5	28.9	22.8	48.3	25.9	32.3	41.9	15.4	84.6	53.9	23.0	23.2
% out of total dataset	9.7	29.0	27.5	26.8	21.2	44.8	22.7	28.4	36.8	15.4	84.6	52.8	22.5	22.7
% of Data considered	66.2			92.9			87.9			100.0		98.1		

Table D-1c. Means of Average Deformation at Different Passes Classes.

No. of Passes to fail samples	Mix Type			Aggregate Type			Grade			Temperature		Additive		
	B	C	D	Gravel	Igneous	L.D.	PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
0-5000	12.5	12.5	11.79	12.5	12.5	12.1	12.5	10.9	12.5	-	12.19	12.5	11.92	12.5
5000 -15000	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
15000 - 20000	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
20000	5.15	5.74	5.06	5.09	4.82	5.47	6.8	5.22	4.78	4.32	5.43	5.01	5.69	5.34
Mean of Category	7.77	8.16	7.65	7.9	5.68	8.39	9.68	7.61	6.1	5.59	7.96	6.51	8.58	8.82

Total data points: 462
Date: 08/05/03
Manually joint database

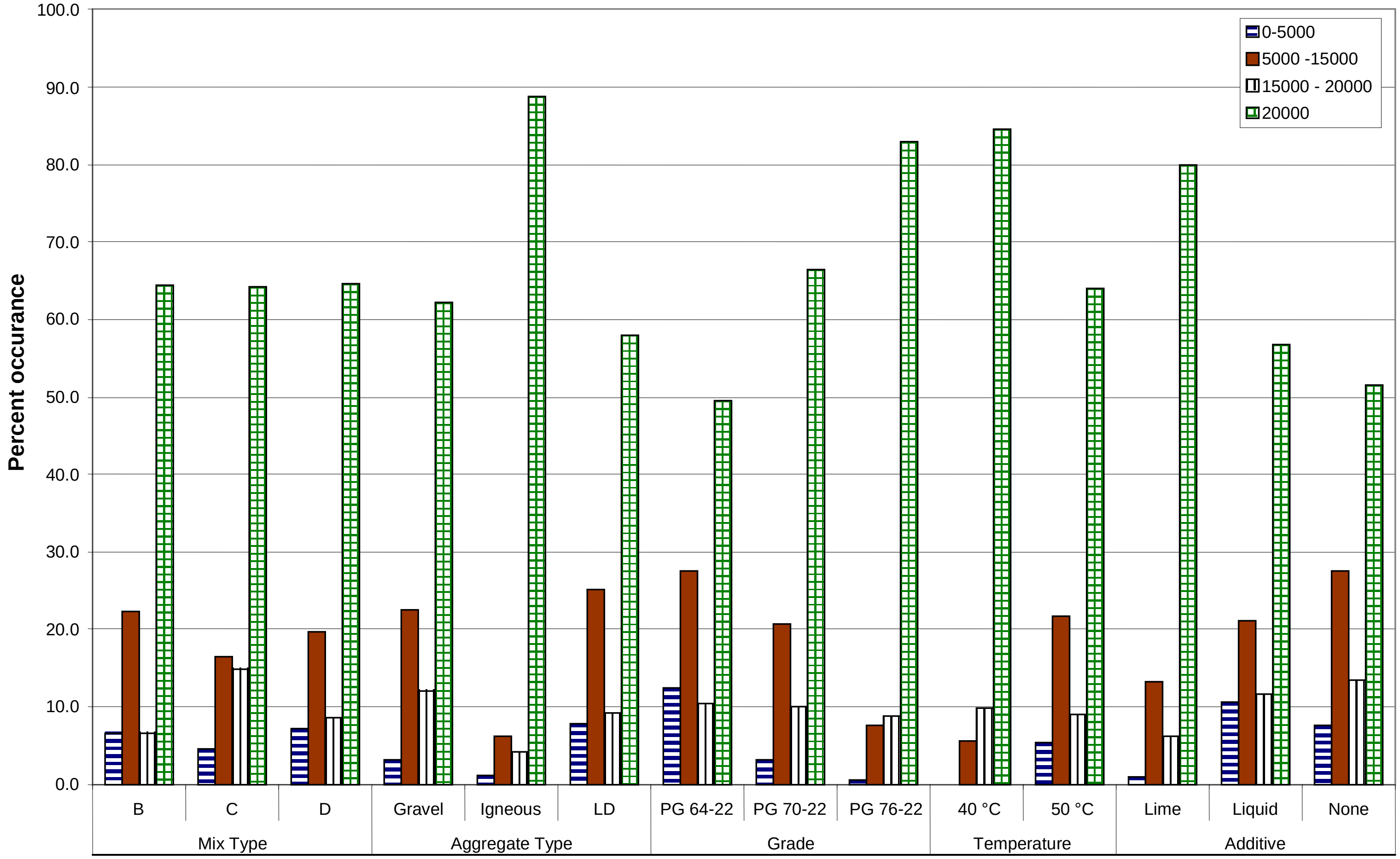

Figure D-1. HAP Database Classification Based on Number of Passes.

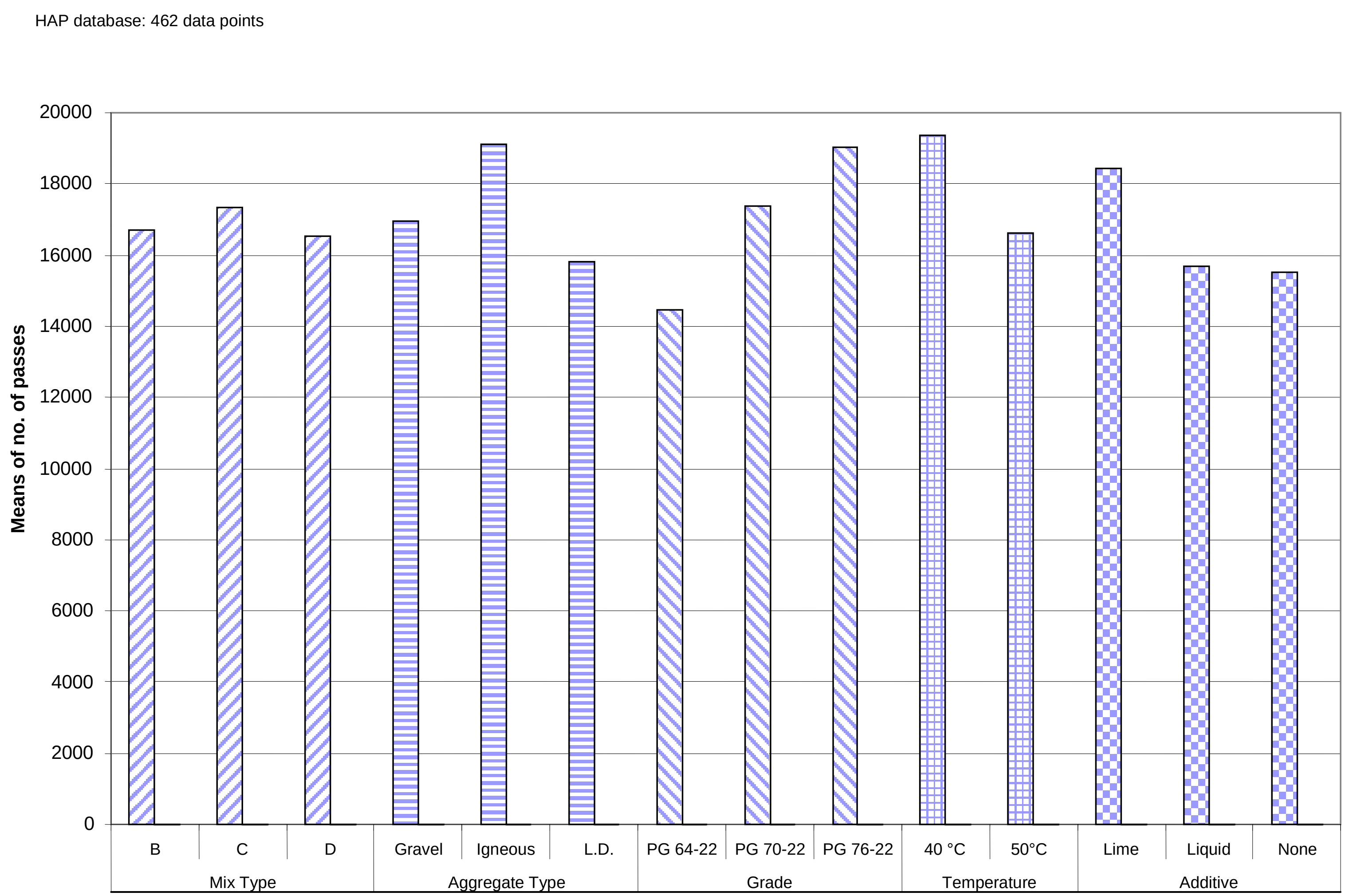

Figure D-2. Performance of Main Variables Expressed by Means of Number of Passes.

Table D-2a. HAP Database Classification Based on Average Deformation (total data points 462).

Avg. Deformation (mm)	Mix Type			Aggregate Type			Grade			Temperature		Additive		
	B	C	D	Gravel	Igneous	L.D.	PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
0 - 5	17	36	49	45	57	60	12	47	91	38	135	119	27	27
5 - 10	10	41	28	26	24	50	29	37	42	20	94	65	26	21
10 - 12.5	2	9	6	6	6	11	11	4	8	2	22	11	7	6
12.5	16	48	44	47	11	86	53	43	29	11	140	49	44	51
Sub Total	45	134	127	124	98	207	105	131	170	71	391	244	104	105
Total	306			429			406			462		453		

Table D-2b. Percent Occurrence for Predominate Parameters.

Avg. Deformation (mm)	B	C	D	Gravel	Igneous	L.D.	PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
	%	%	%	%	%	%	%	%	%	%	%	%	%	%
0 - 5	37.8	26.9	38.6	36.3	58.2	29.0	11.4	35.9	53.5	53.5	34.5	48.8	26.0	25.7
5 - 10	22.2	30.6	22.0	21.0	24.5	24.2	27.6	28.2	24.7	28.2	24.0	26.6	25.0	20.0
10 – 12.5	4.4	6.7	4.7	4.8	6.1	5.3	10.5	3.1	4.7	2.8	5.6	4.5	6.7	5.7
12.5	35.6	35.8	34.6	37.9	11.2	41.5	50.5	32.8	17.1	15.5	35.8	20.1	42.3	48.6
% out of same category	14.7	43.8	41.5	28.9	22.8	48.3	25.9	32.3	41.9	15.4	84.6	53.9	23.0	23.2
% out of total dataset	9.7	29.0	27.5	26.8	21.2	44.8	22.7	28.4	36.8	15.4	84.6	52.8	22.5	22.7
% Data considered	66.2			92.9			87.9			100.0		98.1		

Table D-2c. Means of Number of Passes at Different Deformation Classes.

Avg. Deformation (mm)	Mix Type			Aggregate Type			Grade			Temperature		Additive		
	B	C	D	Gravel	Igneous	LD	PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
0 - 5	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
5 - 10	20,000	20,000	19,357.1	20,000	20,000	19,460	20,000	19,513.5	20,000	20,000	19,808.5	20,000	19,307.7	20,000
10 - 12.5	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
12.5	10,700	12,491	10,400	11,946.2	11,863.6	10,127.9	8996.2	12,396.9	14,203.5	15,745.5	10,674.1	12,265.3	10,195.5	10,787.7
Mean of Category	16,693.3	17,310.2	16,532.3	16,947.3	19,086.7	15,811.6	14,445.7	17,367	19,011.2	19,340.9	16,614.8	18,446.7	15,678.9	15,525.4

Total data points: 462
Date: 08/05/03
Manually joint database

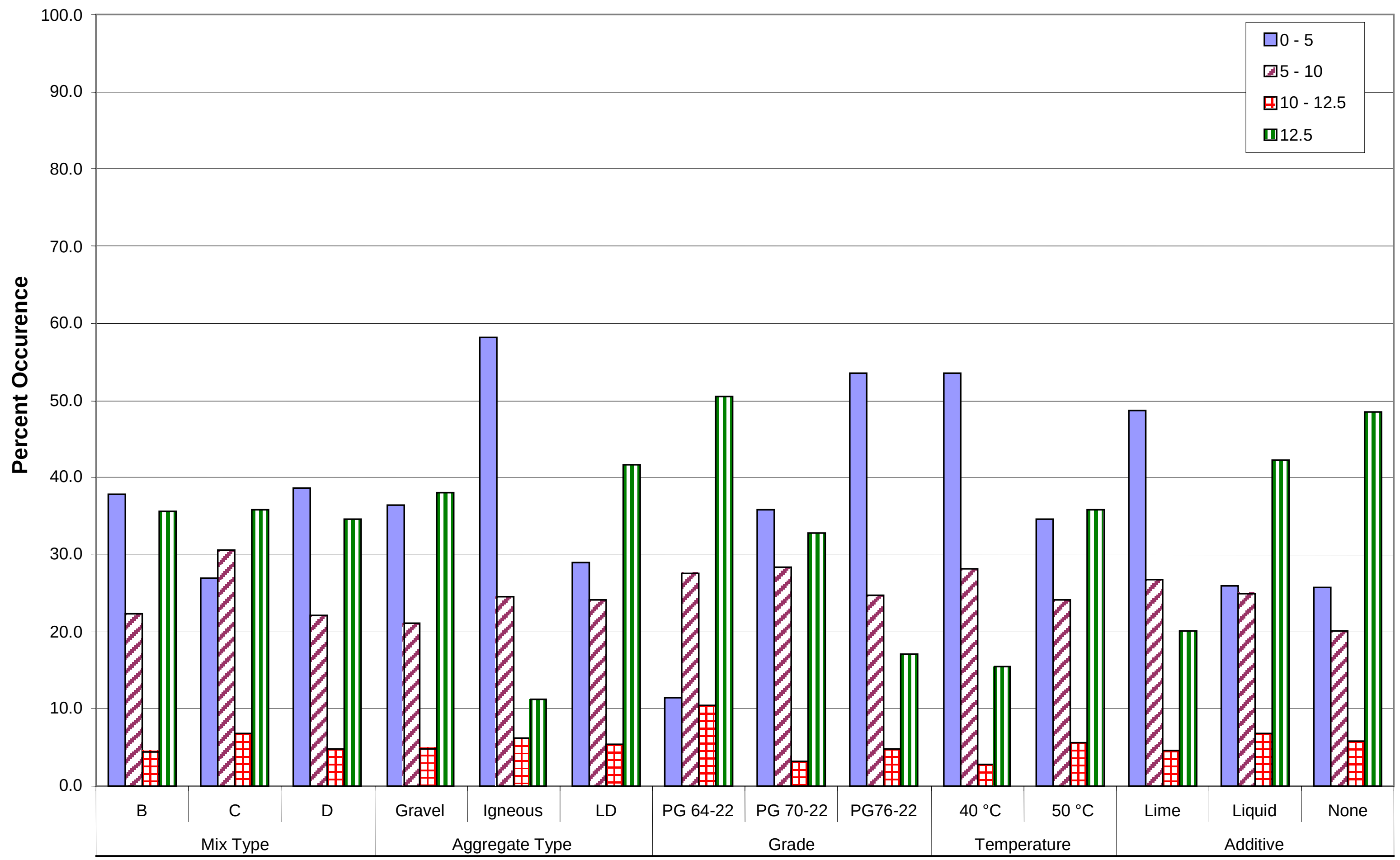

Figure D-3. HAP Database Classification Based on Average Deformation.

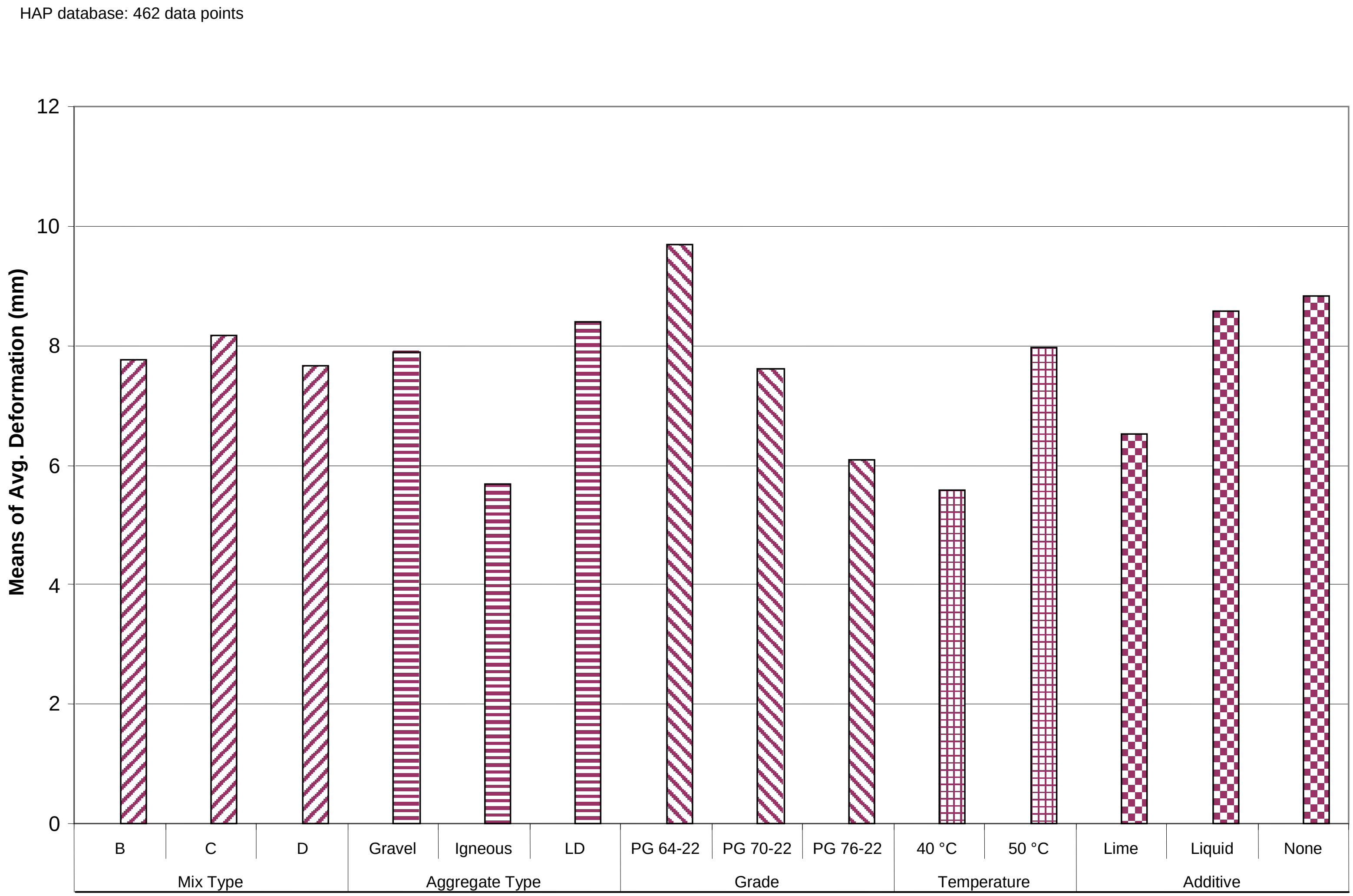

Figure D-4. Performance of Main Variables Expressed by Means of Average Deformation.

Table D-3a. Means of Average MSS at Different Passes Classes.

	Mix Type			Aggregate Type			Grade			Temperature		Additive		
No. of Passes to fail samples	B	C	D	Gravel	Igneous	L.D.	PG 64-22	PG 70-22	PG 76-22	40 °C	50 °C	Lime	Liquid	None
0-5000	7.23	14.07	14.03	5.48	1.4	14.53	13.15	8.2	17.6	-	12.1	5.6	12.83	12.73
5000 -15000	9.79	11.87	11.71	4.17	3.40	14.34	11.78	10.28	9.72	2.84	10.53	11.14	13.1	8.05
15000 - 20000	11.4	11.16	9.16	3.88	3.64	13.99	15.04	9.88	4.87	14.73	7.97	7.55	14.5	6.53
20000	9.93	8.81	8.0	4.19	3.41	13.17	12.34	7.01	6.63	11.0	7.22	7.34	9.3	8.84
Mean of Category	9.82	9.9	9.26	4.19	3.4	13.64	12.57	8.01	6.77	10.91	8.27	7.84	11.08	8.61

Table D-3b. Means of Average MD at Different Passes Classes.

	Mix Type			Aggregate Type			Grade			Temperature		Additive		
No. of Passes to fail samples	B	C	D	Gravel	Igneous	B	C	D	Gravel	Igneous	B	C	D	Gravel
0-5000	12.58	18.82	15.89	7.54	6.4	18.53	17.01	12.15	18	-	15.86	10.2	15.66	17.55
5000 -15000	12.28	15.63	15.36	5.17	7.25	18.44	14.11	13.62	13.54	4.2	13.76	15.27	15.83	10.81
15000 - 20000	15.4	12.71	11.22	4.42	7.85	16.74	16.76	11.05	8.45	16.4	10.33	9.86	16.44	8.41
20000	12.06	11.04	10.27	4.34	6.58	17.57	14.85	9.4	9.44	14.12	9.98	9.9	12.16	12.57
Mean of Category	12.36	12.39	11.75	4.64	6.67	17.78	15.11	10.52	9.72	13.79	11.15	10.61	13.8	11.91

Table 4a. Means of Average MSS at Different Deformation Classes.

	Mix Type			Aggregate Type			Grade			Temperature		Additive		
Avg. Deformation (mm) at failure	B	C	D	Gravel	Igneous	B	C	D	Gravel	Igneous	B	C	D	Gravel
0 - 5	9.16	9.05	6.69	4.3	3.44	12.66	11.45	7.15	6.47	10.28	6.7	6.74	9.15	9.1
5 - 10	10.79	8.68	7.03	4.09	3.47	13.34	13.23	7.28	6.6	12.83	7.62	8.31	9.82	8.06
10 – 12.5	12.2	8.47	10.23	3.82	2.84	14.64	10.94	2.85	8.53	6.34	8.73	8.08	7.65	10.39
12.5	9.61	11.85	11.66	4.19	3.31	13.36	12.79	10.04	7.48	10.40	10.15	9.82	13.55	8.37
Mean of Category	9.82	9.9	9.26	4.19	3.396	13.64	12.57	8.01	6.77	10.91	8.27	7.84	11.08	8.61

Table 4b. Means of Average MD at Different Deformation Classes.

	Mix Type			Aggregate Type			Grade			Temperature		Additive		
Avg. Deformation (mm) at failure	B	C	D	Gravel	Igneous	B	C	D	Gravel	Igneous	B	C	D	Gravel
0 - 5	11.28	11.27	8.36	4.45	6.41	17.1	12.4	9.78	8.78	13.18	9.3	9.34	11.48	12.39
5 - 10	13.28	10.81	12.65	4.01	7.01	17.56	16.01	9.39	10.25	16.13	10.51	11.0	12.52	12.07
10 – 12.5	12.55	11.19	14.48	4.98	6.47	19.27	14.44	4.6	12.69	12.0	11.85	9.49	12.82	15.09
12.5	12.92	14.81	14.6	5.13	7.39	18.2	15.37	12.84	11.06	11.96	13.26	13.40	16.13	11.21
Mean of Category	12.36	12.39	11.75	4.64	6.67	17.78	15.11	10.52	9.72	13.79	11.15	10.61	13.8	11.91