Performance optimization and modeling of slurry seal and micro surfacing utilizing steel slag aggregates.

Mohammad Imran Khan

Civil Engineering

December 1998

Abstract

Harsh climate, heavy traffic, inappropriate mix design and, most importantly, use of low-quality limestone aggregates have resulted in unsatisfactory slurry seal and micro surfacing performance in the eastrn region of Saudi Arabia. The use of emulsified asphalt slurry seal and micro surfacing is convenient and preferable over the other pavement maintenance techniques because they provide all the desirable characteristics of many maintenance techniques without creating any environmental related problems. The major concern is how to improve the performance of slurry seal and micro surfacing mixes to suit local traffic and environmental conditions.

Large amounts of steel slag aggregates, a superior quality industrial aggregate with some of the desirable aggregate qualities, are being produced and put to waste every year at Hadeed company in Jubail, Saudi Arabia.

The research was initiated to understand the potential problems and identify the factors affecting the performance of slurry seal and micro surfacing. In addition, different techniques were analyzed in order to improve certain engineering characteristics of slurry seal and micro surfacing mixes. For this purpose, blending of steel slag aggregates with limestone and modification of these mixes with hydrated lime and cement was carried out after which these mixes were tested in the laboratory for performance evaluation. The obtained test data was analyzed both objectively and statistically for the identification of factors affecting the mix performance. Based upon these test results, both the test parameters and optimum mix design parameters models were generated for the different slurry seal and micro surfacing mixes. The test results indicate that the proper blending of steel slag aggregates with limestone aggregates can significantly improve the performance of slurry seal and micro surfacing mixes.

Performance Optimization and Modeling of Slurry Seal and Micro Surfacing Utilizing Steel Slag Aggregates

by

Muhammad Imran Khan

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

December, 1998

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PERFORMANCE OPTIMIZATION AND MODELING OF SLURRY SEAL AND MICRO SURFACING UTILIZING STEEL SLAG AGGREGATES

BY

MUHAMMAD IMRAN KHAN

A Thesis Presented to the
FACULTY OF THE COLLEGE OF GRADUATE STUDIES
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KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

Dhahran 31261, Saudi Arabia

This thesis, written by **Muhammad Imran Khan** under the direction of his thesis advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of College of Graduate Studies in partial fulfillment of the requirements of the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING.**

Thesis Committee

Dr. Mohammad A. Al-Sughaiyer
Thesis Committee Chairman

Dr. Hamad I. Al-Abdul Wahhab
Thesis Committee Co-Chairman

Dr. Ibrahim M. K. Asi
Member

Dr. Hassan M. Al-Ahmadi
Member

Dr. Omar S. Baghabra Al-Amoudi
Member

Dr. Sahel N. Abduljauwad
Department Chairman

Dr. Abdallah M. Al-Shehri
Dean, College of Graduate Studies

28-12-98
Date

In The Name of ALLAH

The Most Gracious

The Most Merciful

Dedicated to

My esteemed Father,

Mother, Sister and Brother

Whose sincere

Love, prayers and encouragement

Led to this tremendous achievement

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LIST OF ABBREVIATIONS

AEMA	Asphalt Emulsions Manufacturers Association
ANOVA	Analysis of Variance
ASTM	American Standard for Testing and Materials
ISSA	International Slurry Seal Association
LWT	Loaded Wheel Test
MOC	Ministry of Communications
LS	Full Limestone Aggregates
P8LS	Passing Sieve # 8 Limestone Aggregates
P30LS	Passing Sieve # 30 Limestone Aggregates
30%LS	30% Limestone Aggregates by Weight
60%LS	60% Limestone Aggregates by Weight
SS	Full Steel Slag Aggregates
Type I	Aggregate Gradation Type I Recommended by the ISSA
Type II	Aggregate Gradation Type II Recommended by the ISSA
Type III	Aggregate Gradation Type III Recommended by the ISSA
WTAT	Wet Track Abrasion Test

THESIS ABSTRACT

NAME : MUHAMMAD IMRAN KHAN
TITLE OF STUDY : PERFORMANCE OPTIMIZATION AND MODELING OF SLURRY SEAL AND MICRO SURFACING UTILIZING STEEL SLAG AGGREGATES
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DATE OF DEGREE : DECEMBER 1998

Harsh climate, heavy traffic, inappropriate mix design and, most importantly, use of low-quality limestone aggregates have resulted in unsatisfactory slurry seal and micro surfacing performance in the eastern region of Saudi Arabia. The use of emulsified asphalt slurry seal and micro surfacing is convenient and preferable over the other pavement maintenance techniques because they provide all the desirable characteristics of many maintenance techniques without creating any environmental related problems. The major concern is how to improve the performance of slurry seal and micro surfacing mixes to suit local traffic and environment conditions.

Large amounts of steel slag aggregates, a superior quality industrial aggregate with some of the desirable aggregate qualities, are being produced and put to waste every year at Hadeed company in Jubail, Saudi Arabia.

This research was initiated to understand the potential problems and identify the factors affecting the performance of slurry seal and micro surfacing. In addition, different techniques were analyzed in order to improve certain engineering characteristics of slurry seal and micro surfacing mixes. For this purpose, blending of steel slag aggregates with limestone and modification of these mixes with hydrated lime and cement was carried out after which these mixes were tested in the laboratory for performance evaluation. The obtained test data was analyzed both objectively and statistically for the identification of factors affecting the mix performance. Based upon these tests results, both the test parameters and optimum mix design parameters models were generated for the different slurry seal and micro surfacing mixes. The test results indicate that the proper blending of steel slag aggregates with limestone aggregates can significantly improve the performance of slurry seal and micro surfacing mixes.

MASTER OF SCIENCE DEGREE
KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN 31261, SAUDI ARABIA

خلاصة الرسالة

إسم الطالب : محمد عمران خان.

عنوان الدراسة : نمذجة وتحسين أداء الملاط المحسن و الملاط الأسفلتي باستخدام حصمة خبث الحديد.

التخصص : هندسة مدنية (نقل).

تاريخ الدرجة : كانون أول/ديسمبر ١٩٩٨م.

نتج عن كل من المناخ القاسي، والمرور الثقيل، والتصميم الغير ملائم للخلطات، وأهم من ذلك، استعمال حصمة جيرية متدنية النوعية، أداء غير مرضي للملاط الأسفلتي والملاط المحسن في المنطقة الشرقية من المملكة العربية السعودية. ويعتبر استخدام الملاط الأسفلتي والملاط المحسن أفضل من غيرهما من تقنيات صيانة الطرق الأخرى وذلك لأنهما يوفران كل الخصائص المرغوبة من تقنيات الصيانة بدون إيجاد أي مشاكل بيئية. إن الهدف الرئيسي من هذه الدراسة هو تحسين أداء الملاط الأسفلتي والملاط المحسن لكي يناسب المرور المحلي والظروف البيئة المحلية.

وتنتج شركة حديد في مدينة الجبيل في المملكة العربية السعودية، كميات كبيرة من خبث الحديد يتم هدرها سنويا. بالرغم من ذلك، فإن خبث الحديد يعتبر حصمة صناعية ذات نوعية جيدة يمكن استخدامه في الخلطات الأسفلتية إذا ما تم تصميمه تصميما صحيحا.

بدأ هذا البحث بدراسة المشاكل المصاحبة للملاط الأسفلتي والملاط المحسن والعوامل التي تؤثر على أداء تلك الخلطات. بالإضافة لذلك، فقد تم تحليل تقنيات مختلفة لتحسين أداء الخصائص الهندسية لكل من الملاط الأسفلتي والملاط المحسن. ومن أجل ذلك، مزجت كميات مختلفة من خبث الحديد مع الحصمة الجيرية وحضرت خلطات مختلفة، ومن ثم تم تقييم أداء هذه الخلطات بإجراء فحوص خبرية مختلفة. حللت نتائج هذه الاختبارات بشكل موضوعي وبشكل إحصائي للتعرف على العوامل التي تؤثر على أداء الخلطات المختلفة. واعتمادا على نتائج هذه الاختبارات يمكن استنتاج، تم تطوير نماذج رياضية لتصميم خلطات الملاط الأسفلتي والملاط الأسفلتي المحسن لكي تحقق مواصفات الأداء المطلوبة، وكذلك نماذج للتنبؤ بمواصفات الخلطات المختلفة. أشارت نتائج الاختبارات بأنه إذا تم مزج الحصمة الجيرية بخبث الحديد بالنسب الملائمة، فإنه يتم الحصول على خلطات ملاط أسفلتي وملاط أسفلتي محسن ملائم للظروف البيئية وظروف المرور المحلية.

ماجستير علوم هندسية
جامعة الملك فهد للبترول والمعادن
الظهران ٣١٢٦١, المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 General

After the era of rapid infrastructure development of road networks in the Kingdom of Saudi Arabia, the maintenance of the huge existing roadway systems, which began to deteriorate within a very short time, becomes a major concern to the Saudi highway authorities. Early pavement failures in the form of loss of skid resistance, surface aging and deterioration have been observed in most of the areas. The most probable causes of these premature pavement failures in the Kingdom were identified to be the heavy traffic loads, use of marginal aggregates, and the harsh and extreme environment (Al-Dhalaan et al., 1990). In the eastern and eastern part of the central region of the Kingdom, one of the most important causes of early pavement deterioration was the use of low-quality limestone aggregates (Khan, 1988). The aggregates available in these areas are carbonates of marine-origin with low crushing strength, low resistance to abrasion and polishing, and low soundness. At the same time, hundreds of tons of steel slag aggregate (a superior quality industrial aggregate) are being produced and simultaneously put to waste every year as a by-product from the steel manufacturing process by the Iron and Steel Company (Hadeed) in Jubail Industrial City, Kingdom of Saudi Arabia. This dumping of steel slag aggregates (usually exceeding 800,000 tons per year) can also cause a disposal problem (Umaru, 1997).

Most of the pavements in eastern Saudi Arabia have begun to deteriorate, therefore, it is highly desirable to set an appropriate pavement maintenance (both corrective and preventive) program. The type, frequency, and degree of maintenance on such pavements can significantly influence its performance in the long run. In addition, it can influence the time at which major rehabilitation is required. The use of steel slag aggregates has been considered as a potential as well as feasible substitute for the available poor quality aggregates in any roadway construction project all over the world. Hence, it can be utilized as a replacement (either partial or full) for the conventionally-used low-quality limestone aggregates for performance improvements, even for highway maintenance projects.

Maintenance of pavements consists of a set of activities directed towards keeping a structure in a serviceable state. Proper selection of maintenance type and program is important for the increased serviceability life of any pavement. Slurry seal and micro surfacing are considered famous maintenance techniques throughout the world. Figure 1.1 shows the typical performance curves of pavements with or without

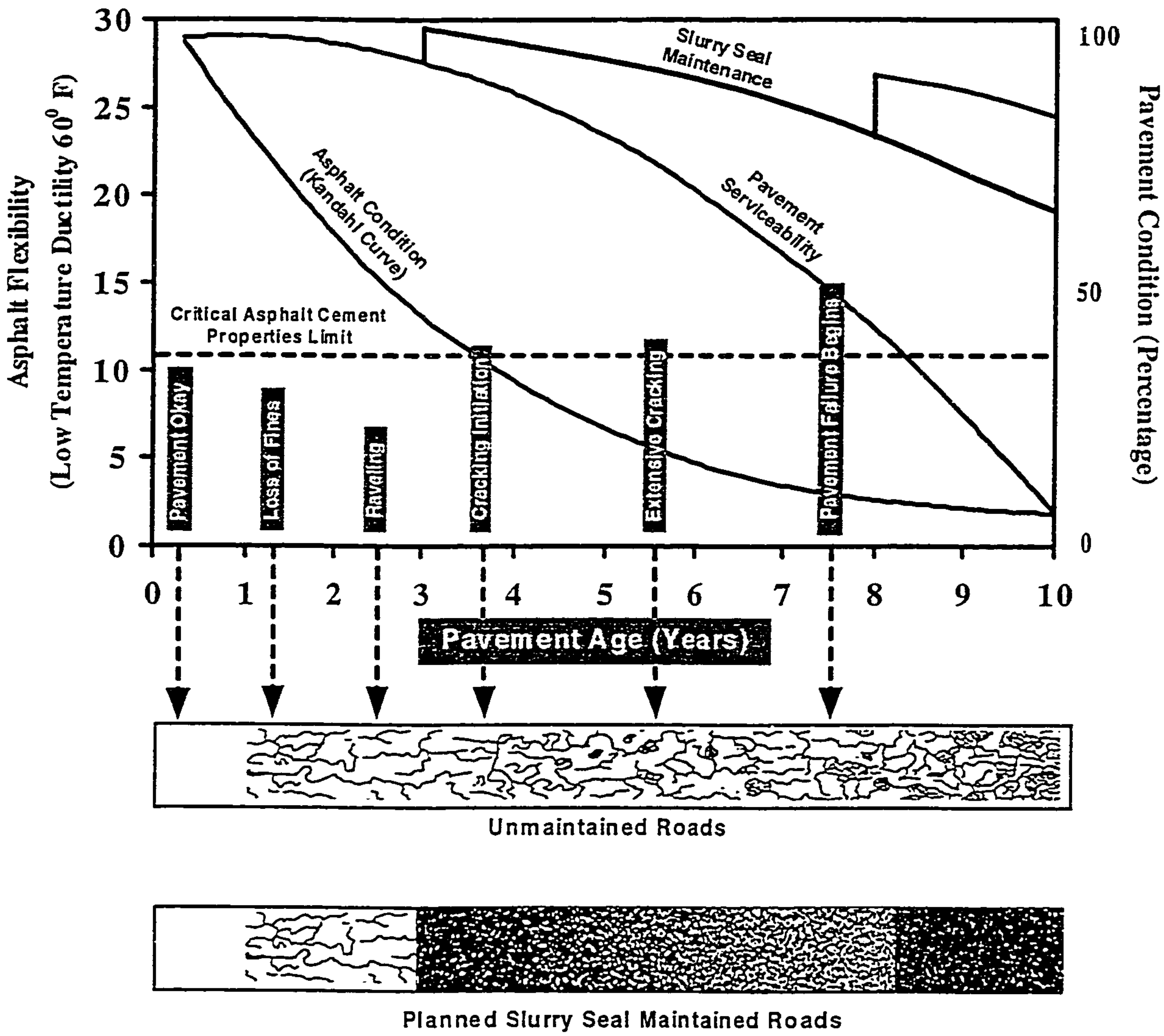


Figure 1.1: Pavement Performance Curve (ISSA, 1986)

having proper maintenance plan utilizing slurry seal; the latter can result in total pavement failure within a short period due to the accumulation of distresses.

Slurry seal and micro surfacing can correct problems of excessive wear, raveling, asphalt flushing, polished aggregate, and surface aging. This is because slurry seal and micro surfacing provide a completely new wearing surface over the existing pavement. On the other hand, overlay on such pavements may be very expensive as well as time-consuming and can cause problems of build-up at curbs, difficulty in maintaining drainage gradient, and manhole depressions due to the considerable increase in the total pavement thickness. This problem can be solved utilizing slurry seal and micro surfacing that require less thickness. They are considered effective, time saving, environmentally friendly, and less expensive solutions towards most of the surface failures of existing asphalt pavements (ISSA, 1991).

In brief, applications of slurry seal and micro surfacing are effective means for serving the following purposes: a) restrict the entrance of moisture to the subgrade through the existing pavement; b) fill surface voids, cracks and minor depressions in the pavement; c) retard further oxidation of the existing pavement; d) provide an anti-skid surface at moderate cost; e) accomplish the above without creating the problems that arise from build-up at curbs, loose aggregate, asphalt bleeding, and atmospheric contamination which may accompany conventional chip or sand sealing and hot-mix. Slurry seal and micro surfacing laying machines are within the means of small contractors and small municipalities (ISSA, 1991, and Young, 1980).

1.2 Problem Definition

Due to the heavy loads and harsh climate of eastern Saudi Arabia, most of the laid pavements have started to fail functionally. Since slurry seal technology has many advantages over the others, it was applied with great enthusiasm for pavement maintenance projects in eastern Saudi Arabia. However, its performance was not adequate on many locations especially on roads with heavy traffic loading. In most of these projects, the laid slurry seal have deteriorated well before its estimated service life. This early deterioration could be attributed to the extreme traffic and environmental conditions, using low quality aggregates, and/or inappropriate mix design.

The use of emulsified asphalt slurry seal and micro surfacing is still preferable over the other maintenance techniques because they provide all the desirable characteristics of any maintenance technique without creating environmental related problems that may accompany conventional chip or sand-sealing and hot-mix. The major concern is how to improve the performance of slurry seal and micro surfacing to suit local traffic and environment conditions.

This research was initiated to understand the potential problems and identify the factors affecting the performance of slurry seal and micro surfacing.

1.3 Research Objectives

The main objective of this research study was to optimize the performance of slurry seal and micro surfacing mixes on the highways of the Eastern Province of Saudi Arabia utilizing steel slag aggregates. Therefore, different techniques were analyzed in order to improve certain engineering characteristics of slurry seal and micro surfacing mixes. For this purpose, blending of steel slag aggregates with limestone and modification of these mixes with hydrated lime and cement was carried out. The obtained test data was analyzed both objectively and statistically for the identification of factors affecting mix performance. Based upon these tests results, both the test parameters models and mix design parameters models were also generated for the different slurry seal and micro surfacing mixes. The following summarizes the research steps:

- Study the factors affecting the performance of slurry seal and micro surfacing mixes.
- Examine the feasibility of blending steel slag aggregates with limestone aggregates in order to improve certain engineering properties of slurry seal and micro surfacing mixes for field applications.

- Study the effectiveness of polymer-modified emulsion, Portland cement, and hydrated lime for increased resistance to high temperature susceptibility, abrasion loss, and asphalt flushing.
- Analyze the test data statistically for different parameters and develop prediction models, based upon the various test results, for generating optimized slurry seal and micro surfacing mix design consisting of steel slag and/or limestone aggregates.
- Perform economic analysis for several slurry seal and micro surfacing mixes.

CHAPTER 2

LITERATURE REVIEW

2.1 General

In the last two decades, the Kingdom of Saudi Arabia has passed through a period of tremendous infrastructure developments. The government has invested billions of Saudi Riyals into the construction of freeways, urban arterial and agricultural roads. Nowadays, when the major road development projects have essentially ended, maintenance of the existing roadway system becomes a primary concern to the highway authorities in Saudi Arabia. Among the various highway maintenance techniques, slurry seal and micro surfacing were adopted into many areas. Slurry seal and micro surfacing composed principally of graded aggregates, asphalt emulsion, water and, if needed, a mineral filler and/or an additive. Since the slurry seal technology has many advantages over the others, it was applied previously with great enthusiasm for pavement maintenance projects in the Kingdom. In the Eastern Province, slurry seal application started in the early 1980 when Saudi-

ARAMCO utilized slurry seal mixes in its maintenance projects at Dhahran, Ras-Tanura, and Abqaiq areas (Naji, 1988). As the desirability of using available materials both readily and locally is obvious in any roadway maintenance technique, locally available limestone aggregates were primarily used in these slurry sealing projects. However, not surprisingly at least now, the performance of the laid slurry layers on many locations, especially on heavily traveled roads, was not satisfactory. The slurry seal layers have deteriorated within 6 to 12 months, especially during the summer with air temperature ranging between 40^0C and 45^0C when the asphalt is relatively soft. It was found later that the major cause of this unsatisfactory slurry seal performance, was the use of low-quality limestone aggregates (Naji, 1988). Local limestone aggregates have inferior particle shape, low crushing strength, low abrasive resistance, low soundness values, low resistance to polishing, and low sand equivalent values (Umaru, 1997). The exceptionally low skid resistance of limestone aggregates as proven by low skid numbers for limestone mixes was also observed in a research project carried out by the Research Institute in 1996 (The Research Institute, 1996). Hence, when used with slurry mixes under harsh environment and heavy traffic conditions in the Eastern Saudi Arabia, these aggregate types show complete deterioration and failure to serve further within a very short period.

Locally available steel slag is a waste by-product of the steel manufacturing process that poses a serious disposal problem unless utilized. Slag aggregate has rough angular and durable particles, which makes its use ideal for surface treatment applications. Slag aggregate shows better surface characteristics than limestone aggregates, specifically; higher skid-resistance, higher sand equivalent value, higher crushing strength, better resistance to polishing and high soundness value (The Research Institute, 1996). However, the use of slag aggregates alone in the slurry seal and micro surfacing mixes may lead to segregation, stripping and mixing problems. This is due to the higher density, less affinity for asphalt as compared to limestone and rough surface texture of slag aggregate particles. The most critical problem with slag, which was noted in previous studies (Anani, et al., 1989), is its high temperature susceptibility (high thermal conductivity) which requires appropriate modification prior to any field application. Feasibility of blending steel slag with limestone aggregates has been investigated in many research studies worldwide. For example, Al-Abdul Wahhab, et al. (1986) have reported that the replacement of the coarse portion of limestone with steel slag can significantly improve the stiffness of asphalt concrete mixes as well as decrease the required pavement thickness as compared to those mixes consisting of pure limestone aggregates. Another study, which was carried out in the United States, indicated that the improvement of asphalt concrete mix properties is very likely to be achieved by proper proportioning of limestone with steel slag aggregates (Noureldin et al., 1990). The use of steel slag aggregates has been considered as a potential as well as feasible substitute for the available poor quality aggregates in any roadway construction project (Anani et al., 1989 and Skerritt 1993).

2.2 Slurry Seal and Micro Surfacing

2.2.1 General Description

Slurry seal mixes are composed mainly of well-graded aggregates, water, mineral fillers, and/or additives uniformly mixed with a specified type of emulsified asphalt. These mixes are cold-mix, free-flowing and self-leveling paving systems and provide an impervious and non-skid surface, filling cracks, and improving night-time visibility. In some cases, they are also employed as a temporary-wearing surface in order to prolong the life of an existing pavement by preventing oxygen and radiation from reaching the original pavement (Bolzan, 1987). Its effectiveness as a method for routine maintenance has been proven in several countries all over the world. Continuing advancements in mixing methods, emulsions and machinery have made slurry surfacing provide durable, low cost paving and surface maintenance (ISSA, 1991).

Slurry surfacing is mixed in specially designed equipment; either truck mounted or self propelled. This equipment carries a quantity of unmixed materials that are blended together in a continuous flow. Mixing and spreading are accomplished in one continuous operation. As the machine moves forward, the mixture is continuously fed into a full width 'surfacing' box which spreads the slurry across the width of a traffic lane in a single pass. The new pavement surface initially has a dark brown color which changes with time to black surface as the water is evaporated and the surface is cured and normally re-opened to traffic within a few hours (Young, 1980).

Micro surfacing is a newer version of slurry seal in which polymer-modified emulsified asphalt is used. The main advantages of using micro surfacing is its thicker layer applications and better resistance to higher temperature damages, when compared with the original slurry seal. This improvement in performance is due to the addition of rubberized polymer materials in the emulsified asphalt that provides higher tensile strength and flow resistance at high temperatures as well as elastic and flexible behavior at low temperatures. It also improves adhesion between the binder and the aggregate as well as better cohesion within the binder (ISSA, 1991).

The service life of a slurry seal or micro surfacing depends mainly upon the selection of materials, effectiveness of design adopted, method of placement, and prevailing environment and traffic conditions (Scrimsher, 1980). Research by Naji (1988), indicated that the aggregate type and quality have a dominating effect on the service performance of slurry seal. A successful slurry seal should normally have the following characteristics (Bolzan, 1987):

- Sufficient levels of abrasion resistance
- A consistency which will ensure that the emulsion does not separate from the aggregate during placement
- An optimum curing time, short enough to ensure that the road is closed to traffic for a minimum length of time, but long enough to ensure that the seal is not washed away by a sudden rainstorm.

Surface conditions, presence of surface and structural cracks, climate and volume and intensity of the traffic loads should all be taken into account when selecting the most suitable slurry seal and micro surfacing type (Mills, 1983).

Cured slurry seal and micro surfacing made with properly-selected and proportioned ingredients provide resistance to skid. Their applications produce no contamination of any kind because no volatile and harmful substances are utilized. No damage can result from bits of flying rock, because all the aggregate is attached to the road through an asphalt bond. Properly-applied slurry seal and micro surfacing is of pleasing appearance being uniform in color and smooth in texture. Their surfaces are normally so thin that undesirable build-up at curbs, gutters, and manholes is avoided. Hence, it is especially suitable for surface treatments within city limits where increase in roadway thickness is not beneficial, as it will affect the drainage gradient (Young, 1980). Where traffic loads are light in volume and low in intensity, multiple courses of micro surfacing placed on properly-prepared bases, can also form a complete quality pavement. Micro surfacing may be applied over old asphalt pavements and over PCC and brick. Multi-layered applications provide economical asphalt surfacing in areas remote from hot-mix plants. Years of extended life may be given to highly-distressed pavements by this method of construction (ISSA, 1991).

2.3 Materials Utilized in Slurry Seal and Micro surfacing Mixes

2.3.1 Emulsified Asphalt

Asphalt (or bitumen) is a naturally occurring product, obtained primarily as the residue from the distillation of crude petroleum. At room temperature, it is neither solid nor liquid. It appears to be solid, but will flow slowly under its own weight. When made to coat almost any material, it adheres with great tenacity. Thus, it constitutes a very effective binder to hold aggregate particles together and to attach them to the road base (Young, 1980). In order that an aggregate may be properly coated with asphalt, it is necessary that the asphalt be made more fluid. This can be achieve by either of three ways, namely a) by heating; b) by dissolving it in a lighter hydrocarbon fraction such as kerosene; or c) by making it into a stable suspension in water, which is known as an asphalt emulsion, or emulsified asphalt. Asphalt in an emulsion form is of primary interest in the slurry sealing and micro surfacing processes. In fact, the development of slurry seal and micro surfacing has been strongly dependent upon progress made in producing asphalt emulsions having the desired characteristics (Young, 1980).

More specifically, an asphalt emulsion is a colloid of water, an emulsifier (surfactant) and asphalt. In emulsified asphalt manufacturing process, the asphalt and uniformly diluted emulsifier solution are pumped at proper temperature into a colloid mill. The mill includes a high-speed rotor that turns at a very close tolerance within a stator. The asphalt is sheared into micron-sized particles. Each particle is surrounded by the emulsifier and emulsion is thus formed (Root, 1979).

Electrically-charged emulsifiers are added in order to suspend the asphalt particles. The particles remain in suspension because all emulsifier layers have the same electrical charge, which makes them repel each other. A negative charge denotes an anionic emulsifier, while a positive charge is found in a cationic emulsifier. Anionic and cationic are the two types of emulsion commonly used for slurry sealing and micro surfacing (Root, 1979).

The emulsion normally has the following major properties according to the standard of ASTM D 2397 (ASTM, 1993):

- Asphalt residue content, 62.5%
- Water content of emulsion, 37.5%
- Saybolt Furol viscosity at 25^0C , 22 sec.

An emulsion breaks when the asphalt droplets begin to re-combine, setting is occurred when all asphalt particles have broken and combined into larger particles. The rate of breaking and setting is controlled primarily by the specific type and concentration of the used emulsifying agent, as well as atmospheric conditions (Root, 1979). Slurry seal or micro surfacing is considered cured when the asphalt particles have re-combined into a continuous film surrounding the aggregates, and the majority of the micro-droplets of water have been removed through evaporation (ISSA, 1991). Water displacement and evaporation can be rapid under favorable weather conditions but high humidity, low temperatures, or rainfall soon after slurry seal and micro surfacing application can deter proper curing (Scrimsher, 1980). Depending upon the emulsifier charge as well as the breaking, setting and curing times of the emulsified asphalt system, there are several types of emulsified asphalt among which the following are the mostly used types (Root, 1979):

- ***Slow Set Emulsion:*** Emulsions for slurries set when the evaporation of the water from the mix occurs. The aggregate type and gradations in the mix also play a significant role towards the determination of set time. Typical designations are SS-1h (anionic slow setting with base asphalt residue hardness one) and CSS-1h (cationic slow setting with base asphalt residue hardness one). These emulsion types are normally used in dense mixes where more time is needed to allow for mixing and lay down.

- ***Quick set emulsion:*** Emulsions for slurries that set by a chemical reaction between the emulsifier and the aggregate and/or other additives in the slurry systems. These are normally designated as CQS-1h and QS-1h.
- ***Micro-Surface emulsions:*** Polymer-modified emulsions, which are normally cationic, and having low pH value.

As discussed earlier, the use and type of emulsified asphalt is determined by the amount and type of added emulsifying agent and the types of used aggregate. However, cationic slow-set emulsions, Css-1h (both polymer-modified and non-polymer-modified), are more common in slurry system jobs because of their maximum stability and binding capabilities with wider range of aggregates. These emulsions are used with dense graded aggregates having high fine content. They have long workability times to ensure good mixing with the dense-graded aggregate (Root, 1979).

The following tests are usually performed for emulsified asphalt characterization (ASTM D 244, 1993):

- ***Particle charge test:*** The particle charge test is carried out to identify the emulsion charge. It is performed by immersing a positive electrode (anode) and a negative electrode (cathode) into a sample of emulsion and connecting electrode to a controlled direct-current electrical source. At the end of a specified period, the electrodes are observed to determine which pole has an appreciable layer of asphalt deposition on it. Cationic emulsions will migrate towards the cathode.

- ***Viscosity test:*** Viscosity is defined as a fluid's resistance to flow. The Saybolt Furol viscosity test as described for asphalt cements is used for emulsified asphalt to measure and specify consistency properties.
- ***Storage stability test:*** This test is used to determine the ability of emulsified asphalt to remain in a uniform dispersion during storage. It is a measure of the performance of the dispersion as related to time. A measured representative sample is placed in two glass cylinders. They are then allowed to stand at laboratory temperature for 24 hours. A 50 g sample from each cylinder is siphoned from the top. The samples are placed for a set time in an oven heated to a prescribed temperature. Then, they are removed, allowed to cool, and weighed. After the top sample is removed, all but a small portion of the asphalt emulsion remaining in each cylinder is siphoned off. A 50 g sample of the portion that is left is put through the same procedure as for the top sample. The storage stability is expressed as the numerical difference between the average percentage of residue in the top samples and the bottom samples.
- ***Residue by evaporation test:*** This test is designed to measure the percentage of asphalt cement in the emulsion by evaporating the water. The residue derived from this procedure usually yields lower penetration and lower

ductility than that from distillation. However, residue from evaporation can be used for other tests.

- ***Penetration test:*** An empirical measure of consistency in which a container of residual asphalt cement is brought to test temperature of 77^0F (25^0C) in a water bath. A needle of prescribed dimension, loaded to a weight of 100g is allowed to bear on the surface of the asphalt cement for 5 seconds. The unit of 0.1 mm, which the needle penetrates into the sample, is defined as the penetration.
- ***Ring and Ball softening point test:*** Used as a measure of consistency of residual asphalt. Samples of asphalt loaded with steel balls are confined in brass rings suspended in a beaker of water one-inch above a metal plate. The liquid is heated at a prescribed rate. As the asphalt softens, the balls and asphalt gradually sink, towards the plate. The moment the asphalt touches the plate, the temperature of the water is recorded and this is designated as the Ring and Ball softening point.
- ***Sieve test:*** The sieve test complements the settlement test and has a somewhat similar purpose. It is used to find the amount of asphalt in the form of large globules that may not be detected in the settlement test and could clog the spraying equipment. Such globules will not provide thin and uniform coatings of asphalt on the aggregate particles. In the sieve test, a representative

sample of emulsified asphalt is poured through a # 20 sieve. For anionic emulsions, the sieve and retained asphalt are then rinsed with a mild sodium oleate solution and finally with distilled water. For cationic emulsions, distilled water only is used for rinsing. After rinsing, the sieve and asphalt are dried in an oven and the amount of retained asphalt are reported as percent of the total weight of the sample. A complete information regarding the definitions and specifications of various emulsified asphalt types and tests that are currently used in paving technology is given in ISSA T-102, ASTM D 977, ASTM D 244 and ASTM D 2397.

The ISSA specifications regarding the recommended quality tests for emulsified asphalt are shown in Table 2.1.

2.3.2 Aggregate

Aggregates of high quality, durability, and crushing strength are mandatory for slurry sealing and micro surfacing jobs otherwise unsatisfactory end-product performance is easily obtained. Aggregate size and gradations also play a fairly important role (Dukatz., 1989). Crushed aggregate is important and should be used as the fractured face allows the particles to seat and lock together to better resist movement. Smooth textured sands of less than 12% water absorption shall not exceed 50% of the total aggregate blend.

Table 2.1: Recommended Quality Tests for the Emulsified Asphalt (ISSA, 1991)

Test	Quality Measurement	ISSA Specification
ASTM D 244	Sieve Analysis	-
ASTM D 244	Particle Charge	Type
ASTM D 2397	Penetration	40 - 90
ASTM D 244	Residue after Distillation	60% min.
ASTM D 36	Softening Point @ 77 F (25° C)	57°C min.
ASTM 2170	Kinematic Viscosity @ 275 F (135° C)	650 cSt/sec.

Aggregate gradation is one of the most important physical characteristics that determine the performance of a mix in the field. The proper grading of an aggregate is important because of its direct influence on the quality and cost of the pavement (O'flaherty., 1973). The gradation of an aggregate or aggregate blend is specified based on the total aggregate gradation, i.e. the total aggregate by weight passing particular sieve sizes. The aggregates generally used for slurry sealing and micro surfacing falls into three standard types according to their gradations. Each gradation is selected according to the surface condition of the pavement to be repaired, as recommended by the International Slurry Seal Association (ISSA, 1991). Table 2.2 lists the three gradation as recommended by the ISSA (ISSA A 105, 1991) and Ministry of Communications (MOC) for use in slurry sealing jobs (MOC, 1982).

Type I aggregate blend is used to seal cracks, fill voids, and correct moderate surface conditions. An approximate application rate of 3.3 to 5.4 kg/m^2 (6 to 12 lbs./yd^2) based on dry aggregate weight is used when standard aggregates are utilized. The fineness of this design provides it with maximum crack penetration properties. A typical example of this type of slurry seal would be on airfields or other areas where only protection from the elements is desired (ISSA A 105, 1991).

Table 2.2: Aggregate Gradation Recommended by the ISSA and MOC

(ISSA, 1991, and MOC, 1982)

		Aggregate Gradation Type		
		Type I % Passing	Type II % Passing	Type III % Passing
Sieve Sizes	3/8 (9.5 mm)	100	100	100
	# 4 (4.75mm)	100	90-100	70-90
	# 8 (2.36 mm)	90-100	65-90	45-70
	# 16(1.18 mm)	65-90	45-70	28-50
	# 30 (600 um)	40-65	30-50	19-34
	# 50 (330 um)	25-42	18-30	12-25
	# 100 (150 um)	15-30	10-21	7-18
	# 200 (75 um)	10-20	5-15	5-15

Type II aggregate blend is used when it is desired to fill surface voids, correct severe surface conditions, provide sealing and have a minimum thickness of wearing surface. An approximate rate of 5.4 to 8.1 kg/m^2 (10 to 15 lbs./yd^2) based on dry aggregate weight is used when standard aggregates are utilized. A typical example of this type of slurry surface would be on pavements with a medium textured surface that would require this size of aggregate to fill the cracks and provide a minimum wearing surface. Another example would be placing general slurry on flexible base, stabilized base, or soil cement (soil modified with small percentages of cement) as a sealer prior to final paving (ISSA A 105, 1991).

Type III aggregate blend is used to provide crown corrections and skid resistant surface. It is applied at the rate of 8.1 kg/m^2 (15 lb/yd^2) or more, based on dry aggregate weight for normal aggregate. A typical example of this type of slurry surface is the first and/or second of a two-course slurry treatment on flexible base, stabilized base or soil cement. Another example of this type of slurry surface would be on pavements that have highly textured surfaces and require this size of aggregate to fill voids and provide a moderate wearing surface (ISSA A 105, 1991).

Individual materials proposed for use in a slurry seal or micro surfacing mix design may individually meet existing specifications but not be compatible. The inability to form a stable slurry or micro surfacing with 3 or 4 minutes of mixing time when proper proportions of each ingredient are used, would indicate a mixture in which the materials are not compatible. While some emulsions break and begin to coat upon contact with an aggregate, there are other combinations of emulsions and aggregates in which the emulsion will not coat the job aggregate. Emulsions are usually anionic and negative charged or cationic and positive charged. Aggregates also posses surface charges that are positive, negative or mixed. Some aggregates tend to have a more predominant surface charge than other aggregates. If such an aggregate is mixed with an emulsion with the same charge, the charges repel each other and the emulsion might not adhere to the aggregate at all. A poor bond between the aggregate and binder may be encountered in such a mixture. A change in emulsion or aggregate is the way to correct this type of incompatibility. A recently crushed aggregate may contain an excessive charge and should be allowed to age (AEMA, 1981).

The following aggregate quality tests are recommended by the ISSA:

- **Sampling and grading (ASTM C 136):** This is the most common test performed on aggregates and covers the determination of the particle size distribution of the fine and coarse aggregate by sieve analysis. Gradation is perhaps the most important property of an aggregate. It affects almost all the important properties of a paving mixture, including stiffness, stability, durability, permeability, workability, fatigue resistance, skid resistance, and resistance to moisture damage.

- **Los Angeles Abrasion (ASTM C 131):** This test is often used to obtain an indication of the desired toughness and abrasion characteristics. This test is performed by mixing 5,000 g of aggregate blended to meet one of several gradings, along with a charge of six to twelve steel balls depending upon the selected aggregate gradations, each approximately 2 inches in diameter and approximately 400g in weight. This mix is tumbled inside a steel drum for 500 revolutions at a speed of 30-33 rpm after which the fines that pass a # 12 sieve are weighed, and the percentage loss by weight of original sample is calculated as the Los Angeles abrasion.
- **Soundness and durability (ASTM C 88):** The soundness test is an empirical screening test that is intended to provide an indication of the aggregate durability due to weathering. This test is useful for evaluating new sources of aggregate for which no service records are available. This test involves submerging the aggregate in a solution of sodium or magnesium sulfate. During this test, salt crystals grow in the aggregate pores and cause the particles to disintegrate in some aggregate. Presumably, this crystal formation simulates that of ice crystals and hence to some extent simulates the effect of freezing and thawing. An oven-dried sample of the aggregate is separated into specified sizes and immersed in a saturated solution of sodium or magnesium sulfate. The aggregate remains in the solution at a constant temperature for

around 18 hours. The sample is then removed from the solution, dried to constant weight at 230^0F and cooled. This cycle is typically repeated five times, after which the sample is washed to remove the salt and is dried. The loss in weight for each size fraction is determined by sieving, and the weighted average percent loss for the entire sample is computed.

- **Sand equivalent (ASTM D 2419):** The sand equivalent test is used to determine the relative proportions of plastic fines and dust in fine aggregates. In this test, 85 ml of aggregate passing a # 4 sieve is agitated in a transparent cylinder which is filled with a mixture of water and a flocculating agent. After agitation and 20 minutes of setting, the sand separates from the flocculated clay, and the heights of clay and sand in the cylinder are measured. The sand equivalent is the ratio of the height of sand to the total height of sand plus clay times 100. Cleaner aggregate will have a higher sand equivalent value.

The ASTM specification limits for the recommended quality tests of aggregates are given in Table 2.3

Based on the type of use, two types of micro surfacing mixes (unlike slurry seal where all the three types of gradation can be utilized) are designated by the International Slurry Seal Association (ISSA), that is, ISSA Type II and ISSA Type III (ISSA A 143, 1991).

Table 2.3: Recommended Quality Tests for the Aggregate (Hasan, 1994)

Test	Quality Measurement	Significance of the Test	Specification
ASTM D 2419	Sand Equivalent	Determines the amount of clay or plastic fines	60 min.
ASTM C 88	Soundness	Durability, Resistance to weathering disintegration and degradation	15 % max. using $NA_2 SO_4$
ASTM C 131	LA Abrasion Resistance	Hardness, Resistance to abrasion under traffic load	35% max.
ASTM C 136	Gradation	Calculation of emulsion content, effects surface texture, workability	ISSA I, II, or III
ASTM C 127 and C 128	Specific Gravity	Useful in making weight-volume conversions and calculating amount of binder required	-

Lee (1974) found that surface texture of paving mixes, which directly affects the skid resistance, is mostly effected by the aggregate gradation. Rice (1958) listed the following properties affecting the aggregate-asphalt adhesion in the presence of water: surface texture, surface coatings, particle size, surface areas, porosity, and adsorption, chemical reactivity and surface energy. In the survey of Fromm et al. (1974), stripping was found more prevalent in the asphalt mixes with aggregate having high silica content.

2.3.3 Additives

Additives may be added to the slurry seal and micro surfacing in order to adjust the workability of the slurry and/or to modify (accelerate or retard) the setting and curing characteristics. In addition, cement and hydrated lime addition most likely contribute to enhanced aggregate-binder bonding characteristics. Additives may come in the form of dry additives, liquid additives, and mineral fillers. Any additives added to the slurry seal or micro surfacing mixture or to any one of the component materials shall be added in a quantity predetermined by laboratory design (Young, 1980 and ISSA, 1991).

2.3.4 Water

Water forms an important part of the stable slurry and micro surfacing mix design it is a major factor determining the consistency of such slurries. It may be present in the form of moisture already in the aggregate, as pre-mixing water, and as one of the two major constituents of the emulsion: water and asphalt. All water used with the slurry seal and micro surfacing mixture shall be potable and free from harmful soluble salts (ISSA, 1991).

2.4 The Process of Deterioration of Pavements

2.4.1 Crack Appearance

Modern specifications for materials and methods of construction normally lead to asphalt pavements that are dense and durable. However, with extended exposure to the weather, the asphalt itself undergoes physical and chemical changes which gradually reduce its capacity to expand and contract with changes in its temperature and with possible small movements within the road base. This is due to age hardening process which results in oxidation of asphalt, that is, an increase in the carbon-oxygen ratio (usually called C/O ratio), which in turn reduces the asphalt flexibility making it hard and stiff. Such changes, supplemented by the forces that are exerted by the traffic, are most responsible for the appearance of cracks in the pavement. Once started, the deterioration proceeds at an accelerated rate, primarily because the cracked surface is no longer impermeable to water. If not sealed promptly and properly at this time, the initiated cracks grow and new ones appear, eventually forming an alligator pattern. Neglecting the distresses at this stage can lead to damage to the base. Then, the asphalt pavement, which has strength in compression only, may fail completely, and costly reconstruction becomes the only alternative (Young, 1980).

2.4.2 Moisture Damage

Stripping is recognized all over the world as a severe pavement problem. A continuos wetting of pavement due to rain, humidity or accidental leakage of water from service pipes is often observed to cause stripping. Fromm (1974) reported that stripping was evident throughout Ontario in Canada. Prithvi et al. (1989) mentioned, "it has been demonstrated experimentally that the tensile strength of asphalt mixes can be lowered to one-fourth of its original values by soaking in water for four days". Several causes of stripping have been advanced by previous investigators. They agreed that stripping is caused by water displacing the asphalt from the aggregate surface and it is mainly related to the aggregate quality and type (Al-Barrak, 1982).

2.5 Preventive Measures

Deterioration evident by the appearance of shrinkage cracks and stripping, can be arrested if such surfaces are sealed promptly and properly. Since slurry seal and micro surfacing are in a semi-fluid state, with most of the asphalt present as unattached droplets, it is a highly effective process for simultaneously filling existing small cracks in a pavement as it provides a completely new exposed surface. In addition to sealing the old pavement against moisture, the cured surface prevents moisture (or water), oxygen and sunlight from reaching the original pavement, thus effectively protecting its asphalt from further deterioration and oxidation as well (Young, 1980).

2.6 Causes of Unsatisfactory Slurry Seal Performance in Saudi Arabia

In Saudi Arabia, utilization of slurry seal is on a small scale. This is primarily because the performance of the laid slurry was usually not satisfactory. The pavement surface is normally abraded and aggregate particles are eroded within six to twelve months after the application of slurry seal Based only on observations the following factors contributed to the deterioration of slurry seal in Saudi Arabia (Bayomy et al., 1989):

Materials Related Factors:

- Type and quality of aggregate used
- Type and quality of additives used
- Type and quality of emulsified asphalt used
- Type and quantity of Portland cement used

Environment Related Factors:

- High temperature
- Heavy traffic
- Humid climate

Construction Related Factors:

- Operation
- Quality Control
- Cure Time

Original Pavement Base Related Factors:

Slurry seal and micro surfacing should not be laid on a pavement that does not have a completely sound base. Like all asphalt pavements, cured slurry seal and micro surfacing have little strength in tension and they will break easily instead of bending. Thus laid over an existing pattern of distress, for example, alligator cracks will soon develop the same pattern of cracks through reflection-cracking process (Young, 1980).

2.7 Discussion of Observed Problems

To date, the primary source of aggregate used for the roadway construction in various parts of eastern Saudi Arabia is limestone that comes into different types. The types of emulsified asphalt mixes used during the slurry and micro surfacing jobs were normally cationic slow setting emulsified asphalt (namely Css-1h). Normally, ordinary Portland cement or lime dust was utilized as mineral filler.

2.7.1 Problems associated with limestone

Aggregate type and quality has a important role in the performance of asphalt mixes. The availability of good quality aggregate is of concern in many countries including the USA and Canada. Limestone is a hydrophobic or water repelling material, with positive charge accumulated on the surface due to the constituting calcium carbonate, and has a good affinity for asphalt. However, the following problems are associated with its use (Roberts, 1992):

- The sand equivalent is relatively low as compared with other available aggregates (such as steel slag aggregate) for a value as low as 26% in the case of Dhahran limestone (Naji, 1988). This low value of sand equivalent indicates an increased amount of silty particles, which pose, reduced asphalt-aggregate bonding and several other problems. Although limestone is considered generally to produce adequate asphalt bonding in many cases throughout the world, the lower sand equivalent values for the local limestone results in a very poor quality of aggregate asphalt bonding. Past experience indicates that, whenever the sand equivalent is below a recommended minimum of 45, some or all of the following disadvantages may be experienced (Young, 1980):

1) the pure asphalt requirement is increased, without any compensating benefit; 2) excessive shrinkage accompanies cure; 3) the resistance to abrasion is decreased; and 4) for some emulsion types, the break is accelerated intolerably. Hence it is unwise to use any aggregate having a sand equivalent of 45 or less in any exposed slurry seal and micro surfacing projects.

- Limestone aggregates have low crushing strength. Due to the fragile nature of limestone aggregates, asphalt concrete pavements contain higher fine content than originally designed due to the break down of larger sizes resulting from compaction during construction and from heavy load repetition as well as the intensity of traffic action while in service (Roberts et al., 1991)
- Limestone consists mainly of soft minerals such as calcite and dolomite. This will tend to polish more rapidly than most other aggregate types. Hence, the skid-resistance of the laid slurry seal and micro surfacing will eventually be lost soon due to the continuing polishing of limestone aggregates (Roberts, 1992).

2.7.2 Problems with Emulsified Asphalt

As discussed previously, slurry sealing involves non-polymer-modified cationic (Css-1h) or anionic (SS-1h) emulsified asphalt. Previously, these two types of emulsified asphalt were used in slurry seal jobs in Saudi Arabia. However, the combination of Css-1h and limestone proved to be of less significance because of similar surface charges on emulsified asphalt particles and limestone aggregates. These phenomena results in similar charges repelling each other, which further results in poor aggregate-asphalt bonding in the long run (Roberts, 1992).

2.8 Steel Slag Aggregate

Slag is a by-product of the process of steel production from pig iron and/or steel scrap. The process used at Hadeed (Jubail, Eastern Saudi Arabia) in the Electric Arc Furnace (EAF) method is shown in Figure 2.1.

Figure 2.1 gives the schematic diagram describing the process of the EAF steel production. The process generally involves the following sequence of operations:

1. Charging the furnace with pig iron, steel scrap, fluxes of lime and dolomite, reducing agents and alloying agents in form of fello-alloys.
2. Addition of oxygen or fuel that melts the charge in the furnace.
3. Oxidation phase that involves the removal of carbon and silicon from the iron and steel scrap by oxidizing them. The lime and dolomitic flux combine with the oxidized constituents to form slag.
4. De-oxidizing or reduction phase in which oxygen and sulfur are removed from the slag.
5. The slag which floats on top of the molted crude steel can be poured off by tilting the furnace.

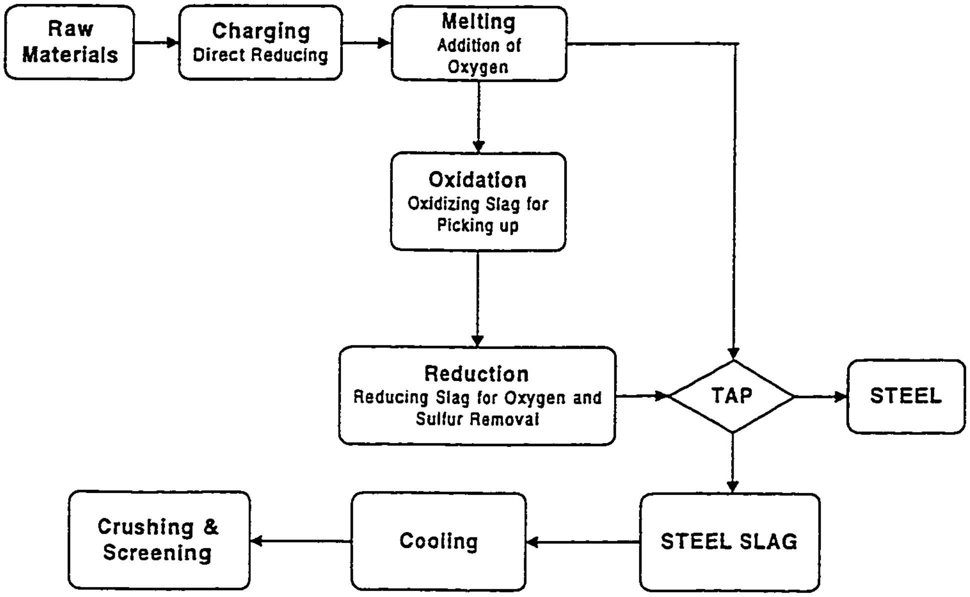


Figure 2.1: The Electric Arc Furnace Process (Heckett MultiServ Co.)

2.8.1 Utilization of Steel Slag Aggregate in Slurry Seal and Micro Surfacing Mixes

Uses of steel slag aggregate in asphalt concrete mixes have been increasingly gaining attention worldwide especially in areas where good quality aggregates are in short. Asphalt mixes consisting of steel slag aggregates have been successfully used in many countries including the United Kingdom, United States, Canada and Australia (Ali et al., 1992). This is mainly because paving mixes containing slag aggregates exhibit higher skid resistance and greater mix stability as compared to those of any other aggregate types (Heaton et al., 1995). The potential for slag aggregate use in the Eastern Province of Saudi Arabia has become an area of research interest to the pavement experts in the region. 800,000 tons of wasteful steel slag by-product are produced and put to waste at Hadeed company in Jubail, Saudi Arabia (Hecket Multiserve Co.). This tends to increase environmental or health risks associated with the disposal of the steel by-products, which could be put into use elsewhere. This may leave a legacy of hazardous points to the future environmentalists as well as the coming generations. Besides, the quarrying operations in the extraction of the conventional aggregates, for example limestone, would aggravate the use of such aggregates due to the nuisance from the accompanying dust, noise from the quarrying machines and rock cleavage and destruction of the natural scenic beauty of the quarry areas (Heaton, 1995). These factors support the idea of using of slag as an alternative to the conventional quarry aggregates. Many studies have been put forward by leading pavement researchers in which slag aggregates were successfully utilized in asphalt mixes. These mixes showed improvement in field performance in terms of resistance to rutting, polishing, and degradation, as well as higher skid resistance, shear strength, resilient modulus, and durability as compared to those of the locally available limestone aggregates (Al -Abdul Wahhab et al., 1995). It is anticipated that when steel slag aggregates are being used in slurry seal and micro surfacing mixes, the same behavior of performance improvement is obtained.

2.9 Properties of Steel Slag Aggregates.

2.9.1 Physical Properties

The load supporting capacity of an aggregate type is of great concern because they are the primary load carriers in a compacted asphalt paving mixture. In case of slurry sealing and micro surfacing systems, the load supporting capacity of aggregate has no less importance. This is due to the relatively thinner layer of slurry seal and micro surfacing mixture as compared with normal asphalt mixture. This thin layer increases the likelihood of aggregate crushing and polishing even faster than that which can be expected from any normal asphalt mixture. Hence, the use of good quality and high strength aggregate becomes inevitable in the slurry sealing and micro surfacing mixes. The following properties of slag aggregate make its use preferable over limestone (Lee, 1974 and Krebs et al., 1971):

- Slag aggregate has high values of sand equivalent normally ranging between 85-90% indicating less silty or clayey impurities.
- Steel slag consists of crushed angular particles with rough irregular surfaces. It is normally 100% crushed and angular in shape and has no flat or elongated pieces. On the other hand, limestone aggregates need to be crushed at the plant to produce the required number of crushed faces for mixes. In compacted mixes, steel slag particles exhibit greater interlock and internal friction, and hence result in mixes with greater mechanical stability as well as higher skid resistant surface.
- Slag aggregates are highly resistant to weathering and the effects due to freezing, thawing and thermal cycling. Sulfate soundness losses are exceptionally low (2-3%). On the contrary, limestone aggregates are less resistant to weathering effects with sulfate soundness losses of 6-12%. Hence, the use of slag aggregate at locations where heavy traffic and harsh climate is expected to yield improved results.
- The hardness of steel slag, which is a measure of its scratchability, is usually 7 as measured on the Moh's scale (Lee, 1974). This is a high value as compared to limestone and dolomite having values of 4 and 3, respectively, on the same

scale of hardness. The high value of its hardness is attributed to its glassy structure. Steel slag mixes, therefore, do not easily change gradation during loading in the field.

- Typical values of Los Angeles abrasion for steel slag range between 15 and 25 percent whilst those of limestone aggregate are between 30 and 40. This shows that the change in pavement surface roughness under traffic loads would be negligible in the asphalt mixes if steel slag were used as the aggregate.
- The only problem with steel slag aggregate is its higher temperature susceptibility as compared to limestone (The Research Institute, 1996).

Table 2.4 presents a comparison of some properties of limestone and steel slag along with ISSA specification limits.

2.9.2 Chemical Properties

The main composition of steel slag is lime, silica and iron oxide. Traces of alumina, magnesia, sulfur and oxides of manganese and titanium can also be found (Lewis, 1980). Table 2.4 gives typical chemical composition of steel slag, while Hadeed slag composition, as reported by the manufacturers is given in Table 2.5. Hadeed slag consists of 14-16% silicon dioxide, 42-45% calcium oxide, 6-8% aluminium, 11-15% magnesium oxide and 2.8-3.2% calcium oxy-silicate. The iron oxide in the slag is about 8-20% depending upon the quality of the steel produced.

Table 2.4: Typical Properties of Steel Slag and Limestone

Property	Steel Slag *	Limestone	ISSA Specification
Bulk Specific Gravity	3.2 - 3.6	2.5 - 2.8	-
Porosity (%)	< 3	-	-
Rodded Unit Weight (pcf) [ASTM C 38]	100 - 120	-	-
Los Angeles Abrasion Loss (%) [ASTM C 131]	15 - 25	30 - 40	35 Max
Sodium Sulfate Soundness (%) [ASTM C 88]	2 - 3	6 - 12	15 Max
Angle of Internal Friction (degrees)	40 - 50	20 - 35	-
Hardness (Moh's Scale)	6 - 7	3 - 4	-
California Bearing Ratio (%)	< 300		-
Polarity	pH (8-10)	-	-
Expansion (%) [ASTM D 4792]	0.2 - 0.5	-	-

*Lee, 1974

Table 2.5: Composition of Steel Slag (Lemass, 1992)

Compound	Composition (%)
Calcium Oxide (CaO)	25 - 42
Silicon Dioxide (SiO_2)	12 - 17
Aluminum Oxide (Al_2O_3)	2 - 4
Magnesium Oxide (MgO)	6 - 10
Iron Oxides (FeO & Fe_2O_3)	20 - 28
Calcium Sulfate ($CaSO_4$)	-
Manganese-IV Oxide (MnO_2)	8 - 12
Titanium Dioxide (TiO_2)	0 - 1
Free-Lime	2 - 4

Table 2.6: Chemical Composition of Hadeed slag

(Bayomy and Al-Abdul Wahhab, 1985)

Compound	Composition (%)
Calcium Oxide (CaO)	42 - 45
Silicon Dioxide (SiO_2)	14 - 16
Aluminum Oxide (Al_2O_3)	6 - 8
Magnesium Oxide (MgO)	11 - 15
Iron Oxides (FeO & Fe_2O_3)	8 - 20
Calcium Oxy-Silicate	2.8 - 3.2

These chemical components of slag indicate a high crushing strength and toughness that make it more resistant to wearing and traffic action.

2.10 Reasons of Poor Performance for Steel Slag Aggregates

Besides many added properties of slag aggregate when compared with those of limestone, it has failed to give satisfactory performance in the service life. The following may be the respective reasons:

- Slag aggregates have high coefficient of thermal conductivity and heat retaining properties resulting in reduced modulus of resilience and indirect tensile strength at high temperatures (Road Research, 1977). Thus, during the summer days, the asphalt mix consisting of slag aggregate becomes very hot resulting in an increased rutting and permanent deformation potential.
- Slag aggregates are acidic in nature. Hence, they have greater affinity for water than asphalt. That is why asphalt mixes consisting of slag aggregates are normally less resistant to stripping under wet conditions as compared to limestone aggregates (Kiggundu et al., 1986).
- Mixing problems are usually observed due to the rough surface texture, high specific gravity and angular particle shapes of steel slag aggregates (Roberts, 1992).

- Segregation problems are normally observed during the laying down of slurry seal and micro surfacing mixes consisting of slag aggregate. This is because of the high density, high specific gravity, and less porosity of slag aggregate.

2.11 Improving Slag Aggregate Performance

Although attempts were made to utilize slag aggregate in slurry seal mixes but no optimal performance was achieved. However, early results indicated that better performance is observed for any paving mixture when blend consisting of slag aggregate for the coarse part and limestone for the finer part is used (Al-Abdul Wahhab et al., 1986). Below is a summary of the different proposed methods to improve the slurry seal and micro surfacing mix performance using steel slag aggregate.

2.11.1 Aggregate Blend Improvement

As mentioned earlier, using slag aggregate alone leads to serious problems such as segregation, stripping and difficulty in mixing. Hence, it would be appropriate to utilize the goodies of slag aggregate, that is, higher crushing and abrasion resistance, by using coarser particles and at the same time utilizing also the goodies of limestone, that is, better bonding properties with asphalt film. This is achieved by replacing the finer part of the mix blend with limestone. Consequently, the end-product becomes more stable and resistant to stripping, abrasion, and crushing of aggregate particles, and will show less segregation and mixing problems.

2.11.2 Lime-Treatment

Lime is a filler material whose effect in the promotion of binder-aggregate adhesion is both mechanical and physio-chemical. Generally, when a mix is immersed in water, the water penetrates gradually into the asphalt-aggregate adhesion interface. For hydrophilic aggregates, the initial asphalt-aggregate adhesion is very weak. The penetrated water gradually builds up into an intermediate film at the interface causing the asphalt to strip off the aggregate (Ishi and Craus, 1977). This explains the swelling and reduction in the mix strength that occurs due to soaking.

Various theories have been put forward to explain the action of lime. When lime filler is added to the aggregate, the lime-asphalt mastic coats the aggregate. During penetration of the water through the mastic, hydration of lime occurs resulting into hydrated lime. In the presence of a water film at the binder-aggregate interface, the calcium ions of hydrated lime replaces the hydrogen ions in the silica acid formed due to reaction between water and the hydrophilic siliceous aggregate ions. In the process, calcium silicate coats the active points of the interface thus transforming the acidic aggregate surface into basic. The positive calcium ions have a high affinity to the acidic components of the asphalt which results into chemical adsorption between the two. This causes the asphalt to wet and spread on the hydrophilic aggregate surface. The excess hydrated lime is incorporated into the mastic forming an inverse asphaltic emulsion (Goetz., 1958)

Plancher et al. (1977) have reported that the effect of lime on the asphalt is to remove the polar molecules namely benzoic acid and phenols (quinolones). Removal of these polar functionalities reduces the ratio of asphaltenes formed to oxidation products formed on aging. Lime-treated asphalt mixes thus have reduced hardening due to oxidative aging. These mixes have less possibility to low temperature cracking since brittleness is lessened.

Research by Ishai and Craus (1977) has shown that when the hydrated lime-asphalt mastic coats the hydrophilic (water loving) aggregate, a substantial modification of the interface phenomenon can be observed. This modification creates durable adhesion in the presence of water, and hence improves greatly the stripping resistance of aggregate.

This process can be easily understood by considering the case of hydrophilic aggregate coated with a limestone filler-asphalt mastic. Since calcium carbonate ($CaCO_3$) is insoluble in water, the introduction of limestone filler in the asphalt will not modify the water penetration and the stripping resistance compared to pure asphalt. However, in the case of hydrated lime-asphalt mastic, a substantial modification of the interface phenomenon can be observed. The physio-chemical mechanism in the aggregate-asphalt interface is modified, which improves the adhesion properties, by the chemical adsorption between the acid radical of the asphalt and the calcium ions which coat the aggregate surface after the introduction of hydrated lime, and because of this effect asphalt tends to spread and wet the aggregate surface forming a better asphalt-aggregate bonding (Geotz, 1958). Thus, instead of using limestone filler, using hydrated lime is likely to significantly modify the surface chemistry of the hydrophilic aggregate.

Al-Barrak (1982) studied the effect of lime on the performance of hot mix asphalt. He prepared mixes by using lime at filler replacement of 0, 2, 4, and 6%. The results of his study on the effectiveness of anti-stripping agents showed that lime at a filler replacement of 2% is the most effective additive in improving moisture resistance of the local mixes in the Eastern province of Saudi Arabia. The loss in resilient modulus due to soaking improved by 14% after adding lime to the filler portion. Baig (1995) evaluated the performance of Hedmanite and lime modified asphalt mixes for the local mixes in the wearing course and base course. He prepared mixes in the laboratory at 0, 1, 2, 4, and 5.5% of lime. He determined the engineering properties of the mixes namely stability, split tensile strength, resilient modulus, fatigue and permanent deformation. His results show that lime at 2% is effective in enhancing moisture damage resistance of the local mixes. The stability loss improved by an average of 17% after lime addition.

Umaru (1997) replaced the filler portion of aggregates with 2% hydrated lime in the asphalt mixes. He reported that this replacement can significantly reduce the moisture susceptibility of asphalt mixes.

Another study performed by Peterson et al. (1982) has shown that lime treatment of asphalt mixes reduced asphalt age hardening, increased high-temperature stiffness of un-aged asphalt, reduced stiffness in aged asphalt at higher temperatures, and increased asphalt tensile-elongation at low temperature. These effects benefit the asphalt pavements by increasing asphalt durability, reducing rutting, shoving and other forms of permanent pavement deformation, improving fatigue resistance in aged pavements, and improving pavement resistance to low-temperature transverse cracking.

2.11.3 Addition of Ordinary Portland Cement (OPC)

The most commonly used cement is ordinary Portland cement, which is a finely powdered hydraulic cement, essentially consisting of hydraulic calcium silicates (specifications in AASHTO M 85 and ASTM C 150). The particle size of Portland cement ranges from 0.5 to 80 μm, with the major part of it passing ASTM # 200 sieve, and the specific gravity of the particles ranges from 3.12 to 3.20. The major compounds in Portland cement are tricalcium silicate, dicalcium silicates, tricalcium aluminate, and tetracalcium aluminoferrite. These compounds react with water to form very stable hydrated silicates and aluminates and also calcium hydroxide.

The use of cement in treating asphalt concrete mixes is not a new concept. Cement can be added as part of the filler in which case it affect the properties of the binder or it can be applied in slurry form to coat the aggregate. The later treatment method increases the aggregate surface roughness and improves the adhesion between the asphalt and aggregates. In coarse-grained soils, the cementation effect is similar to that in concrete, but cement paste does not fill the voids of the additive and is cemented only at the contact points. Cement paste bonds soil particles together by surface adhesion forces between the cement gel and particles surfaces. This cementing improves the shear strength, compressive strength and other engineering behavior of coarse-grained soils

Ishai (1977) concluded that adjusting the filler control in the mix improves the adhesion and he suggested that the use of Portland cement as a filler is a viable candidate. It was also noted that 1 to 2 % Portland cement was used in British practice to reduce stripping (Fromm, 1974). Geotz (1958) reported an increase in mix stability with the addition of cement to asphalt emulsion treated mixes.

Another research conducted by Bayomy (1992) has introduced a new technique of improving aggregates for the use of asphalt mixes. This proposed technique is referred to as “Cement Coating Technique” (CCT). The CCT addresses the surface texture of aggregate particles and improves the bond between the particle surface and the asphalt binder. The concept of the CCT is based on shielding the surface of the aggregate particles by a hydrated Portland cement film. The new cement coated aggregate can then be used in asphalt mixes following the usual mix procedures. Performance evaluation of such mixes indicated significant improvement achieved in permanent deformation, fatigue and moisture damage resistance (Bayomy, 1992).

Al-Barrak (1982) studied the effect of Portland cement on the performance of hot mix asphalt. He tried the cement at dosages of 0, 2, 4, and 6 percent. His results indicated that cement is effective in improving the 24hr. stability of local asphalt concrete mixes due to the hardening resulting from the hydration of cement when in contact with water.

The Ministry of Communications (MOC) calls for the use of cement as part of filler when stability loss exceeds 20 %. In the current study, it is envisaged that the technique of treating slag mixes with cement may present a solution to the stripping problem as well as other pavement distresses attributable to aggregate characteristics.

Cement can be added to the micro surfacing mix as part of the filler in order to enhance certain properties of the end-product. For example, the addition of cement improves the aggregate-asphalt bonding and helps produce more stable slurries.

In the current study, it is envisaged that the technique of treating slag mixes with cement may present a solution to the stripping problem as well as other pavement distresses that may be attributed to aggregate characteristics.

2.11.4 Polymer Modification of Emulsified Asphalt

In micro surfacing, polymer-modified emulsified asphalt is used. The polymer material is milled or blended in the asphalt or blended into the emulsifier solution prior to the emulsification process (ISSA, 1991).

Polymer modifiers offer a valuable tool in the improvement of asphalt mixes in problematic situations such as heavy traffic, high stress, poor aggregate and variable and harsh climates. The elasticity, tensile strength, adhesion, and resistance to temperature susceptibility of polymer-modified asphalt mixes impart improved stiffness moduli, rutting resistance, fatigue life, adhesion and stripping. Test results have been consistent with numerous field trials in demonstrating the effectiveness of polymer modification (Willliam, 1987). Temperature susceptibility of paving asphalt mixes can be improved by the addition of small percentages of polymers easily (Norman, 1987). Some polymer systems improve the age-hardening characteristics of the asphalt.

Polymer compatibility with asphalt is of utmost concern. If polymer separation occurs during shipping and storage at elevated temperatures, problems associated with inconsistent binder quality will develop. Materials, low in polymer content will not, however, exhibit the desired enhanced properties. This is a problem specially if the polymer is used to improve adhesion with stripping-sensitive aggregate or if the base asphalt was intentionally soft to maximize flexibility or cracking resistance. (Harold et al., 1987).

The polymer modifiers generally consist of rubberized materials. Styrenic block copolymers are normally employed to modify the physical and rheological properties of asphalt mixes. These thermoplastic block copolymers are composed of glassy, polystyrene endblocks and rubbery, polybutadiene mid-blocks. The polystyrene and polybutadiene blocks exist as two separates phases at typical pavement service temperatures. The resulting structure is a three-dimensional network of hard, spherical polystyrene domains in a rubbery matrix. These polystyrene domains act as physical cross-links which impart strength to the system. At temperatures above 100°C, the polystyrene remains soft and flows when shear is applied. Consequently, at elevated temperatures in the presence of shear, these polymers can be incorporated into asphalt easily. Upon cooling, the domains reform spontaneously, and the resulting rubbery network imparts elastic properties to the binder (Shulur et al., 1987). Research by Shuler et al. on polymer-modified asphalt binders has revealed the following conclusions (Shulur et al., 1987):

- The addition of certain block copolymers imparts increased viscosity, ductility, softening point, toughness, and tenacity to the original binder
- Rheology of the modified binders indicates that these materials exhibit much greater elasticity at elevated temperatures. In addition, the elastic modulus is reduced at low temperature and increased at high temperatures. Thus, providing improvement in temperature susceptibility of binder.

Many studies have been done locally on the use of polymers in asphalt mixes. Al-Dubabe (1996) carried out research on polymer modification of Arab Asphalt to suit the Gulf countries' performance requirements. The asphalt physical and rheological characteristics for locally produced binders were studied. A procedure for modifying asphalt binders using polymers was implemented so as to satisfy the performance requirements of the Gulf countries by considering rutting, fatigue and low temperature cracking. Temperature zoning that was done for these countries indicated that more than 50% of the Gulf countries experience a maximum pavement temperature of 76oC. The results of his study showed that styrene-butadiene-styrene (SBS) block copolymer at 3% by weight of asphalt, crumb rubber tyres (CRT) at 10% by weight of asphalt, polyethyrene-Grade 1182 at 3% by weight and polypropyrene-Grade 500U at 1.5% by weight of total asphalt blend, and their combinations were the most effective in improving the performance of the neat Arab asphalt binder rheological properties to meet and satisfy the performance requirements of the Gulf countries.

In another study carried out by Al-Abdul Wahhab (1994) entitled, "A Laboratory Study of Asphalt Mix Improvement Techniques and Test Methods to Assess Rutting Potential", two polymeric binder additives namely Novophalt and polybelt were used. Different combinations of dosages were tried for the two polymers. The results of his study showed that Novophalt at 4.4% by weight of mix and polybelt at 4% by weight of 40/50 penetration asphalt were highly effective in reducing rutting susceptibility of asphalt mixes in the hot Gulf environment.

Al-Dhalaan et al. (1990) carried out research on the comprehensive study of the rutting problem in Saudi Arabia. Their research shows that as part of the strategies laid by the Ministry of Communications, a methodology was developed to repair the pavement segments that had already rutted. Test sections were made on almost all corridors of the Kingdom. On the Riyadh-Qassim corridor, seventeen sections were made with varying asphalt concrete material compositions. Polymer modified asphalt concrete (Novophalt) was used in some of the sections on this highway with thicknesses of up to 15-cm. Tests on Novophalt and conventional 60-70 penetration grade asphalt were made. The results show that treatment with Novophalt improved the asphalt penetration from 60.7 mm to 32.1 mm, while the softening point increased from 49.3^0 C to 81.3^0 C for the wearing course. Non-conventional testing methods that were carried out on the mixes include resilient modulus, creep, split tensile strain, deflection testing (Dynaflect, FWD, Benkelman Beam) and ride-quality evaluation (Mays Ridemeter). After two years of continuous monitoring and testing, the Novophalt test sections showed better performance than those of conventional asphalt.

2.12 Mix Design and Evaluation Techniques

The design of slurry seal and micro surfacing mixture is an art rather than mere engineering and specifications. The present design methods are based on the experience of engineers and contractors and on the performance of existing slurry seal and micro surfacing coats. Since the conditions and materials vary widely with time and locality, only general specifications and guidelines for slurry seal and micro surfacing mixture designs have resulted from these experiences. There are many methods available for the design of slurry seal and micro surfacing. One such method is that of the American Society for Testing and Materials (ASTM D 3910) "Standard Practice for Designing, Testing, and Construction of Slurry Seals". The Ministry of Communications (MOC, 1982) has also specified the standard test method for "Design and Testing of Slurry Seal" (MRD Test Method 427), which is basically the adaptation of ASTM D 3910. In addition, the International Slurry Seal Association (ISSA) regularly publishes technical bulletins dealing with both slurry seal and micro surfacing mix design. In general, these standards enumerate the design requirements as aggregate gradation, emulsion content, mix consistency, and abrasion resistance of the mixture. These properties directly reflect the short and long term performance of slurry seal and micro surfacing under normal circumstances.

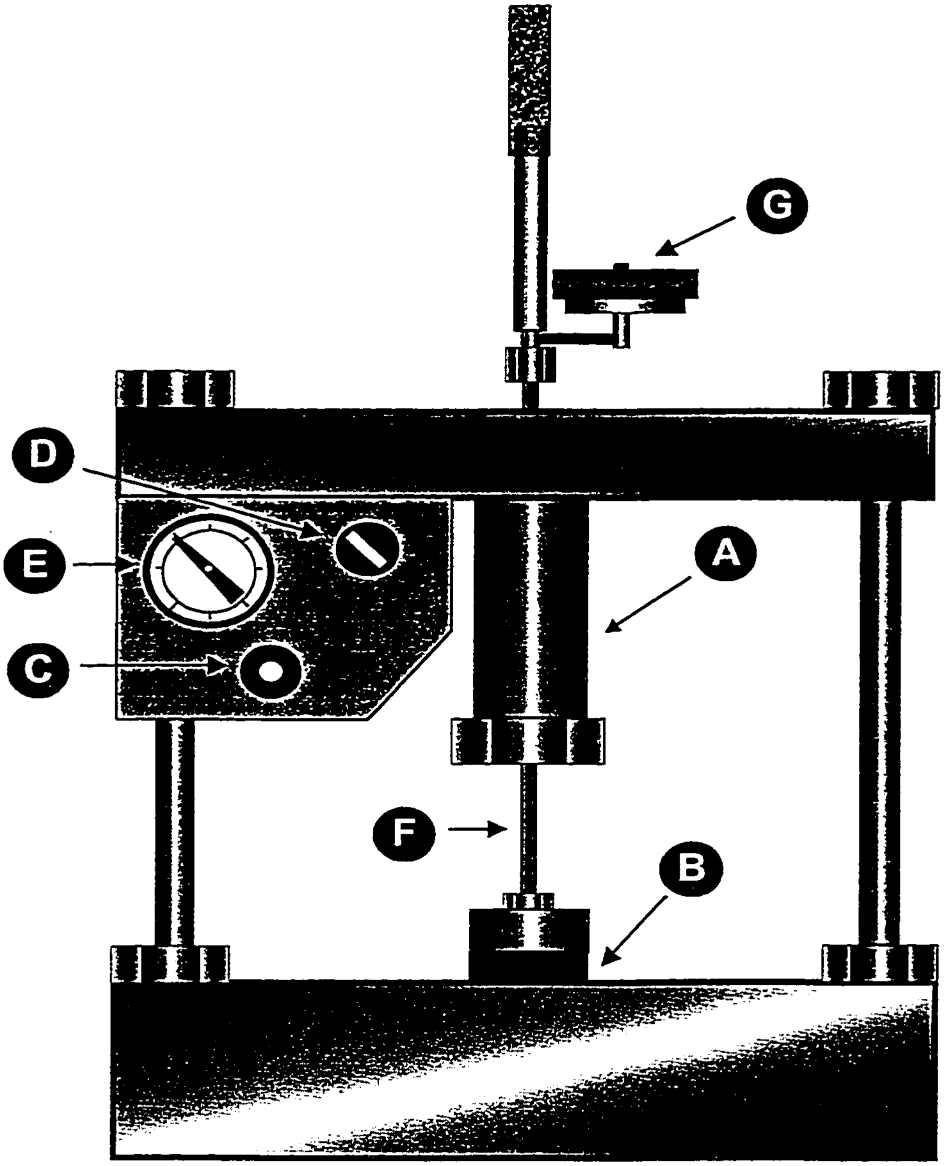
There are four basic objectives in the design of successful slurry seal and micro surfacing. These are : (i) a consistency that will allow placement at the proper thickness without causing separation of the emulsion and aggregate, (ii) sufficient emulsion to provide a "gluing" action to bond the slurry together and to the surface overlaid, (iii) a relatively stable and quick-setting characteristic that will permit unrestricted traffic use within two to three hours and will also resist the flushing by a sudden rainstorm, and (iv) a surface that, after curing, will provide the desired surface texture as well as strength characteristics (Young, 1980).

Since slurry seal and micro surfacing are mixtures of various materials, any change in a single component may change the performance of the system. Accordingly, a number of laboratory specimens are prepared and subjected to empirical testing. This involves the preparation of trial mixes with variations in the content of asphalt emulsion, water and mineral filler, and additives as desired to determine the effects of change on mixing, breaking, and setting characteristics in order to ensure a good control of the system in the field (Hasan, 1994).

A variety of test methods and procedures has been developed over the years to characterize slurry seal and micro surfacing mixes. Hveem surface area design method, developed by the Public Works, is used to determine the amount of asphalt required to coat the surface area of the aggregate, the absorption characteristics of the aggregate, and the total asphalt content (Root, 1979). Methylyne Blue Value (MBV) should also be calculated in order to determine the compatibility of the emulsion and aggregate. MBV also indicates the aggregate reactivity and aids in determining the additives requirements. This test measures the pH of the water that is exuded from the sample patty using a litmus paper. A pH change of 2 to 10, of the emulsified asphalt mixture immediately on setting, is considered desirable for any slurry seal and micro surfacing mixes (Hasan, 1994).

A consistency test is normally performed to determine the optimum mix design for emulsion, aggregate, mineral filler and water for proper consistency for pavement surface placement. When tested in accordance wit ASTM D 3910, the mix design shall have radial flow limits between 2.0 to 3.0 centimeters. For this purpose, a mold in the form of a frustum of a cone 38 mm in diameter at the top, 89 mm in diameter at the bottom and 76 mm in height is utilized as the slump measuring device. The center of a 228 by 228 mm piece of 3 mm thick metal plate is inscribed with a circle 89 mm in diameter. Three to four additional circles, each 13 mm greater in diameter than the preceding circle, are inscribed on the metal plate around the center circle. These circles serve as flow measuring means. The mold is loosely filled with a test slurry mix and struck off. The mold and contents are then inverted in the center of the metal plate and is removed and the contents are allowed to flow over the inscribed circles until the flow of the slurry seal or micro surfacing stops after which the flow distance is measured (ISSA, 1991). An extremely simple test for slurry consistency that can be made anywhere is to draw a solid object, such as a stick, through a sample of the mixture concerned. If the resulting surface depression persists more or less indefinitely, the slurry is of proper consistency. On the other hand, if such a depression fills quickly with the liquids present, leaving an essentially smooth horizontal surface indicates an excess of liquid in the slurry. This indicates that less water or more filler is required for better consistency (AEMA, 1981).

The modified cohesion test (ISSA TB 139), the test setup is shown in Figure 2.2, is used to classify the slurry and micro surfacing by set time and traffic time. The cohesion tester is a power steering simulator that measures the torque required to tear apart 6 or 8 mm thick and 60 mm in diameter specimen under the action of a 32 mm diameter rubber foot loaded to 200 kPa. Torque measurements are made at suitable time intervals such as 20, 30, 60, 90, 150, 210, and 270 minutes after sample casting. These measurements are taken at these intervals until the traffic time criteria have been achieved or until the sample is cured (when no increase in torque value is observed between two successive test readings). A system is defined as quick-set if it develops a torque value of 1.2 N.m within 20 to 30 minutes. Similarly, a quick traffic system is defined as the mixture that develops 1.96 N.m torque within 60 minutes. A torque of 1.2 N.m is considered the cohesion value at which the mixture is set, water resistant and cannot be remixed. At 1.96 N.m, sufficient cohesion has developed to allow rolling traffic. A



Apparatus Parts Code

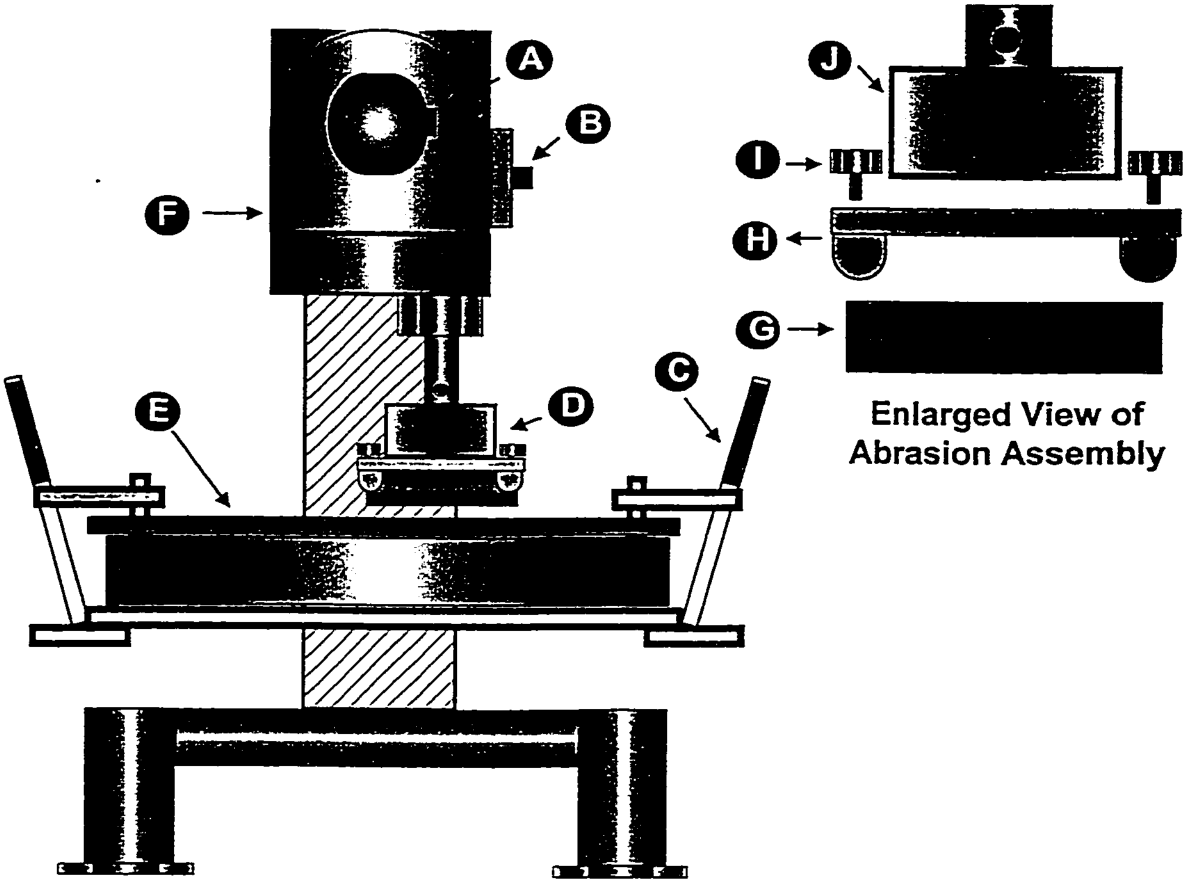
A. 1-1/8" dia double rod end air cylinder with 5/16" dia rods and 3" stroke
B. 1/4" x 1-1/8" dia 60 durometer neoprene rubber foot
C. Air pressure regulator with a variable down stream bleed valve so that constant pressure is maintained
D. Four-way directional control valve with exhaust port regulating valves
E. Air pressure guage with a 0 to 700 kPa (kg/sq.cm) pressure guage
F. 700 kPa (100 psig) air supply
G. Torque meter capable of measuring and marking at least 35 kilogram-centimeters (kg-cm) torque

Figure 2.2 : Apparatus Setup for Wet Cohesion Test

properly-designed slurry seal and micro surfacing mix should be completely cured and opened to traffic at the end of 24 hours after placement (ISSA TB 139, 1990).

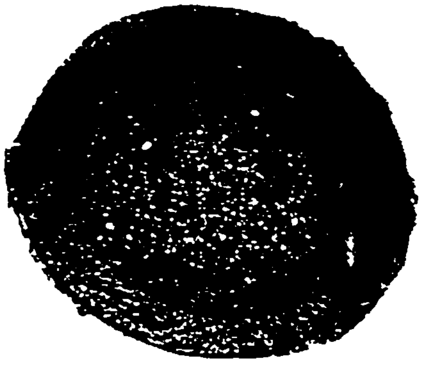
Wet track abrasion test (WTAT) is intended for measuring the wearing qualities of the slurry seal and micro surfacing surfaces by simulating wet abrasive conditions such as vehicle turning and braking. It may also be used for design purposes in selecting the optimum emulsion and water content to use in slurry seal and micro surfacing mixes. The test apparatus is shown in Figure 2.3. A cured sample, 6 mm thick and 280 mm in diameter that has been soaked for period of 1-hour, is immersed in a water pan at 25^0C temperature and is wet abraded by a rotating weighted (2.3 kg) rubber hose for 5 minutes at the same temperature. The abraded specimen is dried to 60^0C and weighed. When tested in accordance with ISSA TB100, the slurry seal should have a loss of not more than 800 g/m^2. In the case of micro surfacing, the specification limit changes to 538 g/m^2 under the same test conditions (ISSA TB 100, 1990).

Loaded wheel test is used to determine the maximum asphalt content that can be used without causing asphalt flushing in slurry and micro surfacing systems. This is accomplished by specifying and measuring the fine sand that adheres to the sample subjected to simulated wheel loading. The ISSA recommends a maximum sand adhesion value of 0.54 kg/m^2 at room temperature for heavy traffic. However, this specification limit extends to 0.61 kg/m^2 if the testing temperature is increased to 50^0C (details given in Chapter 4). If the sand



Hobart A120 Mixer Setup for WTAT Abrasion Loss Test

Enlarged View of Abrasion Assembly



Abraided Sample

Apparatus Parts Code

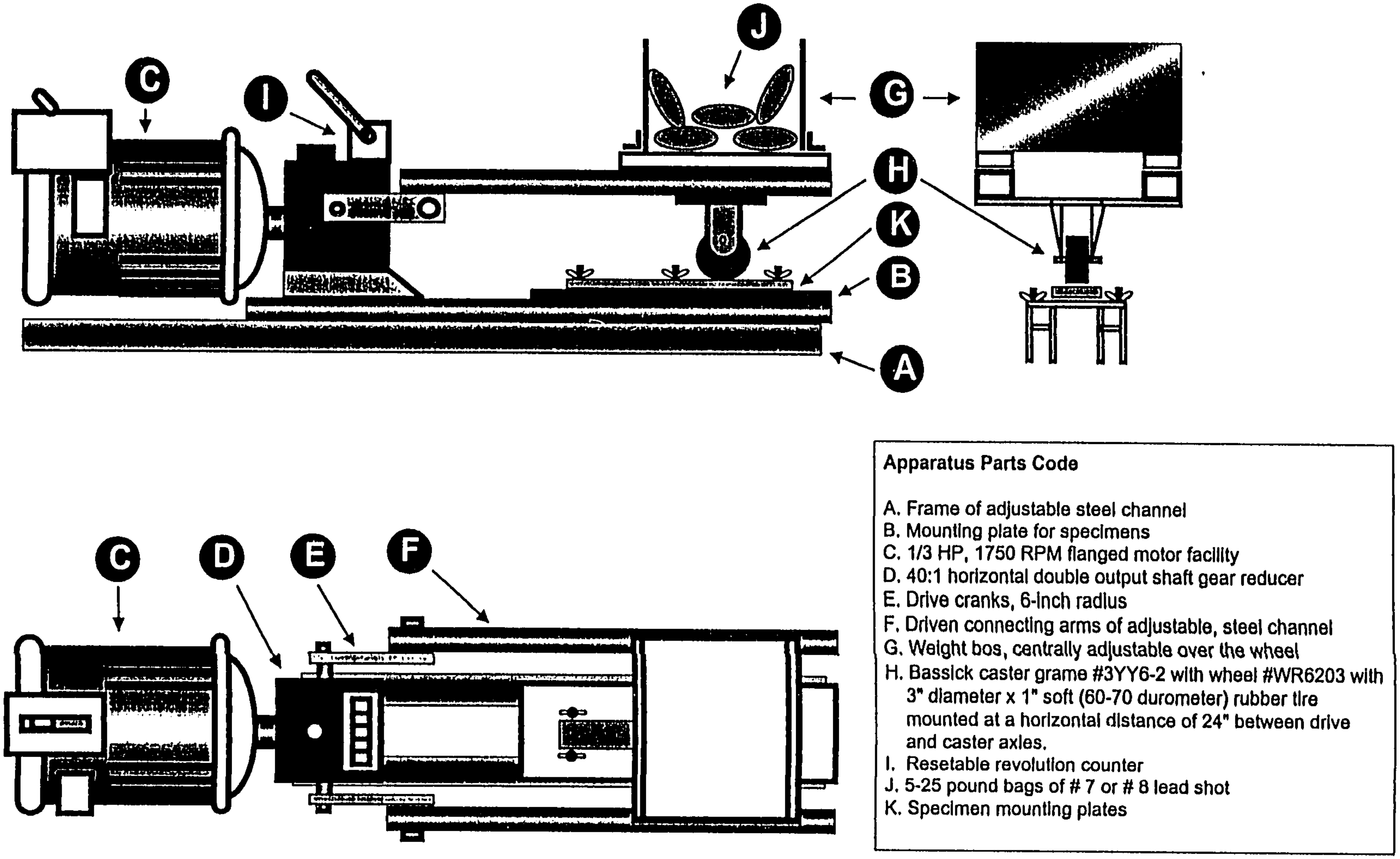
A. Speed selection switch
B. On/Off switch
C. Quick-clamp base setup
D. Abrasion assembly
E. WTAT sample pan
F. 60 cycles motor
G. Rienforced rubber covered wear hose
H. Hose holder
I. Flathead machine screws
J. Weight assembly (2.27 kg)

Figure 2.3 : Apparatur Setup for Wet Track Abrasion Test (WTAT)

adhesion is below this maximum value, the bleeding of slurry seal and micro surfacing mixes is likely not to occur. In this test, a 50 mm wide by 375 mm long specimen of desired thickness (generally 25% thicker than the coarsest particle) is fastened to the mounting plate, which holds a weight of 57 kg inside the weight box and is then compacted with 1000 cycles at room temperature. At the end of compaction, the specimen is washed, dried to a constant weight at 60°C, and weighed. A measured quantity of hot sand (normally 200-300 grams heated at 83°C) is then carefully and uniformly spread over the sample inside the sand mold, and the loaded wheel test is repeated for a specified (usually 100) number of cycles. All loose sand is removed with the help of vacuum cleaner or similar device and the specimen is removed and weighed. The increase in weight due to sand adhesion is noted. The LWT equipment setup is shown in Figure 2.4. Table 2.7 presents the applicable tests for slurry seal and micro surfacing mixes as well as the ISSA specifications (ISSA TB 109, 1990).

2.13 Previous Research Work and Field Evaluation Projects

Bolzan (1987) incorporated a new test method called the New California Test 355 developed by the California Department of Transportation for evaluating the abrasion resistance of aggregates used in slurry seals. This test utilizes three steel



Apparatus Parts Code

A. Frame of adjustable steel channel
B. Mounting plate for specimens
C. 1/3 HP, 1750 RPM flanged motor facility
D. 40:1 horizontal double output shaft gear reducer
E. Drive cranks, 6-inch radius
F. Driven connecting arms of adjustable, steel channel
G. Weight bos, centrally adjustable over the wheel
H. Bassick caster grame #3YY6-2 with wheel #WR6203 with 3" diameter x 1" soft (60-70 durometer) rubber tire mounted at a horizontal distance of 24" between drive and caster axles.
I. Resetable revolution counter
J. 5-25 pound bags of # 7 or # 8 lead shot
K. Specimen mounting plates

Figure 2.4 : Apparatur Setup for Loaded Wheel Test (LWT)

Table 2.7 : Slurry seal and Micro Surfacing Performance Evaluation Test and Their Specifications As Recommended by the ISSA, ASTM and MOC

<table>
<tr><th>ISSA Test</th><th>Test Description</th><th colspan="2">ISSA Specification</th><th>ASTM D 3910 & MOC Specifications</th></tr>
<tr><td>ISSA T106</td><td>Slurry seal consistency</td><td colspan="2">20 - 30 mm</td><td>20 - 30 mm</td></tr>
<tr><td>ISSA TB-109</td><td>Excess asphalt by Loaded Wheel Test (LWT) sand absorption</td><td colspan="2">*610 g/m^2
@ 50^{0}C</td><td>N.A*</td></tr>
<tr><td rowspan="2">ISSA TB-100</td><td rowspan="2">Wet track abrasion
(WTAT) loss
(One hour soak)</td><td>Slurry Seal</td><td>800 g/m^2</td><td rowspan="2">800 g/m^2
(Slurry seal)</td></tr>
<tr><td>Micro Surfacing</td><td>538 g/m^2</td></tr>
<tr><td>ISSA TB-139</td><td>Wet cohesion
(For quick traffic systems)</td><td colspan="2">12 kg-cm after 30 minutes
20 kg-cm after 60 minutes</td><td>**N.A</td></tr>
</table>

* Details given in Chapter 4
**N.A = No ASTM and MOC Specification Available

balls, instead of the conventional rubber hose, to produce abrasion in the slurry seal sample. The abrasion losses for each specimen is plotted against emulsion content in order to determine the optimum emulsion content. He concluded that the conventional WTAT test, and the New California Test 355 produced a high degree of accuracy and repeatability. He further stated that the grading of the aggregates used in the laboratory mixes should be approximately in the middle of the specified range in order to avoid superposition of grading limits. It was also suggested that the maximum particle size for the Types I, II and III gradings should be 2.36 mm, 4.75 mm and 9.5 mm respectively so that the undesirable scatter in abrasion loss readings be avoided. He designed six field trials incorporating a variety of slurries types in accordance with the modified procedure and concluded that the new method was suitable for use in service.

Bayomy et al (1989) investigated various factors that contribute to the fast deterioration of slurry seal mixes. He evaluated the performance of different slurry seal mixes utilizing WTAT test. He concluded that the aggregate type has more pronounced effect over other factors. Hard aggregate with low absorption exhibited better performance than low quality absorptive aggregates with a high sand equivalent. Pre-treatment of low quality aggregates and blending with others of good quality would improve their performance in slurry seal mixes. In many cases, mixes made with a blend of iron slag and natural sand indicated good performance. He also studied the effect of various filler materials as well as emulsion types upon the slurry seal performance. When cement was used as filler material, significant improvement in wear resistance was observed. However, emulsion type was not found to be of any significance.

The Texas State Department of Highways and Public Transportation conducted a survey in November of 1990 to assess the usage of slurry seal in Texas State. Sixteen out of twenty four districts reported that they had used slurry surfacing and the most common reason listed in the survey for applying a new slurry layer was to correct rutting. The next two most frequent applications were to improve the skid resistance and to correct flushing. Slurry surfacing was reported to have been used successfully to improve ride quality and to overlay dry pavement (Lisa, 1991).

The inability of the slurry surfacing to prevent reflective cracking was documented by virtually every district; however, when the cracks were sealed prior to the overlay, the slurry seals generally had no further problems with cracking. Several districts used slurry sealing to repair potholes. This practice yielded mixed results. Very little maintenance of the slurry seals was documented in the survey. Ralumac was used in 32 out of the 34 slurry surfacing projects during that year. All the aggregates used for these projects were obtained from local sources and the most common aggregate type used was crushed sandstone. Rhyolite and limestone were often used, as well. The over all performance and the cost effectiveness of the slurry seals were very good. The average cost of slurry seals was US $ 1.26 per square yard (Lisa, 1991).

A field evaluation research project was conducted by the Oklahoma Department of Transportation in which micro surfacing with natural latex (rubber) modified asphalt emulsion was utilized. This modified emulsion was mixed with aggregate and other additives in a traveling pug mill similar to, but larger than, that of a regular slurry seal machine. A 14-year old test section of four-lane and three miles in length, which was badly cracked and had ruts up to 0.7 inches deep, was selected for micro surfacing application. The evaluation of presented data shows that the service life, load supporting ability, riding quality, skid resistance, of the test section had been significantly enhanced. Further, a comparative analysis between the designed micro surfacing application with a thick application of micro surfacing and with an application of conventional hot mix asphaltic concrete on the same test section revealed that no benefit was observed from the application of the extra thick micro surfacing as opposed to the normal one, i.e., slurry seal. Furthermore, there was no appreciable difference between the three test treatments with regard to their effects on the load supporting ability of the roadway. However, the asphalt concrete section performed better than the micro surfacing treatment in resisting cracking. On the other hand, both micro surfacing treatments performed better than the asphalt concrete in resisting re-rutting. This research recommended that micro surfacing be used as a means to restore flexible pavements that have produced rutting or cracking but should be avoided on pavements that lack adequate load supporting ability (Carl, 1986).

Another field evaluation study was performed utilizing slurry seal and micro surfacing by the Public Works Department, Saskatoon, Canada. A seal coat program was implemented in 1996 in the city of Saskatoon as a preventive maintenance for local streets. Road sections were selected for sand seal, slurry seals and micro surfacing programs using the 1995 pavement condition data. For severely cracked pavements with little or no surface deformations, a sand seal treatment was used. Severe to moderately raveled sections with minor pavement surface defects were treated with slurry seal and micro surfacing techniques. For three to four weeks, alligator cracks reflected through sand seal sections but the intensity of cracks was reduced while the slurry seal and micro surfacing provided a homogenous appearance and improved surface texture even after this period (Puttagunta et al., 1997).

The Ministry of Transportation of Ontario (Canada) had conducted a field study in order to review the performances of various methods for increasing the service lives of its freeway surfaces before any major repair should become necessary. One method considered was the use of micro surfacing to seal, level, and provide a thin, durable, skid-resistant wearing surface on existing and deteriorated asphalt pavements. In 1991 the Ministry undertook two demonstration projects utilizing micro surfacing. It was concluded that this type of surface treatment successfully extends the service lives of freeways exhibiting various premature surfacial deteriorations (Kazmierowski et al., 1995).

2.14 Review of Statistical Analysis Concepts

Experimental design is a broad area in the field of statistics and a designed experiment is a test or series of tests in which purposeful changes or selections are made to the independent variables of a process or system so that we may observe and identify the reasons for changes in the output response (Montgomery, 1991). Statistical methods can not prove that a factor (or factors) has a particular effect, they can only provide guidelines as to the reliability and validity of the results. Properly-applied statistical techniques do not allow anything to be proved, at least experimentally, but they do allow us to measure the likely error in a conclusion or to attach a level of confidence to a statement. The primary advantage of statistical methods is that they add objectivity to the decision making process. Statistical techniques coupled with good engineering or process knowledge and common sense will usually lead to sound and robust conclusions (Montgomery, 1991).

Stepwise regression is a valuable tool in identifying significant variables as well as dropping out variables that are insignificant in the prediction of the dependent variables. In stepwise regression, the computer does not build one big equation with all the independent variables included. It builds a sequence of equations, the first equation including only one independent variable, and each succeeding equation including one extra independent variable. We say that the independent variables are entered one at a time in a stepwise manner. Furthermore, they are entered in a definite order. The first equation includes the independent variable most highly correlated with the dependent variable. Then, the second independent variable entered is the one that explains the most of what remains unexplained after the first variable. Similarly, the third independent variable entered is the one that explains the most of what remains unexplained after the first two independent variables. After each variable is entered, the computer also checks whether any of the previously entered variables can be discarded from the equation. This occurs when the effect of such a variable can be explained by a combination of other variables that have entered the equation by that time. This process of entering variables and possibly discarding variables continues until: (i) all the independent variables have entered, or (ii) the independent variables not included in the equation explain an insignificant amount of the variation left unexplained. If the latter occurs, the final equation does not include all the potential independent variables (Hines and Montgomery, 1990; Christain, 1987).

The stepwise regression is popular because we are able to see the steps involved in building the final equation. We are able to see which variables entered in which order and we can see how each explains a certain portion of the dependent variable's total variation. Hence, we can come up with the relative ranking of the independent variables in terms of statistical significance (Christain, 1987).

The statistical significance of a factor is an estimated measure of the degree to which it is "true" (in the sense of "representative of the population"). More technically, the value of the p-level (the term first used by Brownlee, 1960) represents a decreasing index of the reliability of a result. The higher the p-level, the less we can believe that the observed relation between variables in the sample is a reliable indicator of the relation between the respective variables in the population. Specifically, the p-level represents the probability of error that is involved in accepting our observed result as valid, that is, as "representative of the population." For example, a p-level of 0.05 (i.e.,1/20) indicates that there is a 5% probability that the relation between the variables found in our sample is a insignificant. In other words, assuming that in the population there was no relation between those variables whatsoever, and we were repeating experiments like ours one after another, we could expect that approximately in every 20 replications of the experiment there would be one in which the relation between the variables in question would be equal or stronger than in ours. In many areas of research, the p-level of 0.05 is customarily treated as a "border-line acceptable" error level.

In addition to determining the statistical significance of each factor, one most important aspect of multiple regression analysis is to develop a statistical model which is a mathematical equation that describes the numeric relationship between two or more variables (Christain, 1987). A regression model includes two types of variable: one independent and the other dependent. The dependent variable is the one being explained and the independent variable is the one used to explain the variation in the dependent variable.

Some of the pertinent statistical tools to test a model include the following (Montgomery, 1991):

- Multiple Correlation Coefficient (R) which gives the degree of relationship between the dependent and the independent variables. The closer it is to one, the better the model that has been calibrated. The R^2 value, often known as Coefficient of Multiple Determination, will also be studied since it gives the portion of the variability in the dependent variables that is explained by the independent variables. The higher the R^2 value, the better the model that has been calibrated.
- Test for the significance of the independent variables that have been used in the estimation of the demand. The t-statistic for each regression coefficient, which is the ratio of that coefficient to its standard error, is checked and should have a value of at least 1.65 for a 95% level of confidence or at least 2.0 for a 99% level of confidence for a reliable confirmation. If the above condition is not satisfied, the independent variable is dropped from the model. Stepwise regression is a valuable tool in dropping out variables that are insignificant in the prediction of the dependent variable. The technique will regress the

independent variables in succession starting with the most significant variable to a level when no improvement in the model is possible. An alternative measure of significance is the use of the F-statistic, which gives the ratio of variability due to regression to the variability that is not explained. It is desirable that this value is as high as possible such that the probability of its improvement is very low.

- Graphic plots of the estimated values and the actual values used in the model calibration are made. This gives a measure of the goodness-of-fit of the model to the data. A linear relationship reveals a perfect model.

2.15 Summary

Emphasis of this Chapter was on the available literature on the characteristics of slurry seal and micro surfacing. The properties of steel slag aggregates and limestone aggregates were also discussed in details. The different tests used to evaluate the performance of slurry seal and micro surfacing mixes were discussed with appropriate specifications. Various techniques were reviewed regarding the improvement of slurry seal and micro surfacing mixes utilizing steel slag aggregates. Previous research work and field evaluation projects were also presented.

CHAPTER 3

RESEARCH METHODOLOGY

This Chapter deals with the research methodology that was adapted in this laboratory work. The main objective was to develop trends (curves) of the performances of both slurry seal and micro surfacing mixes under variety of test conditions with different material proportions after which various performance prediction models were to be developed. As shown in Figure 3.1, the experimental program consists of four main phases: 1) Materials collection and characterization in the laboratory. 2) Aggregate blending and mixture preparation utilizing aggregates, water, emulsified asphalt, and additives according to the ISSA specifications. 3) Testing, performance evaluation, and data analysis of slurry seal and micro surfacing mixes accordingly. 4) Effects of additives on mix performance.

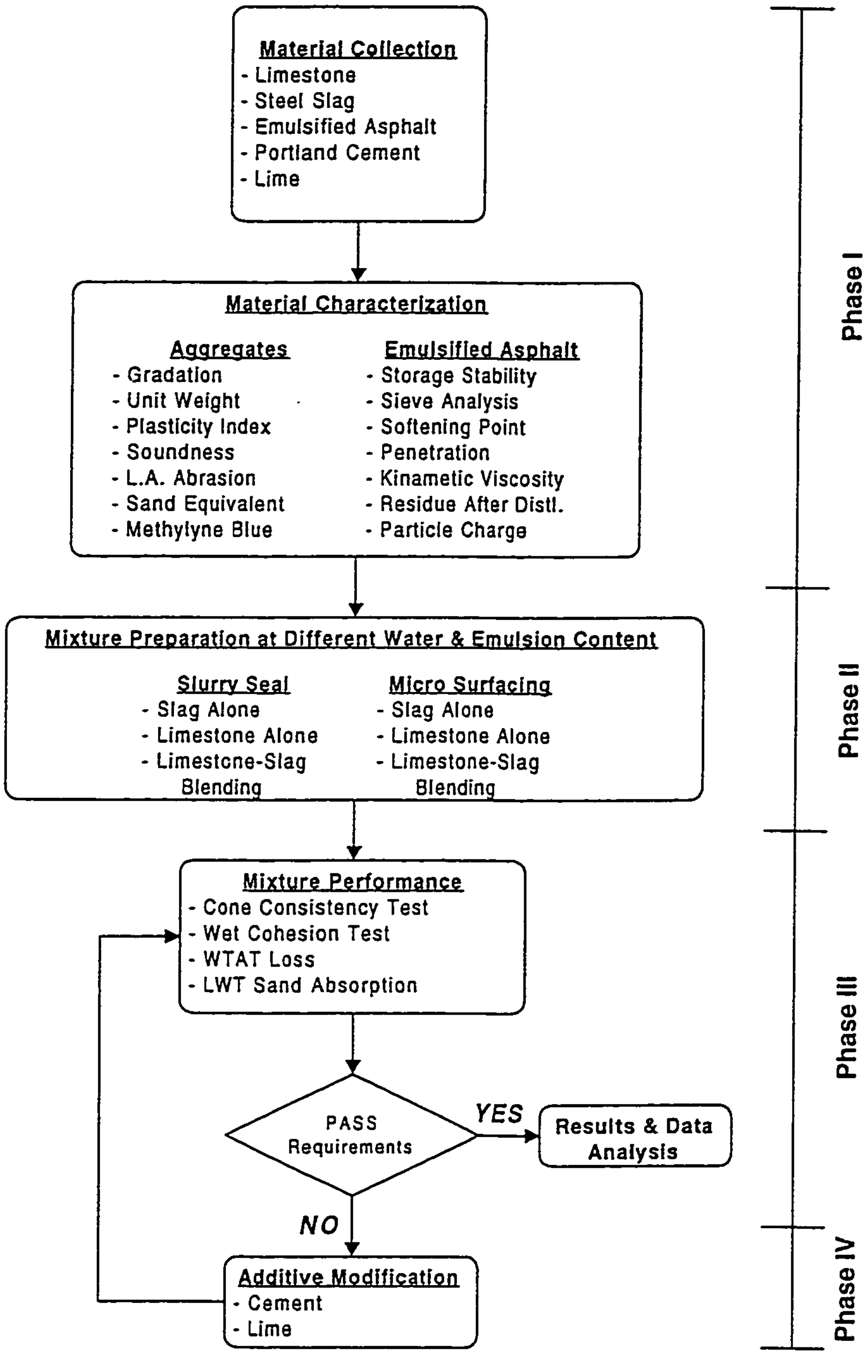


Figure 3.1 : Schematic Diagram of Laboratory Experimental Program

3.1 Material Collection (Phase I)

3.1.21Aggregates

For this study, Type I, Type II, and Type III for slurry seal, and Type II and Type III for micro surfacing, as designated by the ISSA, were incorporated. The specific details of these types of aggregates are explained in Chapter 2. The two types of aggregates namely steel slag and limestone utilized in this investigation were originated, respectively, from eastern Saudi Arabia near Hadeed steel manufacturing factory located at Jubail and Abu-Hadriyah limestone quarry (Al-Dossary Crusher). The design gradation curves of the aggregates, as per ISSA specifications, are shown in Figure 3.2. In addition, Table 3.1 shows the selected aggregate gradation that was used for this study.

3.1.2 Filler

Fine limestone was used as a filler material. The mixture containing slag alone consisted of slag passing # 200 sieve.

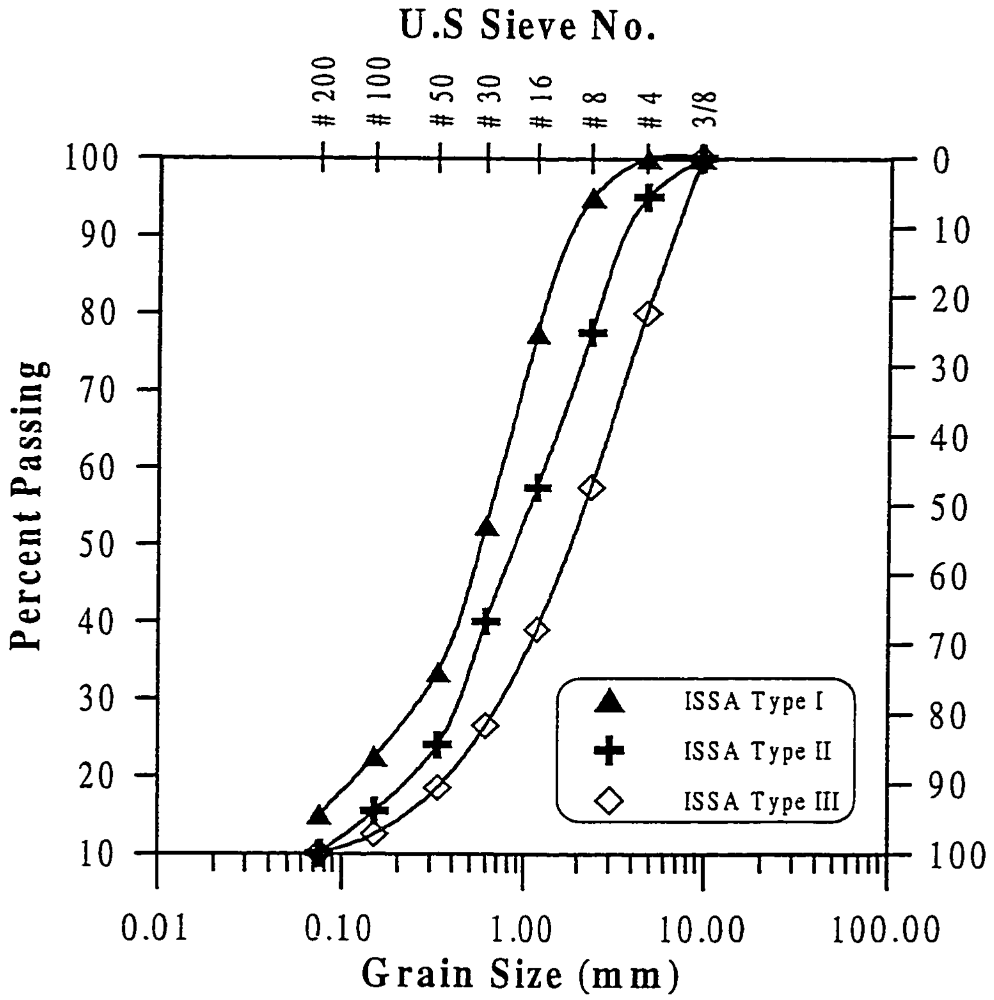


Figure 3.2: Curves of the Selected Aggregate Gradations for Slurry Seal and Micro Surfacing Mixture Design (ISSA, 1991)

Table 3.1: Selected Aggregate Gradation For Slurry Seal and Micro Surfacing Mixes (ISSA, 1991)

	Type I	Type II	Type III
Sieve Sizes	% Passing	% Passing	% Passing
3/8 (9.5 mm)	100	100	100
# 4 (4.75mm)	100	95	80
# 8 (2.36 mm)	95	77.5	57.5
# 16 (1.18 mm)	77.5	57.5	39
# 30 (600 um)	52.5	40	26.5
# 50 (330 um)	33.5	24	18.5
# 100 (150 um)	22.5	15.5	12.5
# 200 (75 um)	15	10	10

3.1.3 Ordinary Portland Cement (OPC)

OPC was used mainly to improve the setting and curing characteristics as well as the aggregate bonding characteristics in the slurry seal and micro surfacing mixes. Three percent of OPC (Type I) was used as a part of the filler mixture.

3.1.4 Emulsified Asphalt

Slow-setting cationic emulsified asphalt type (Css-1h) was used because of its compatibility with a wider range of aggregates and its common utilization as liquid binder all over the world. In micro surfacing polymer-modified Css-1h emulsified asphalt was used according to the ISSA specifications.

3.1.5 Water

Regular potable water was used in all the mixes. The percentages of emulsion, water and OPC were selected based on the dry weight of the aggregate.

3.2 Experimental program and mixture preparation (Phase II)

The common practice in both the slurry sealing and micro surfacing jobs is to test the selected materials for quality, construct a suitable mix design matrix, and check the cone-consistency, set-time, traffic rolling time, and the wet-track abrasion loss of the slurry seal and micro surfacing. Once all of these tests are carried out according to proper test specification with the minimum amount of emulsified asphalt required is determined from WTAT, the maximum amount of emulsified asphalt content is then calculated by performing loaded wheel test. The same methodology was adapted to this study. The four-step experimental program of the investigation is shown in Figure 3.1.

The following three percentages of emulsified asphalt contents in both the slurry seal and micro surfacing mixes, 9%, 11% and 15%, were used as determined by the Centrifuge Kerosene Equivalent (CKE) and surface capacity of coarse aggregate method (Root, 1979). The main objective was to develop a trend (curve) of slurry seal performance with different emulsified asphalt contents.

Each of the blends was given a notation code (legend) to specify the various material proportions. Blend numbers starting with letters LS, P8LS, P30LS, 30%LS, 60%LS, and SS correspond, respectively, to 100% limestone, slag plus limestone passing #8 sieve size, slag plus limestone passing #30 sieve size, 70% slag plus 30% limestone, 40% slag plus 60% limestone, and 100% slag. Hence, for example, blend reference "P8LS" translates to aggregate gradation consisting of slag plus limestone passing #8 sieve size. The nomenclature of the aggregate blend is given in Table 3.2. The experimental design matrix, shown in

Table 3.2 : Nomenclature for Slurry Seal and Micro Surfacing Mixes

LS	Mixes consisting of 100% limestone aggregates
P8LS	Mixes consisting of slag plus passing # 8 sieve limestone aggregates
P30LS	Mixes consisting of slag plus passing # 30 sieve limestone aggregates
30%LS	Mixes consisting of slag plus 30% limestone aggregates by weight
60%LS	Mixes consisting of slag plus 60% limestone aggregates by weight
SS	Mixes consisting of 100% slag aggregates

Table 3.3, consisted of different aggregate blends with different emulsified asphalt content.

3.2.1 Experiment Design

This investigation was conducted with slurry seal and micro surfacing mixes containing combinations of the two aggregates (limestone and steel slag) at six levels of blending and three levels of different emulsion contents. In addition, three levels of aggregate gradation and three levels of treatment were also investigated for the effectiveness on mix performance. Various mixes were designed and evaluated for performance according to the ISSA and ASTM test specifications in order to account for the effect of variation of aggregate type as well as combination of these aggregates on test performance. Other factors were the variation of both emulsified asphalt content and type, aggregate gradation, and addition of additives (cement and hydrated lime). The selected aggregate gradation with various engineering properties of slurry seal and micro surfacing mixes are shown in Table 3.4 through Table 3.6.

To check the required number of samples in order to generate the different models, a confidence limit of 95% for the selected parameters was chosen. Additionally, the acceptable amount of error and standard deviation in estimating the dependent variables were limited to be less than 5% and 10%, respectively.

Table 3.3 : Experimental Design Matrix for Laboratory Testing Program and Statistical Analysis

			Slurry Seal Mixes Type						Micro Surfacing Mixes Type					
	Gradation	Treatment Type	LS	P8 LS	P30 LS	60% LS	30% LS	SS	LS	P8 LS	P30 LS	60% LS	30% LS	SS
Consistency	Type I	Normal	v	v	v	v	v	v	*	*	*	*	*	*
	Type II	Normal	v	v	v	v	v	v	v	v	v	v	v	v
	Type III	Normal	v	v	v	v	v	v	v	v	v	v	v	v
Cohesion	Type I	Normal	x	x	x	x	x	x	*	*	*	*	*	*
	Type II	Normal	x	x	x	x	x	x	x	x	x	x	x	x
	Type III	Normal	x	x	x	x	x	x	x	x	x	x	x	x
WTAT Loss	Type I	Normal	x	x	x	x	x	x	*	*	*	*	*	*
		Lime	x	x	x	x	x	x	*	*	*	*	*	*
		Cement	x	x	x	x	x	x	*	*	*	*	*	*
	Type II	Normal	x	x	x	x	x	x	x	x	x	x	x	x
		Lime	x	x	x	x	x	x	x	x	x	x	x	x
		Cement	x	x	x	x	x	x	x	x	x	x	x	x
	Type III	Normal	x	x	x	x	x	x	x	x	x	x	x	x
		Lime	x	x	x	x	x	x	x	x	x	x	x	x
		Cement	x	x	x	x	x	x	x	x	x	x	x	x
LWT Sand Absorption	Type I	Normal	x	x	x	x	x	x	*	*	*	*	*	*
		Lime	x	x	x	x	x	x	*	*	*	*	*	*
		Cement	x	x	x	x	x	x	*	*	*	*	*	*
	Type II	Normal	x	x	x	x	x	x	x	x	x	x	x	x
		Lime	x	x	x	x	x	x	x	x	x	x	x	x
		Cement	x	x	x	x	x	x	x	x	x	x	x	x
	Type III	Normal	x	x	x	x	x	x	x	x	x	x	x	x
		Lime	x	x	x	x	x	x	x	x	x	x	x	x
		Cement	x	x	x	x	x	x	x	x	x	x	x	x

"V" represents test readings of samples at different total water content

"X" represents test readings of samples at 9, 11, and 15% emulsified asphalt content (when applicable)

* These mixtures are not normally used in the field (not recommended by the ISSA)

Table 3.4 : Selected Aggregate Blends and Properties for ISSA type I Gradation

Blend Code	Aggregate Description	Emulsion %	Adjusted Bulk Density	Adjusted Apparent Density	Surface Area of the Aggregates (m^2/kg)[1]	Asphalt Film Thickness (Microns)[2]
LS	100% Limestone	9% Emulsion	2.502	2.650	14.949	1.502
LS	100% Limestone	11% Emulsion	2.502	2.650	14.949	2.338
LS	100% Limestone	15% Emulsion	2.502	2.650	14.949	4.011
P8LS	Slag + Limestone passing #8	9% Emulsion	2.539	2.685	14.927	1.597
P8LS	Slag + Limestone Passing # 8	11% Emulsion	2.539	2.685	14.927	2.435
P8LS	Slag + Limestone Passing # 8	15% Emulsion	2.539	2.685	14.927	4.110
P30LS	Slag + Limestone passing #30	9% Emulsion	2.905	3.028	14.711	2.412
P30LS	Slag + Limestone passing #30	11% Emulsion	2.905	3.028	14.711	3.262
P30LS	Slag + Limestone passing #30	15% Emulsion	2.905	3.028	14.711	4.961

[1] California Highways method

[2] Public Works (HVEEM) method

Table 3.4 : Continued

Blend Code	Aggregate Description	Emulsion %	Adjusted Bulk Density	Adjusted Apparent Density	Surface Area of the Aggregates (m^2/kg)[1]	Asphalt Film Thickness (Microns)[2]
30%LS	30% Limestone + Slag	9% Emulsion	2.742	2.877	14.806	2.075
30%LS	30% Limestone + Slag	11% Emulsion	2.742	2.877	14.806	2.919
30%LS	30% Limestone + Slag	15% Emulsion	2.742	2.877	14.806	4.608
60%LS	60% Limestone + Slag	9% Emulsion	3.034	3.146	14.636	2.655
60%LS	60% Limestone + Slag	11% Emulsion	3.034	3.146	14.636	3.509
60%LS	60% Limestone + Slag	15% Emulsion	3.034	3.146	14.636	5.217
SS	100 % Slag	9% Emulsion	3.534	3.594	14.354	3.442
SS	100 % Slag	11% Emulsion	3.534	3.594	14.354	4.313
SS	100 % Slag	15% Emulsion	3.534	3.594	14.354	6.055

[1] California Highways method

[2] Public Works (HVEEM) method

Table 3.5 : Selected Aggregate Blends and Properties for ISSA type II Gradation

Blend Code	Aggregate Description	Emulsion %	Adjusted Bulk Density	Adjusted Apparent Density	Surface Area of the Aggregates (m^2/kg)[1]	Asphalt Film Thickness (Microns)[2]
LS	100% Limestone	9% Emulsion	2.498	2.647	10.787	2.932
LS	100% Limestone	11% Emulsion	2.498	2.647	10.787	4.091
LS	100% Limestone	15% Emulsion	2.498	2.647	10.787	6.409
P8LS	Slag + Limestone passing #8	9% Emulsion	2.674	2.814	10.712	3.373
P8LS	Slag + Limestone Passing # 8	11% Emulsion	2.674	2.814	10.712	4.540
P8LS	Slag + Limestone Passing # 8	15% Emulsion	2.674	2.814	10.712	6.874
P30LS	Slag + Limestone passing #30	9% Emulsion	3.030	3.144	10.562	4.118
P30LS	Slag + Limestone passing #30	11% Emulsion	3.030	3.144	10.562	5.302
P30LS	Slag + Limestone passing #30	15% Emulsion	3.030	3.144	10.562	7.669

[1] California Highways method

[2] Public Works (HVEEM) method

Table 3.5 : Continued

Blend Code	Aggregate Description	Emulsion %	Adjusted Bulk Density	Adjusted Apparent Density	Surface Area of the Aggregates (m^2/kg)[1]	Asphalt Film Thickness (Microns)[2]
30%LS	30%Limestone + Slag	9% Emulsion	2.738	2.874	10.684	3.521
30%LS	30%Limestone + Slag	11% Emulsion	2.738	2.874	10.684	4.691
30%LS	30%Limestone + Slag	15% Emulsion	2.738	2.874	10.684	7.030
60%LS	60%Limestone + Slag	9% Emulsion	3.030	3.144	10.562	4.118
60%LS	60%Limestone + Slag	11% Emulsion	3.030	3.144	10.562	5.302
60%LS	60%Limestone + Slag	15% Emulsion	3.030	3.144	10.562	7.669
SS	100 % Slag	9% Emulsion	3.531	3.593	10.359	4.937
SS	100 % Slag	11% Emulsion	3.531	3.593	10.359	6.144
SS	100 % Slag	15% Emulsion	3.531	3.593	10.359	8.557

[1] California Highways method

[2] Public Works (HVEEM) method

Table 3.6 : Selected Aggregate Blends and Properties for ISSA type III Gradation

Blend Code	*Aggregate Description*	Emulsion %	Adjusted Bulk Density	Adjusted Apparent Density	Surface Area of the Aggregates (m^2/kg)[1]	Asphalt Film Thickness (Microns)[2]
LS	100% Limestone	9% Emulsion	2.488	2.639	9.080	3.866
LS	100% Limestone	11% Emulsion	2.488	2.639	9.080	5.243
LS	100% Limestone	15% Emulsion	2.488	2.639	9.080	7.996
P8LS	Slag + Limestone passing #8	9% Emulsion	2.843	2.974	8.954	4.717
P8LS	Slag + Limestone Passing # 8	11% Emulsion	2.843	2.974	8.954	6.113
P8LS	Slag + Limestone Passing # 8	15% Emulsion	2.843	2.974	8.954	8.905
P30LS	Slag + Limestone passing #30	9% Emulsion	3.173	3.277	8.840	5.354
P30LS	Slag + Limestone passing #30	11% Emulsion	3.173	3.277	8.840	6.768
P30LS	Slag + Limestone passing #30	15% Emulsion	3.173	3.277	8.840	9.596

[1] California Highways method

[2] Public Works (HVEEM) method

Table 3.6 : Continued

Blend Code	Aggregate Description	Emulsion %	Adjusted Bulk Density	Adjusted Apparent Density	Surface Area of the Aggregates (m^2/kg)[1]	Asphalt Film Thickness (Microns)[2]
30%LS	30% Limestone + Slag	9% Emulsion	2.728	2.867	8.994	4.465
30%LS	30% Limestone + Slag	11% Emulsion	2.728	2.867	8.994	5.855
30%LS	30% Limestone + Slag	15% Emulsion	2.728	2.867	8.994	8.634
60%LS	60% Limestone + Slag	9% Emulsion	3.020	3.138	8.892	5.075
60%LS	60% Limestone + Slag	11% Emulsion	3.020	3.138	8.892	6.480
60%LS	60% Limestone + Slag	15% Emulsion	3.020	3.138	8.892	9.292
SS	100 % Slag	9% Emulsion	3.523	3.590	8.723	5.914
SS	100 % Slag	11% Emulsion	3.523	3.590	8.723	7.347
SS	100 % Slag	15% Emulsion	3.523	3.590	8.723	10.213

[1] California Highways method

[2] Public Works (HVEEM) method

Hence, the minimum required sample size for each prediction model using the above criterion was as follows (Montgomery and Peck, 1982):

$$n = \left(\frac{z_{\alpha/2}\, \sigma}{e} \right)^2 \tag{3.1}$$

Where:

$z_{.025} = 1.96$
$\alpha = 0.05$
$e = 0.05$
$\sigma = 0.1$

Therefore, the required minimum number of samples becomes:

$$n = \left(\frac{1.96 * 0.1}{0.05} \right)^2 \quad = \quad 15.37 \cong 16$$

The samples selected for each of the tests were all exceeding the above criteria as follows:

1. Cone consistency test: 150 samples depending upon the water content, aggregate blend, and emulsified asphalt type.
2. Wet cohesion test: 90 samples depending upon aggregate blend, emulsified asphalt content, emulsified asphalt type, and treatment type.
3. WTAT loss: 210 samples

4. LWT sand absorption: 180 samples depending upon aggregate blend, emulsified asphalt content, emulsified asphalt type, and treatment type.

3.3 Testing (Phase III)

All the test procedures for slurry seal and micro surfacing mixes were carried out according to ASTM D 3910 and ISSA A105 and A143 guidelines. Firstly, premixing of water was carried out to enhance the surface properties of the aggregates. Afterwards, optimum proportions of aggregate, emulsified asphalt, mineral filler, and water were determined through the cone consistency test. The consistency is normally ranging between 20 to 30 mm, to qualify the field workability and flow conditions.

Set-time and traffic rolling time were then determined through modified cohesion test by curing the specimens. Disk-shaped samples, 11 inches in diameter, were prepared for the Wet Track Abrasion Test (WTAT). To keep the testing temperature constant during the WTAT test, each sample was fully covered with water having a temperature of 25°C in the WTAT machine. Loaded Wheel Test (LWT) was then performed in accordance with the ISSA TB 109 specifications in order to examine the behavior of slurry seal and micro surfacing mixes under heavy and repeated loading at high temperatures. This test is useful to identify, in the laboratory, those slurry mixes, which are likely to exhibit asphalt flushing problems under heavy traffic loads and hot environmental conditions. For this purpose, the LWT test was performed at 50^0C to simulate the field temperature conditions likely to be encountered most of the time in eastern Saudi Arabia.

3.4 Effect of Additives on Mix Performance (Phase IV)

In this phase, the effect of additives on the slurry seal and micro surfacing mixes was evaluated. The mineral additives used include ASTM C 150 Type I ordinary Portland cement (OPC) obtained from Saudi Cement Factory in Hofuf, and hydrated lime from Saudi Lime Brick & Building Materials Company. Portland cement and lime were added to the filler portion of the gradations at a replacement ratio of 3%, with the new amount of Portland cement as 6%. It is worthwhile mentioning that the normal mixture had already contained 3% of Portland cement. This pre addition of 3% cement had been justified in previous research works for giving significantly improved mix performance in the field (Naji, 1988; Bayomy et al. 1989). The mixes were first evaluated for WTAT loss and then for LWT sand absorption in order to analyze the performance improvement of slurry seal and micro surfacing mixes with the addition of a mineral filler. Various trial mixes were tested for the effect of additives on the consistency and wet cohesion test values. No significant difference in test results was observed between modified and normal mixes. Hence, these two tests (consistency and wet cohesion) were not carried out on all the modified mixes.

3.5 Statistical Analyses and Modeling of Test Performance and Related Properties

While undertaking this present research, one of the objectives was to statistically determine the relative significance of factors affecting the various performance measures (consistency, cohesion, WTAT, and LWT). In addition, the test data were utilized for the development of prediction models for the following two purposes:

- Prediction of test parameters (consistency, cohesion, WTAT, and LWT) for a given combination of material type and quantity.
- Prediction of optimum water and emulsified asphalt content in order to achieve a slurry seal and micro surfacing mix design conforming to consistency, WTAT, and LWT test specifications.

Hence, the experimental design was formulated keeping this objective in mind. Table 3.7 shows the general arrangement of test results optimized for model generation.

In this study, the stepwise regression analysis was utilized in order to study the effects of different factors (i.e., material type, material gradation, emulsified asphalt type and content, and treatment type) on the mix performance (i.e., consistency, set time, cure time, WTAT loss, and LWT sand absorption) and also to develop mathematical models in order to predict these performance measures.

Table 3.7 : General Arrangement of Optimized Test Results for The Development of Water and Emulsion Content Prediction Models

			Slurry Seal Mixes Type						Micro Surfacing Mixes Type					
	Gradation	Treatment Type	LS	P8 LS	P30 LS	60% LS	30% LS	SS	LS	P8 LS	P30 LS	60% LS	30% LS	SS
Consistency	Type I	Normal	W	W	W	W	W	W	*	*	*	*	*	*
	Type II	Normal	W	W	W	W	W	W	W	W	W	W	W	W
	Type III	Normal	W	W	W	W	W	W	W	W	W	W	W	W
WTAT & LWT	Type I	Normal	E	E	E	E	E	E	*	*	*	*	*	*
		Lime	E	E	E	E	E	E	*	*	*	*	*	*
		Cement	E	E	E	E	E	E	*	*	*	*	*	*
	Type II	Normal	E	E	E	E	E	E	E	E	E	E	E	E
		Lime	E	E	E	E	E	E	E	E	E	E	E	E
		Cement	E	E	E	E	E	E	E	E	E	E	E	E
	Type III	Normal	E	E	E	E	E	E	E	E	E	E	E	E
		Lime	E	E	E	E	E	E	E	E	E	E	E	E
		Cement	E	E	E	E	E	E	E	E	E	E	E	E

"W" represents optimum water content meeting design consistency

" E" represents optimum emulsified asphalt content meeting acceptable test values of both WTAT and LWT simultaneously

* These mixtures are not normally used in the field (not recommended by the ISSA)

Models were obtained as regressor variables were added one by one depending on their respective significance to the dependent variable. This statistical analysis was performed utilizing *STATISTICA* software utility (Stat-soft, 1997). Statistically significant results are obtained whenever p-level is less than the significance level (S.L), i.e., $p < \alpha$. This means that for 95% S.L, p-level should be less than 0.05 in order to achieve a significant effect of any factor. These tests are discussed in detail in Chapter 6.

3.6 Summary

This Chapter provided details about the selected test samples and the experimental work. The experimental program consisted of four main phases: 1) Materials collection and characterization in the laboratory. 2) Aggregate blending and mixture preparation utilizing aggregates, water, emulsified asphalt, and additives according to the ISSA specifications. 3) Testing, performance evaluation, and data analysis of slurry seal and micro surfacing mixes accordingly. 4) Effects of additives on mix performance.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

This Chapter presents the results acquired through various tests performed on slurry seal and micro surfacing mixes. The main idea was to develop a practically suitable slurry seal and micro surfacing mix design without compromising the field performance and economy as well. The test results are presented and discussed under five sections: (1) Material Characterization. (2) Consistency Test. (3) Wet Cohesion Test. (4) Wet Track Abrasion Test (WTAT). (5) Loaded Wheel Test (LWT). The Consistency, WTAT, and LWT results are considered as major indicators towards the slurry seal and micro surfacing field performances. The statistical analyses, utilizing forward stepwise regression procedure, were intended identify and prove statistically the significance of various factors affecting the mix performance. In addition, performance prediction models were also generated utilizing obtained test data.

4.2 Material Characterization Results

Laboratory material characterization tests were performed on aggregates and emulsified asphalt. For each of these materials, the results of characterization are presented along with ISSA and ASTM specification limits, when applicable.

4.2.1 Aggregates

The aggregates were tested for the desired engineering properties in any slurry seal and micro surfacing mixes and specified in ISSA and/or ASTM. The results are presented in Table 4.1. The specific gravity and water absorption results indicate that steel slag is relatively heavier and less absorptive to water than limestone. As expected, the Los Angeles abrasion of steel slag is lower than that of limestone and well under the specification limit indicating greater hardness and resistance to abrasion under traffic loads. The low soundness of steel slag indicates its high durability and resistance to weathering disintegration. In the case of limestone, the soundness value has just met the nominal specification range identified by the ISSA. Steel slag aggregates usually have little or no traces of contamination by clay or plastic fines. This can be confirmed by looking at the sand equivalent values, which is significantly higher than that of limestone. The fine and filler portions of both steel slag and limestone are non-plastic as confirmed from the

Table 4.1 : Results of Quality Tests on The Aggregates Used

TEST	Steel Slag			Limestone			ISSA Specification
Abrasion, % (ASTM C 131)	18.3			29.4			35% Max.
Sand Equivalent, % (ASTM D 2419)	85			60			60% Min.
Specific Gravity	*Type I*	*Type II*	*Type III*	*Type I*	*Type II*	*Type III*	
Bulk (ASTM C 127) Apparent (ASTM C 128)	3.534 3.594	3.531 3.593	3.523 3.590	2.502 2.650	2.498 2.647	2.488 2.639	-
Water Absorption, %	0.783	0.715	0.671	3.548	2.953	2.667	-
Soundness Loss using Na_2SO_4, % (ASTM C 88)	1.18	1.22	1.33	14.3	15.84	16.5	15% Max.
Plasticity Index (AASHTO T 88)	Non-Plastic			Non-Plastic			Non-Plastic
Methylyne Blue Value (MBV)	0.08 (Reactive)			0.108 (Reactive)			15 Max.

plasticity index results. The Methylyne Blue Value was determined for both steel slag and limestone mixes and were found to be under specification limits.

4.2.2 Emulsified Asphalt

Two types of cationic slow setting (Css-1h) emulsified asphalt were utilized for this study; normal (slurry seal) emulsions and polymer modified (micro surfacing) emulsions. A range of quality tests, which included the residue after distillation, sieve analysis, particle charge, storage stability, softening point, penetration and kinematic viscosity, were performed on these emulsions and the results are depicted in Table 4.2 along with the recommended specification limits by the ISSA and ASTM. The results comply with the ISSA and ASTM specifications.

4.3 Cone Consistency Test Results

Cone consistency test is used to determine the required amount of total water content (premix water, water already present in the aggregates, and water in the emulsified asphalt) for different mixes in order to achieve the required workability. Cone consistency test (slump test) was performed to check for the proper consistency (mix-design with proper ratio of aggregate, filler, water, and emulsion) as related to flow and workability for slurry seal surface placement in the field (ISSA, 1991). Normally, the flow reading value in the cone consistency test

Table 4.2 : Cationic Slow Setting (Css-1h) Emulsified Asphalt Properties

Property	Test Results		ASTM D2397 Specifications	
	Normal Emulsions	Polymer Emulsions	Minimum	Maximum
Viscosity at 25^{0}C, poises	22	30	20	100
Storage Stability, %	0.9	0.8	-	1.0
Sieve Test, %	0.1	0.1	-	0.1
Residue, %	62.5	65	57	-
Water Content, %	37.5	35	-	43
Penetration for Residue at 25^{0}C, dmm	46	40	40	90
Cement Mixing Test, %	0.9	0.9	-	2
Particle Charge	Positive	Positive	Positive	Positive

between 20 and 30 mm is considered practical for field applications (ISSA, 1991). Trial mixes were tested for consistency in order to study the effect of addition of lime and cement. However, no significant differences were observed between the consistency values of normal and modified mixes. Hence, the modified mixes were not tested for consistency. The test results of cone consistency revealed that the mixes containing higher percentages of limestone normally require higher water content to achieve the desired flow. This phenomenon can be related to the higher porosity, absorption, and surface adsorption of limestone particles (Lee, 1974) as compared to those of steel slag aggregates, which need lower quantities of water for similar flow (consistency). In addition, due to the higher densities of steel slag aggregates, the weight-volume relationship also alters the required water content. Lesser amount of water is required to wet a unit weight of steel slag because the volume of steel slag is less than that of limestone. An example is the SS mixes for type III slurry seal that required only 11.25% total water content in order to achieve the design flow of 25mm. On the other hand, the LS mixes for the same combination of aggregate gradation and slurry seal have acquired 18.75% total water content. Aggregate gradation has also affected the flow: higher amount of water content is required for finer material because, under normal circumstances, the water absorption of fine aggregates is relatively higher than that of coarse aggregates due to their large surface areas. In addition, due to the large surface area of fine particles, higher amount of water is required in order to coat the aggregate surface as compared to coarse materials. That is why type I materials (fine gradation) have consumed the highest amount of water content in order to reach the design consistency values. Mixes consisting of micro surfacing emulsion have shown greater requirement of water to produce specified consistency. This is due to the addition of certain cross-linked block copolymers (rubberized materials) that impart increased viscosity which in turn resulted in increased resistance to flow. Hence, higher water content is required in micro surfacing emulsions to produce similar flow value as in slurry seal emulsions. Consistency results are plotted in Figure 4.1 through Figure 4.5. The design flow was taken as 25 mm and the corresponding total water content was determined and used for sample preparation for each of the mixes type. The test observations are summarized in Table 4.3. Details are given in Chapter 5

4.4 Wet Cohesion Test Results

Wet cohesion testing device was used to determine the set time, initial traffic rolling time, and final torque characteristics of emulsified asphalt mixes. Set time is defined as the elapsed time after casting when a slurry system may not be remixed into a homogeneous slurry; when no lateral displacement is possible when compacting the specimen; when an absorptive paper towel is not stained when depressed lightly into the surface of the slurry; or, when an emulsion has coalesced

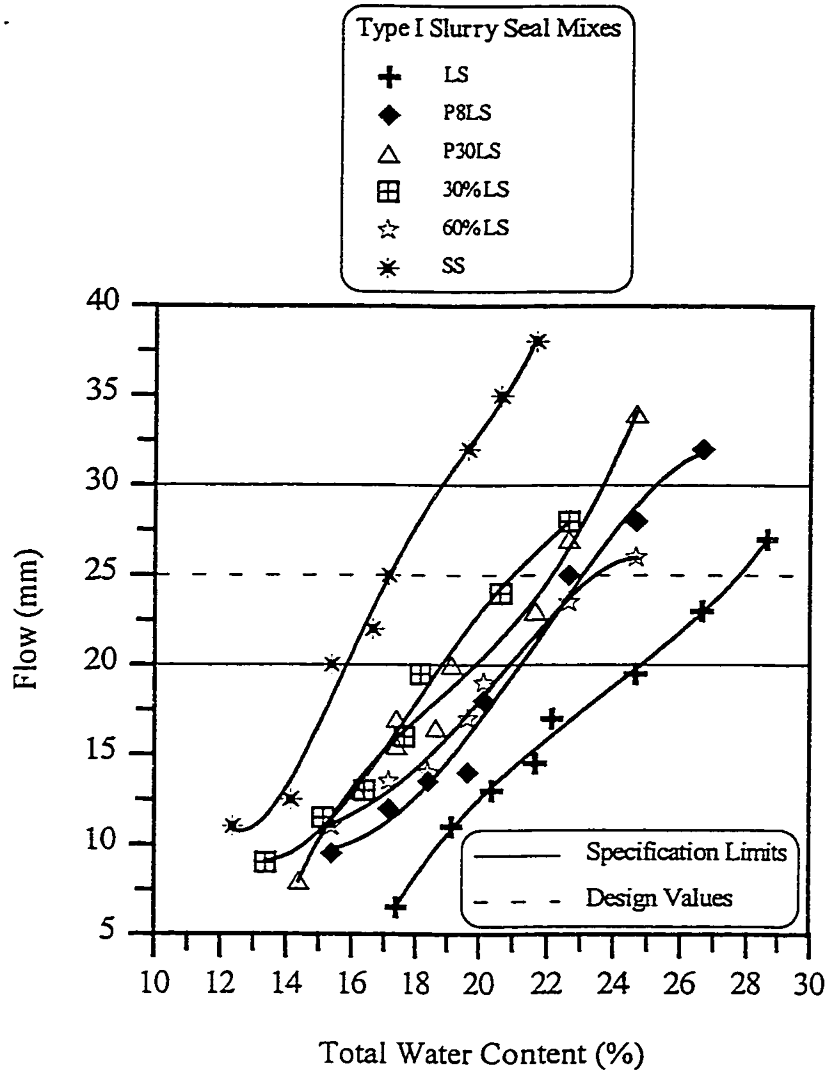


Figure 4.1: Cone Consistency Results of Type I Slurry Seal Mixes

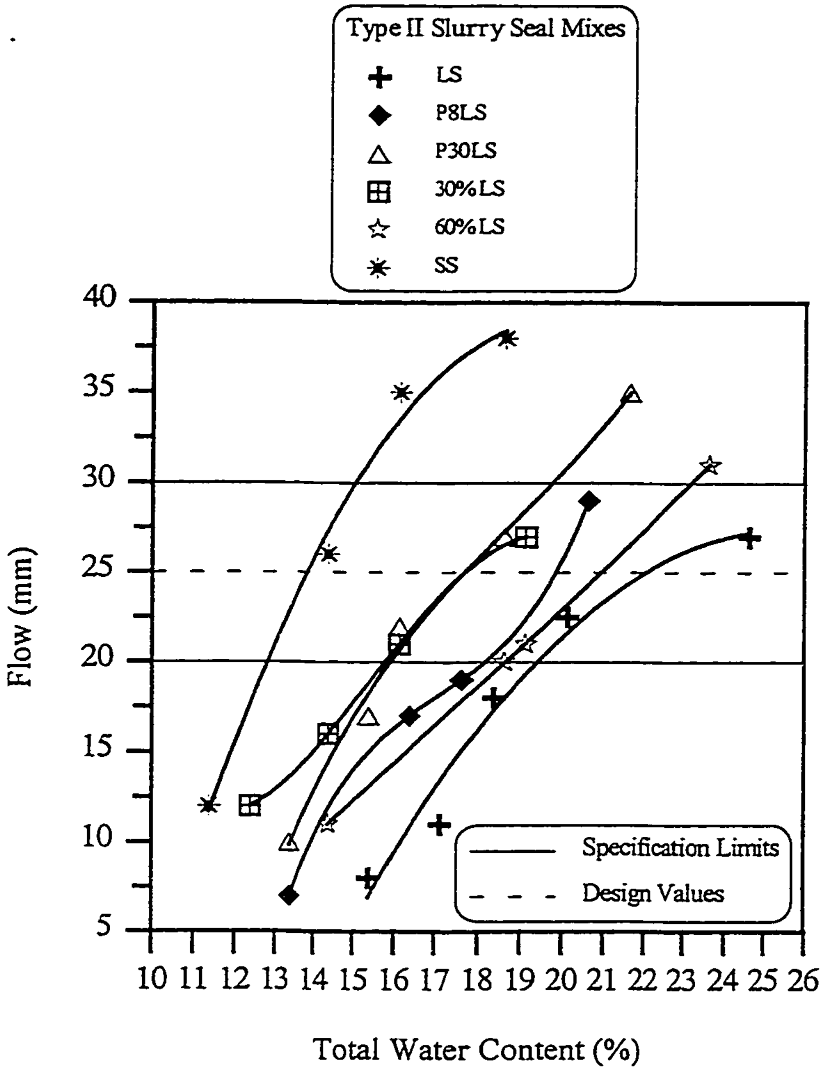


Figure 4.2: Cone Consistency Results of Type II Slurry Seal Mies

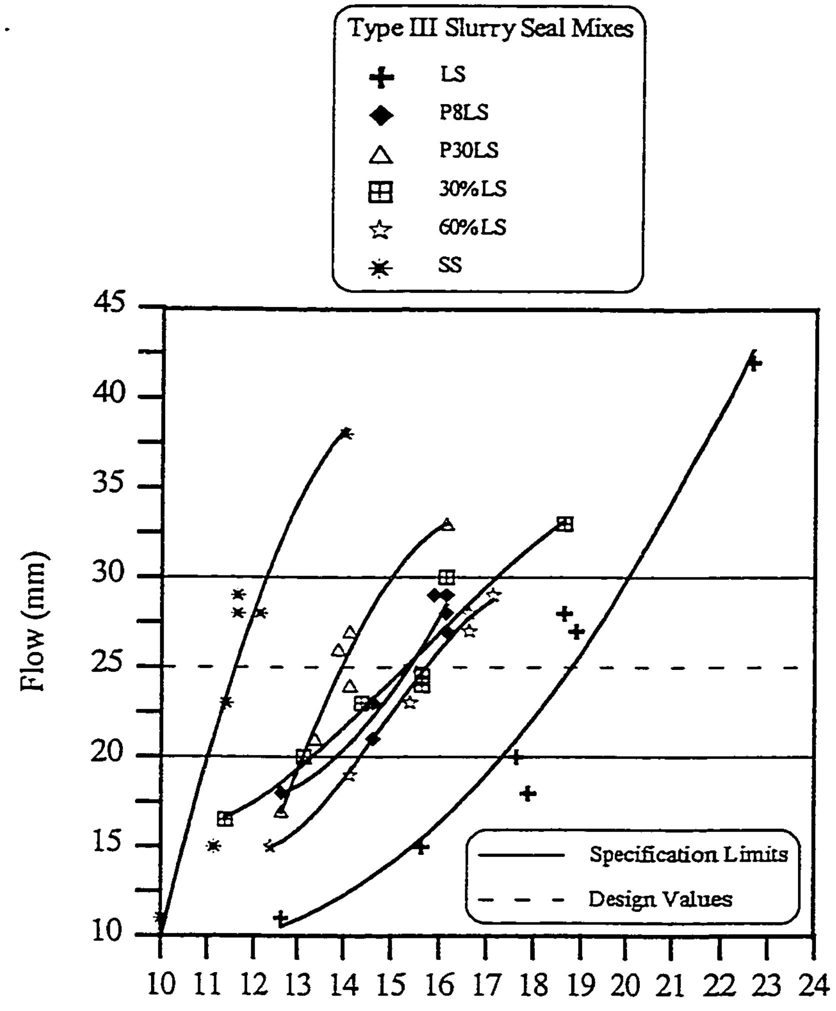


Figure 4.3: Cone Consistency Results of Type III Slurry Seal Mixes

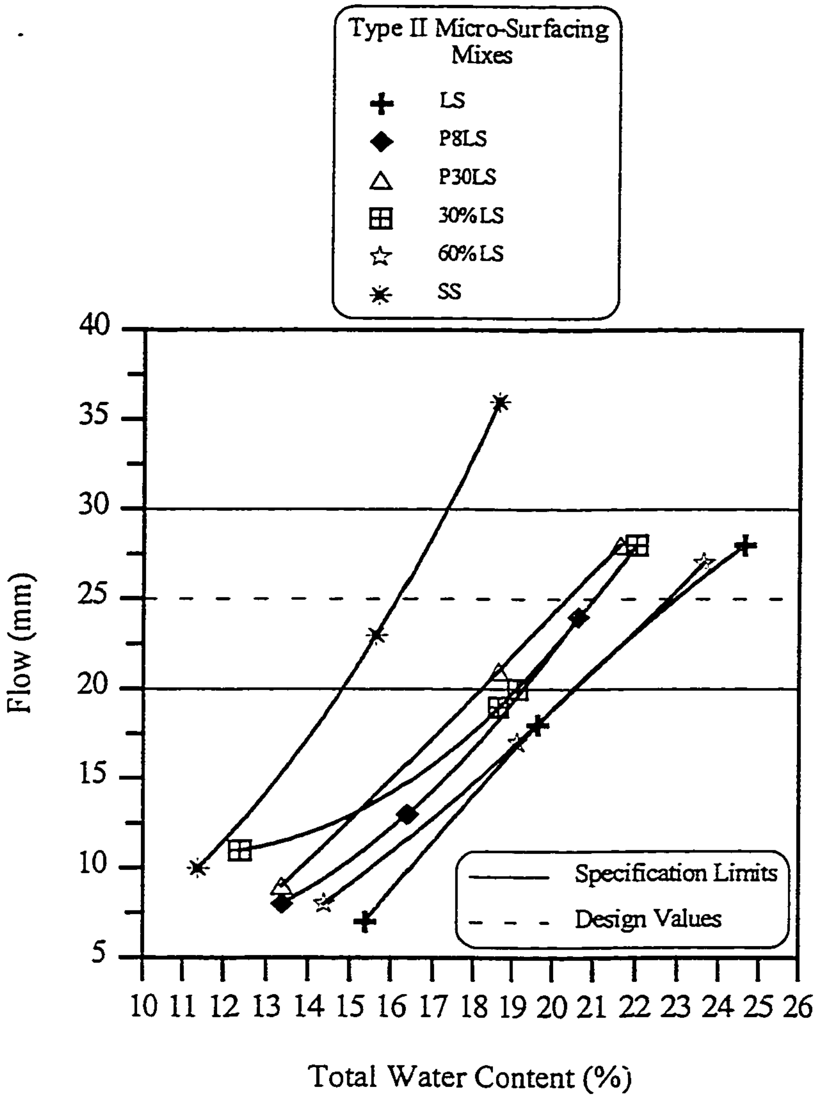


Figure 4.4: Cone Consistency Results of Type II Micro Surfacing Mixes

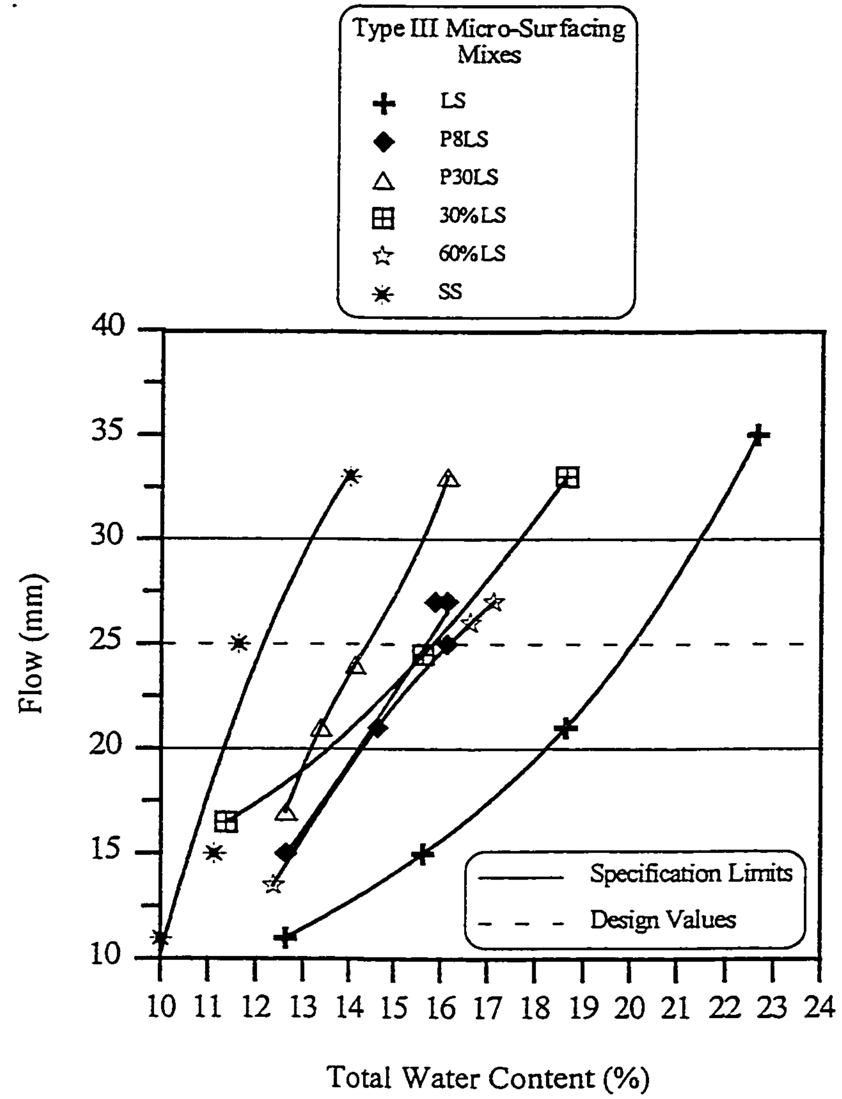


Figure 4.5: Cone Consistency Results of Type III Micro Surfacing Mixes

Table 4.3 : Cone Consistency Test Results for Slurry Seal & Micro Surfacing Mixes

		Slurry Seal Mixes Type						Micro Surfacing Mixes Type					
		LS	P8 LS	P30 LS	30% LS	60% LS	SS	LS	P8 LS	P30 LS	30% LS	60% LS	SS
Aggregate Gradation	Type I	27.5	23	22	21	23.5	17	*	*	*	*	*	*
	Type II	22	19.	17.	17.7	21	15	23	21	20.5	21	22.5	16
	Type III	18.7	15.	14	14.8	15.5	11.5	20	15.8	14.5	16	16.2	12.2

Cell readings represent total water content in percent to acquire a design slump of 25 mm
* Mixes are not normally used in the field (not recommended by the ISSA)

and is not available to lubricate the mixture; when initial setting of asphalt emulsion droplets have occurred; and, when no free emulsion may be diluted and washed away with water (ISSA TB 139, 1990). The set time occurs at the torque level of 12-13 kg-cm. Traffic time is the time required after which traffic can be allowed on the laid slurry seal and micro surfacing and it occurs at a torque level of 20-21 kg-cm when measured with the wet cohesion test device. Final torque normally represents the skid resistance properties of the slurry seal and micro surfacing mixes. It is the torque level measured after the complete curing of emulsified asphalt mix has occurred. The curing of emulsified asphalt mix occurs when there is no difference in torque levels between two successive readings (ISSA TB 139). Trial mixes were tested for wet cohesion in order to study the effect of the addition of lime and cement in slurry seal and micro surfacing mixes. However, no significant differences were observed in test values between normal and modified mixes. Hence, the modified mixes were discouraged for further testing.

Slag particles have a lower affinity for asphalt, lower surface porosity and adsorption, and rough as well as angular surface texture as compared to those of limestone aggregates (Lee, 1974). This was confirmed at the end of cohesion tests as higher set and traffic times as well as final torque values were observed for mixes consisting of higher amounts of slag aggregates. Similarly, higher torque values, with lesser time required to achieving set and for initial traffic rolling, were observed for micro surfacing mixes as compared to those of normal slurry seal mixes. This is due to the addition of polymer modifiers that resulted in increased binder stiffness. It is important to note that all micro surfacing mixes have failed to achieve a set time of 30 minutes and a traffic time of 60 minutes for quick traffic systems as specified by the ISSA. This is due to the aggregates requiring higher amounts of water content for desired consistency and the test method itself. The ISSA recommends wet cohesion test to be performed at room temperature which should be kept constant all the time. However, this is contrary to actual field conditions, especially in the Eastern Saudi Arabia where the ambient air temperature change from morning to afternoon is significantly high. Hence testing of slurry seal and micro surfacing samples at room temperature will not simulate actual field conditions. Thus, either the ISSA specifications should be revised or the testing should be carried out in fresh air rather than in the laboratory. The results of cohesion test have been depicted in Table 4.4 and the following observations were established . Details are given in Chapter 5:

- ***ISSA Type I Slurry Seal mixes:*** Mixes containing higher steel slag proportions have undoubtedly produced higher torque values with higher time required to set. The maximum torque value (25 kg.cm) was observed for SS mixes with 15% emulsified asphalt content, and the minimum value (13.5 kg.cm) was noticed for LS mixes with 9% emulsified asphalt content. Exactly the same trend was observed for set time where the set time required was 4 hours for LS

Table 4.4 : Results of Set Time, Traffic Rolling Time, and Final Torque Values of Slurry Seal and Micro Surfacing Mixes

			Slurry Seal Mixes Type						Micro Surfacing Mixes Type					
		Gradation	*LS*	*P8 LS*	*P30 LS*	*30% LS*	*60% LS*	*SS*	*LS*	*P8 LS*	*P30 LS*	*30% LS*	*60% LS*	*SS*
9 % Emulsified Asphalt	Set Time (HRS)	Type I	4	5	5.5	5.5	4.2	5.5	*	*	*	*	*	*
		Type II	4.5	5.5	5.7	5	4.5	4	3	4.5	3	3	3.5	3.5
		Type III	4	3.8	3.5	3.25	4	3	3.5	3	3.5	3.25	3	3.5
	Traffic Time (HRS)	Type I	-	-	-	-	-	11	*	*	*	*	*	*
		Type II	-	12.5	9.5	8	10	8.5	11.5	9	8.75	9	10	6.5
		Type III	11	10.5	10	9.5	10	7	8	7	7	8	8.5	6.5
	Final Torque (kg.cm)	Type I	13.5	16	18.5	18	16.5	22.4	*	*	*	*	*	*
		Type II	17.5	21	22	21	19.5	27	20	24	26	23.5	21	29.6
		Type III	21	28	29	32	23	30.5	23.4	31	33.5	29.7	26	34
11 % Emulsified Asphalt	Set Time (HRS)	Type I	4.5	5.5	6	5.75	4.5	6	*	*	*	*	*	*
		Type II	5	6	6.3	5.5	4.75	5	3.5	5	3.25	3.5	4	4
		Type III	4.5	4	3.5	3.5	3.25	3.25	4	3.25	4	3.5	3	3.75
	Traffic Time (HRS)	Type I	-	-	13	13	-	12	*	*	*	*	*	*
		Type II	-	12	11	8.5	10	9	11	9.5	9.25	10	9.5	8
		Type III	11.2	10.7	9.5	9	10.5	7.5	9	7.25	7.25	8.5	9.5	6.75
	Final Torque (Kg.cm)	Type I	16	16.5	21	20	18	23	*	*	*	*	*	*
		Type II	19	22	23.5	22	21.5	29.6	21	25.2	26.5	24	21.5	31
		Type III	24	28.5	31	31	20	31	27.3	31.5	35	31.4	28.3	35
15 % Emulsified Asphalt	Set Time (HRS)	Type I	4.7	6	6.5	6	5	6.5	•	•	•	•	•	•
		Type II	5.5	6.25	6.5	5.75	5.2	5.5	4	5	4	4	4.5	4.25
		Type III	4.25	4.25	4	3.75	3.25	3.25	4.5	4	5.25	3.5	3.25	4
	Traffic Time (HRS)	Type I	-	-	13	12	-	11.5	*	*	*	*	*	*
		Type II	-	12.5	11.5	10.5	12	9.5	8.5	9.5	9.5	10.5	9	7.8
		Type III	11.2	11	9.25	9	10.2	8	9.5	7.5	8	8.75	9.25	7.25
	Final Torque (Kg.cm)	Type I	17.1	17	22.5	21.5	19	25	*	*	*	*	*	*
		Type II	17.6	22.5	24.5	22.5	21	29	22.5	25.7	25	24	22.3	28.4
		Type III	24.5	30	33	31	21.5	32	25.9	32	31	32	28.5	34.1

* Mixes are not normally used in the field (not recommended by the ISSA)

\- Mixes have failed to acquire such stage mixes with 9% emulsion, and for SS mixes with 15% emulsion, this value was 6.5 hours. However, mixes containing higher slag particles have shown less time required to allow traffic rolling. This is because these mixes have attained the required torque value (20 kg.cm) more rapidly due to the presence of slag particles exhibiting rough and angular surface properties. Many mixes containing higher amount of limestone (LS, P8LS, and 60% LS) have failed to attain a final torque of 20 kg.cm and hence no traffic rolling time criteria can be applied to such mixes. This is due to the fine gradation as well as high amount of smooth surface textured limestone particles used in these mixes. Hence, such mixes are not practical for application as a wearing surface as these mixes are lacking the required skid resistance. Generally, the final torque values of mixes are increased with the increase in emulsified asphalt content. However, this also caused a slight increase in set and traffic rolling time of such mixes.

- *ISSA Type II Slurry Seal mixes:* Generally, the same behavior was observed for this case as in ISSA Type I, i.e., higher slag proportions exhibited higher torque values as well as lesser required traffic rolling time. In this case, only LS mixes have failed to attain traffic rolling torque value. This is because the gradation has now become coarse and the particle sizes are increased making the end torque values of all the mixes relatively higher than those of ISSA Type I. The maximum torque value (29.6 kg.cm) was achieved by SS mixes with 11% emulsified asphalt content, which is at least 18.4% higher than the maximum observed torque value of ISSA Type I gradation. The set time and traffic time required were generally increased with the increase in emulsified asphalt content. P30LS mixes with 15% emulsified asphalt content have taken the longest time to set. On the other hand, SS mixes with 9% emulsified asphalt have required the least time to set. In general, due to the change in aggregate gradation (fine to coarse), the average decrease in traffic rolling time of ISSA Type II mixes was around 16%, and the increase in final torque value was 18%, as compared to those of ISSA Type I mixes.

- ***ISSA Type III Slurry Seal mixes:*** The highest values of final torque were observed in this gradation category for slurry seal mixes. For example, SS mixes have shown a final torque values of 32 kg.cm which is approximately 8.3% higher than those observed in Type II slurry seal mixes. The set time and traffic rolling time have generally decreased as compared to those in Type II slurry seal mixes. This is due to the further increase in coarse aggregate particles that provide additional resistance to twisting movements in lesser time when measured by the torque meter. Mixes containing higher amounts of steel slag aggregates have generally set and cured for initial traffic rolling earlier than those mixes containing higher proportions of limestone aggregates.
- ***ISSA Type II Micro Surfacing mixes:*** The use of polymer emulsified asphalt has simultaneously increased the final torque values (10% average increase)

and decreased the set and traffic rolling time (11% average decrease) for nearly all the mixes types. In addition, an average decrease of 38% set time is also observed as compared to that of ISSA Type II normal slurry seal mixes. As expected, higher values of final torque and lower values of traffic rolling time were noticed for mixes containing higher amounts of steel slag aggregate. LS mixes with 9% emulsified asphalt content have shown the lowest value of final torque, i.e., 20 kg.cm, and SS mixes with 11% emulsified asphalt content have given the highest torque value of 31 kg.cm. It is important to note that all the mixes have passed the initial traffic rolling requirements. All these factors are affected by the use of an improved type of emulsified asphalt, i.e., polymer-modified emulsion. As indicated in Chapter 2, the polymer modification of emulsified asphalt normally increases the elasticity, tensile strength and, most importantly, the adhesion and cohesion properties as well as toughness and improvement of the aggregates-binder system. This is because of the introduction of cross-linked rubberized materials that ultimately increases the adhesion between binder and aggregates as well as better cohesion within the binder itself (Aglan et al., 1989). Hence, better aggregate to aggregate bonding is achieved in less time than the normal slurry seal mixes.

- *ISSA Type III Micro Surfacing mixes:* An average improvement of 25% is gained in terms of the final torque values. The set time and traffic rolling time have decreased to about 6% and 14%, respectively. This is due to an increase in the coarse aggregate proportions as compared to ISSA Type II gradation. The highest torque value (35 kg.cm) was observed for SS mixes consisting of 11% emulsified asphalt and the lowest torque value (23.4 kg.cm) was attained by LS mixes with 9% emulsified asphalt. P8LS with 9% emulsion, 60%LS with 9% and 11% emulsion content have shown the least time required to set (3 hrs). The highest time required to set (5.25 hrs) was observed in the case of P30LS with 15% emulsion content. Similarly, the least time required to achieve traffic rolling stage was 6.5 hrs (SS with 9% emulsion) and the longest time required was 9.5 hrs (LS with 15% emulsion).

4.5 Wet Track Abrasion Test (WTAT) Results

Wet track abrasion test (WTAT) reveals the field performance of slurry seal and micro surfacing mixes by simulating the abrasion of wearing surface produced by power steered rubber tires under wet conditions. Higher wear loss is observed with those mixes in which aggregates not having proper binding characteristics and greater potential for polishing. This may be due to the inferior aggregate and binder quality, improper aggregate gradation, and inadequate binder content. For slurry seal mixes, the specification limits of WTAT loss, according to the ASTM D3910 and/or ISSA A105, and A143, is 800 g/m^2 and for micro surfacing mixes, this reduces to 530 g/m^2. WTAT was performed on all samples (normal and treated with lime as well as with cement). Generally, the mixes containing higher percentages of steel slag gave lesser WTAT loss due to the greater abrasion resistance of steel slag particles. Similarly, the aggregate gradation and emulsified asphalt content and type also played a significant role in WTAT loss. Coarse aggregate gradation, higher emulsified asphalt content, and the use of polymer-modified emulsion resulted in reduction of wear loss. Mixes treated with cement and lime showed further reduction in WTAT loss, with the cement modification being more effective in most of the cases. This is due to the improvement in aggregate bonding characteristics of the mixes when treated with cement or lime. The test results of WTAT loss are summarized in Table 4.5. The graphic presentations are shown in Figure 4.6 through Figure 4.17. The testing of modified mixes at 11% emulsified asphalt content was not carried out because the trend of test performance was obvious in the case of 9% and 15% emulsified asphalt content. Hence, there was no need to further test these mixes at 11% emulsified asphalt content. The following observations are recorded . Details are given in Chapter 5:

- *ISSA Type I Slurry Seal mixes:* Generally, this aggregate gradation showed significantly poor performance with only P30LS (cement + 15% emulsion), 30%LS (cement + 15% emulsion), 60%LS (cement + 15% emulsion), and SS (lime + 15% emulsion) passing the ISSA requirements (maximum 800 g/m^2). The rest have failed primarily because of the larger amount of inferior quality

Table 4.5 : WTAT Loss Results for Slurry Seal and Micro Surfacing Mixes

			Slurry Seal Mixes Type						Micro Surfacing Mixes Type					
	Gradation	Treatment	*LS*	*P8 LS*	*P30 LS*	*30% LS*	*60% LS*	*SS*	*LS*	*P8 LS*	*P30 LS*	*30% LS*	*60% LS*	*SS*
9 % Emulsified Asphalt	Type I	Normal	2100	1480	1450	1250	1550	1250	*	*	*	*	*	*
		Lime	1900	1450	1450	1180	1350	910	*	*	*	*	*	*
		Cement	1600	1380	1100	920	1100	1100	*	*	*	*	*	*
	Type II	Normal	1600	1350	1280	1100	1300	750	950	515	480	420	520	210
		Lime	1500	1300	1200	970	1200	500	900	450	450	400	430	180
		Cement	1300	1100	900	720	910	630	800	360	390	330	385	280
	Type III	Normal	1105	903	853	760	840	430	510	250	310	230	310	110
		Lime	935	765	700	670	780	400	410	200	260	220	285	60
		Cement	876	690	625	630	700	386	390	180	200	190	200	130
11 % Emulsified Asphalt	Type I	Normal	1800	1400	1300	1200	1300	960	*	*	*	*	*	*
		Lime	-	-	-	-	-	-	*	*	*	*	*	*
		Cement	-	-	-	-	-	-	*	*	*	*	*	*
	Type II	Normal	1400	1000	1100	900	1060	500	820	450	330	300	300	170
		Lime	-	-	-	-	-	-	-	-	-	-	-	-
		Cement	-	-	-	-	-	-	-	-	-	-	-	-
	Type III	Normal	930	730	700	650	740	310	400	200	210	190	240	50
		Lime	-	-	-	-	-	-	-	-	-	-	-	-
		Cement	-	-	-	-	-	-	-	-	-	-	-	-
15 % Emulsified Asphalt	Type I	Normal	1700	1100	1000	900	1290	900	*	*	*	*	*	*
		Lime	1500	1080	900	850	1100	680	*	*	*	*	*	*
		Cement	1300	900	700	700	650	930	*	*	*	*	*	*
	Type II	Normal	1100	950	810	600	700	350	500	550	280	130	210	90
		Lime	1100	800	700	530	700	210	450	310	220	140	220	101
		Cement	1000	600	600	410	500	320	410	250	200	180	200	200
	Type III	Normal	630	571	530	350	590	195	370	180	200	101	110	30
		Lime	589	490	438	371	531	230	300	170	200	101	110	30
		Cement	500	431	333	280	454	210	300	120	110	90	101	80

Cell readings represent WTAT loss results in g/m^2

* Mixes are not normally used in the field (not recommended by the ISSA)

\- Mixes were not tested

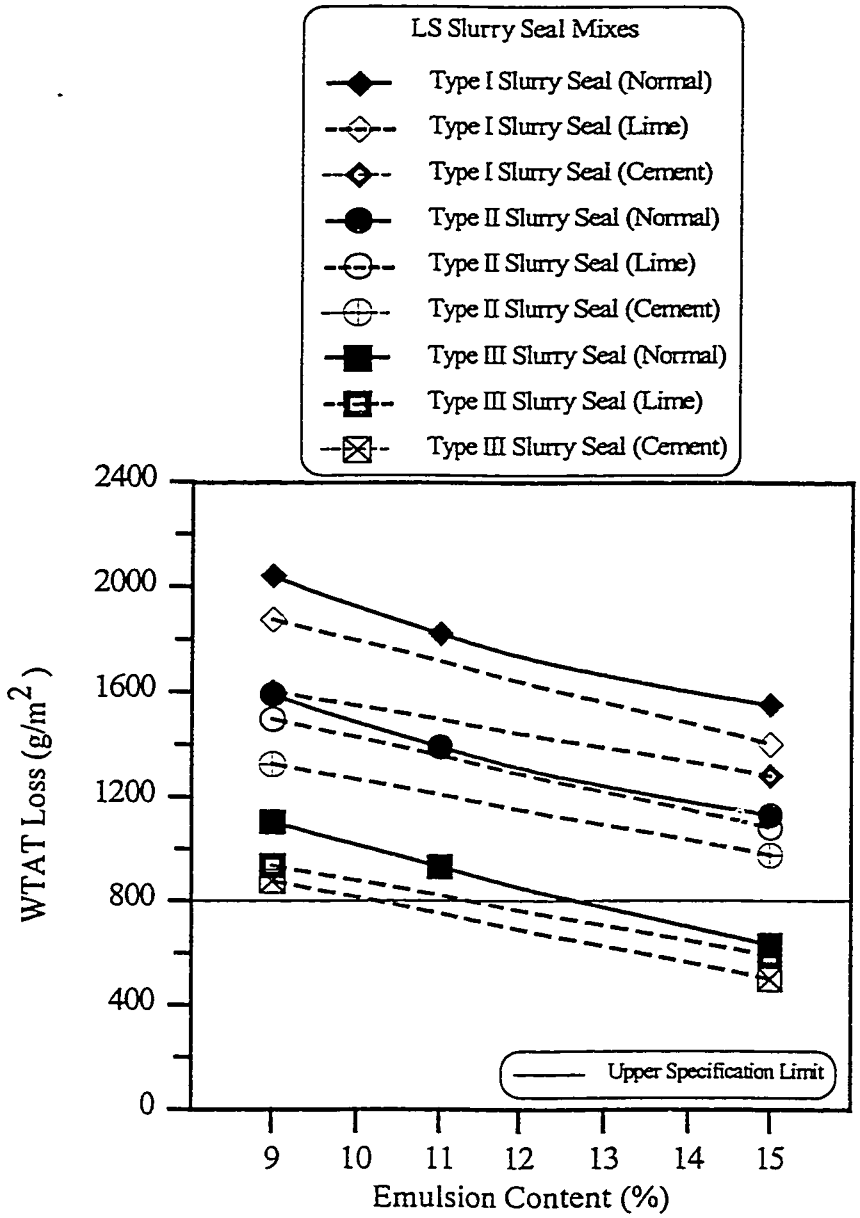


Figure 4.6: WTAT Results For LS Slurry Seal Mixes

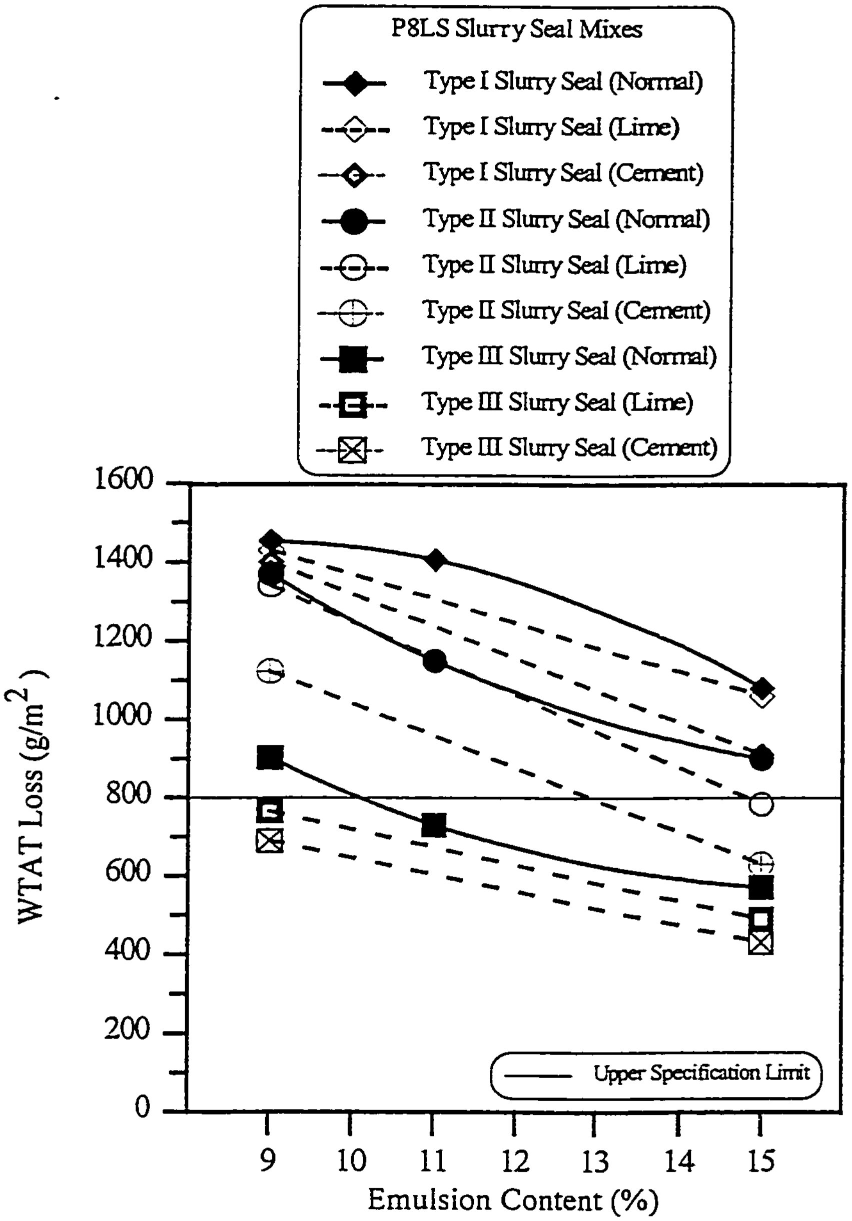


Figure 4.7: WTAT Results For P8LS Slurry Seal Mixes

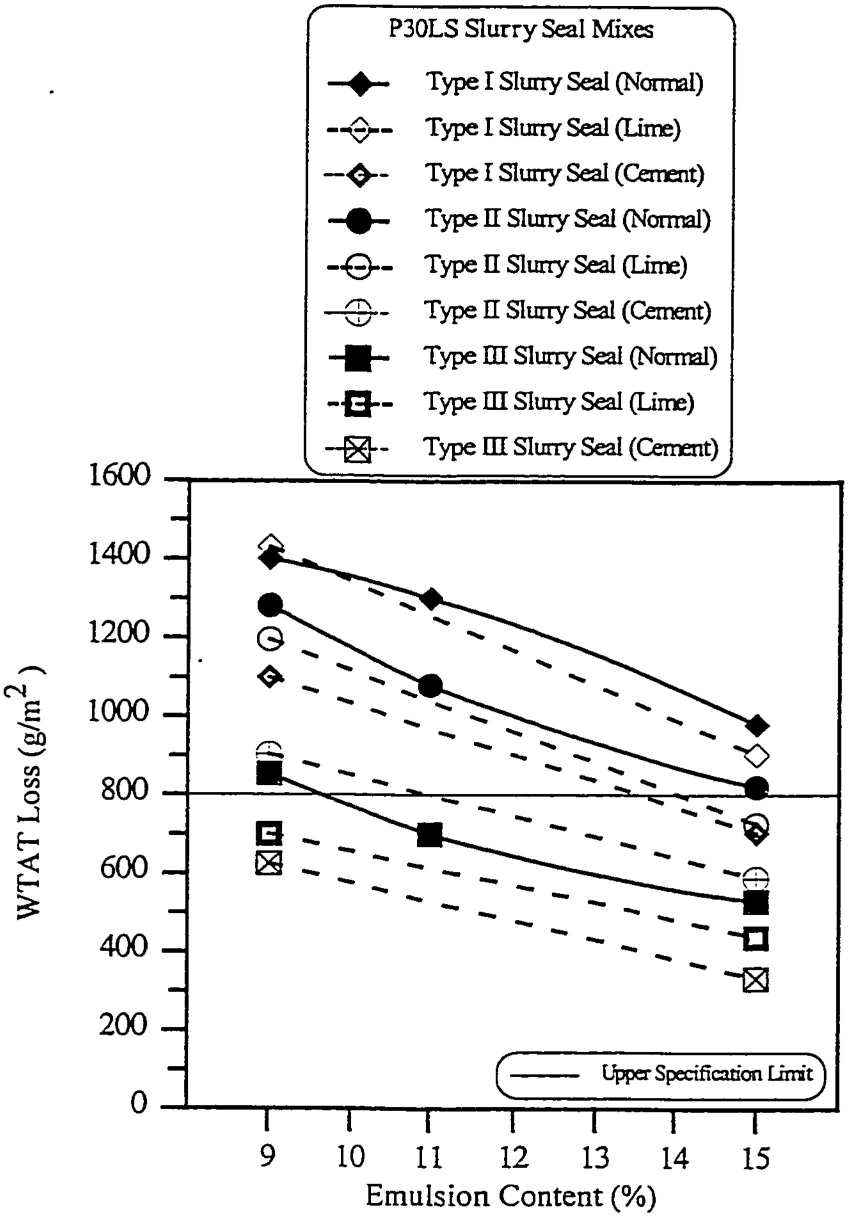


Figure 4.8: WTAT Results For P30LS Slurry Seal Mixes

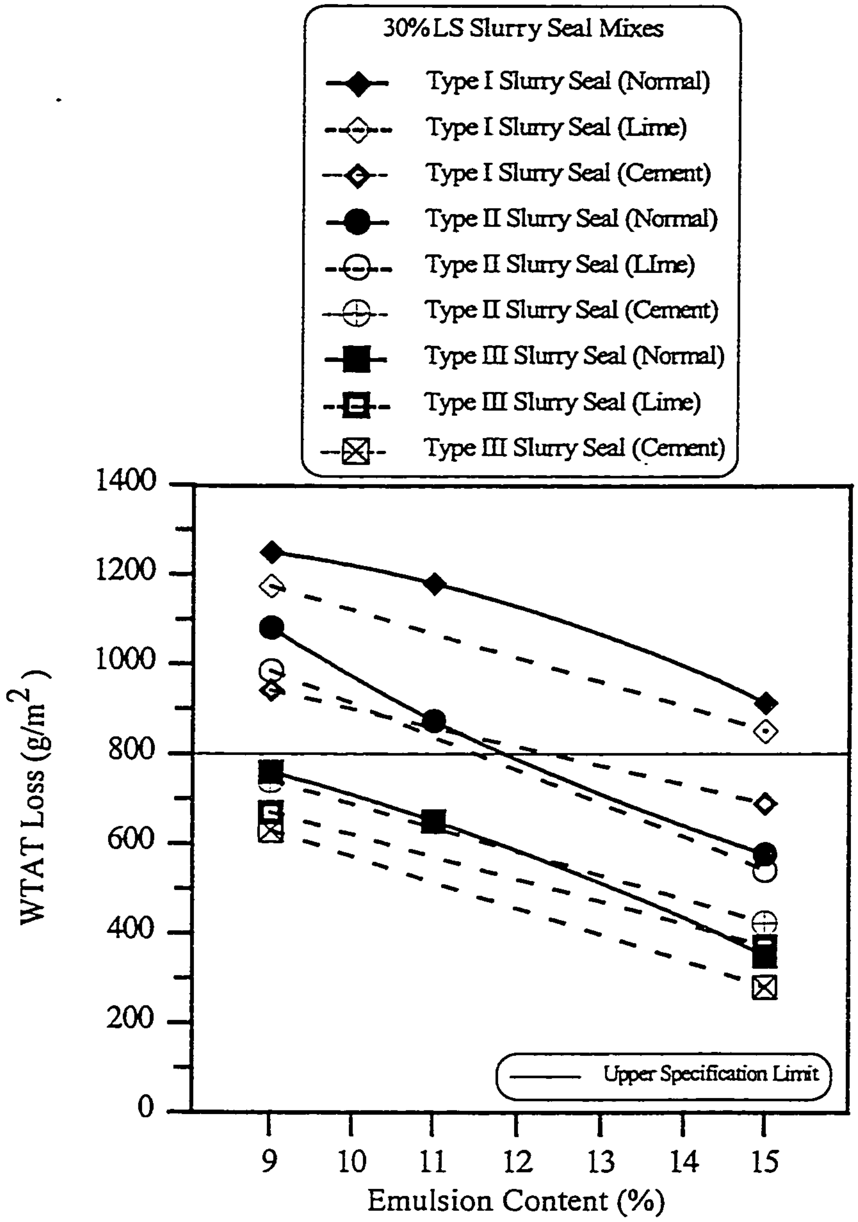


Figure 4.9: WTAT Results For 30%LS Slurry Seal Mixes

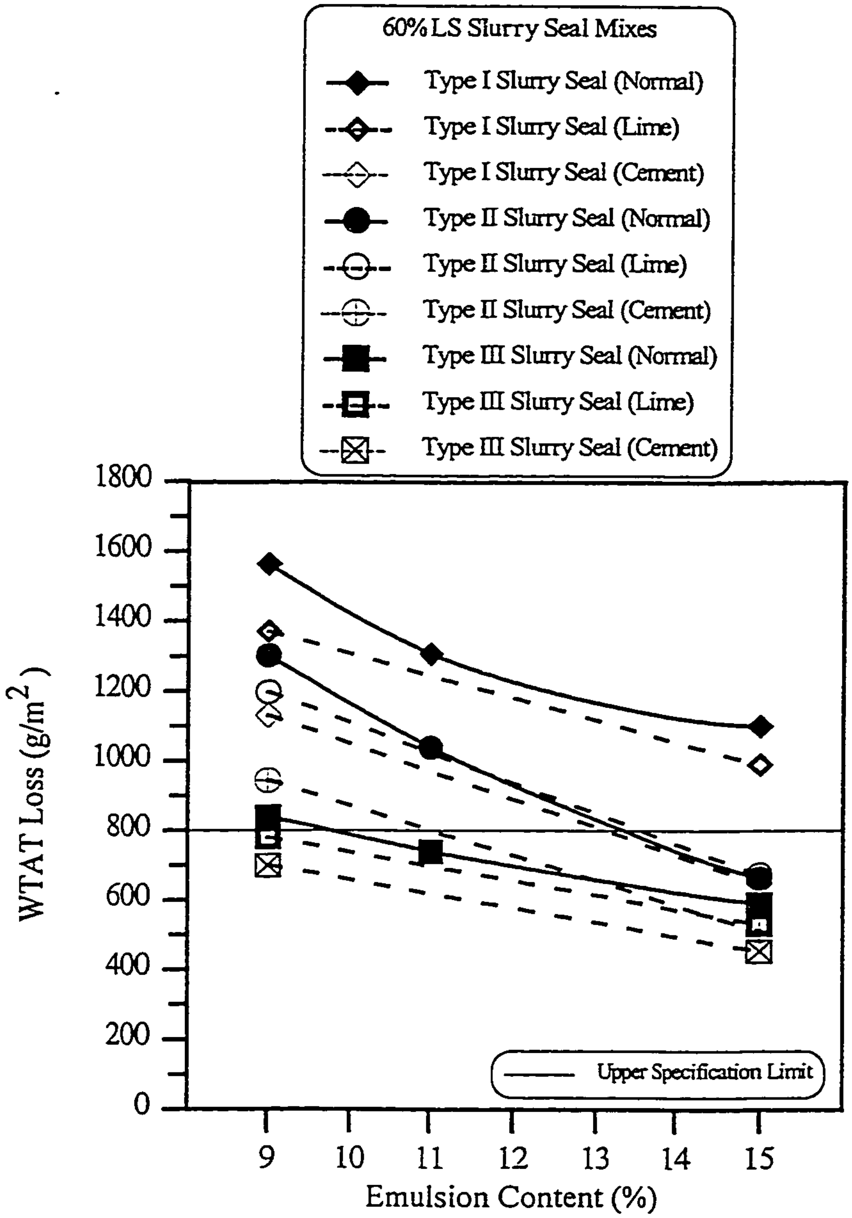


Figure 4.10: WTAT Results For 60%LS Slurry SealMixes

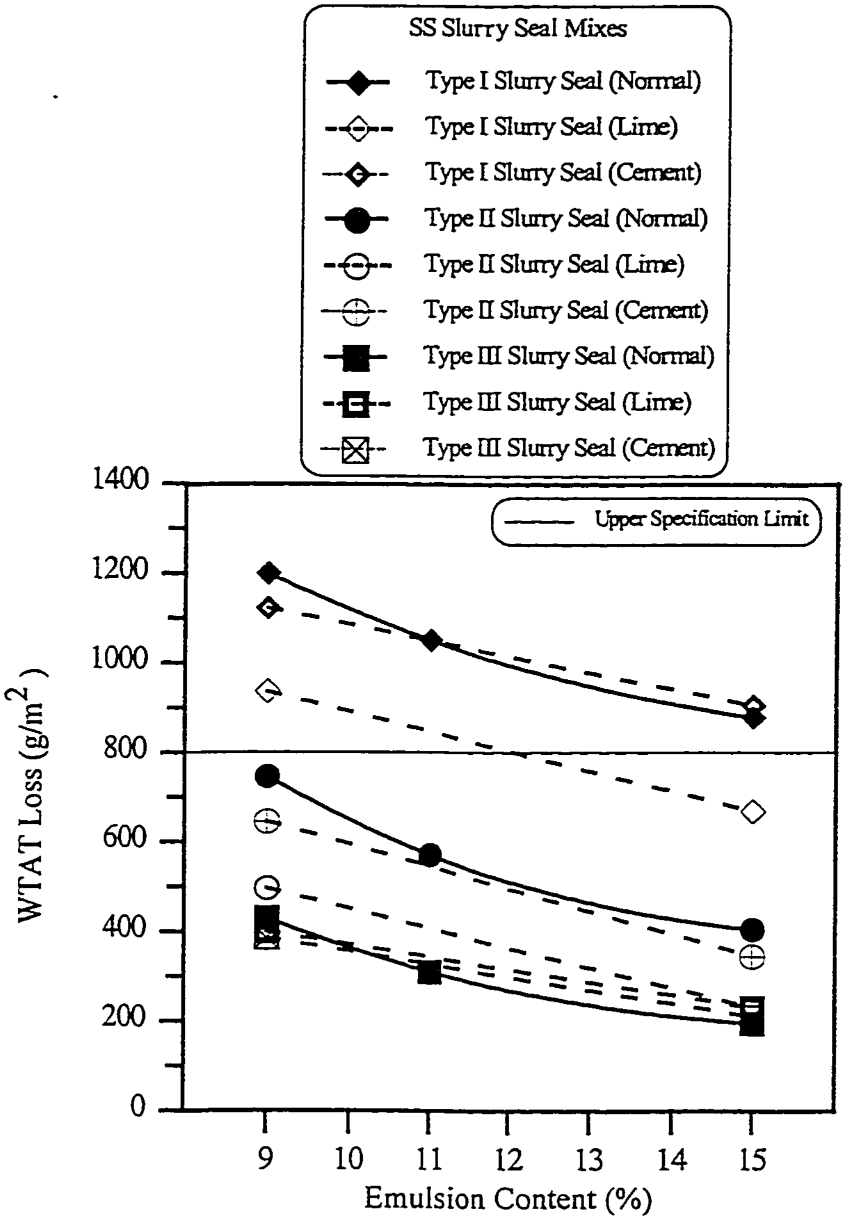


Figure 4.11: WTAT Results For SS Slurry Seal Mixes

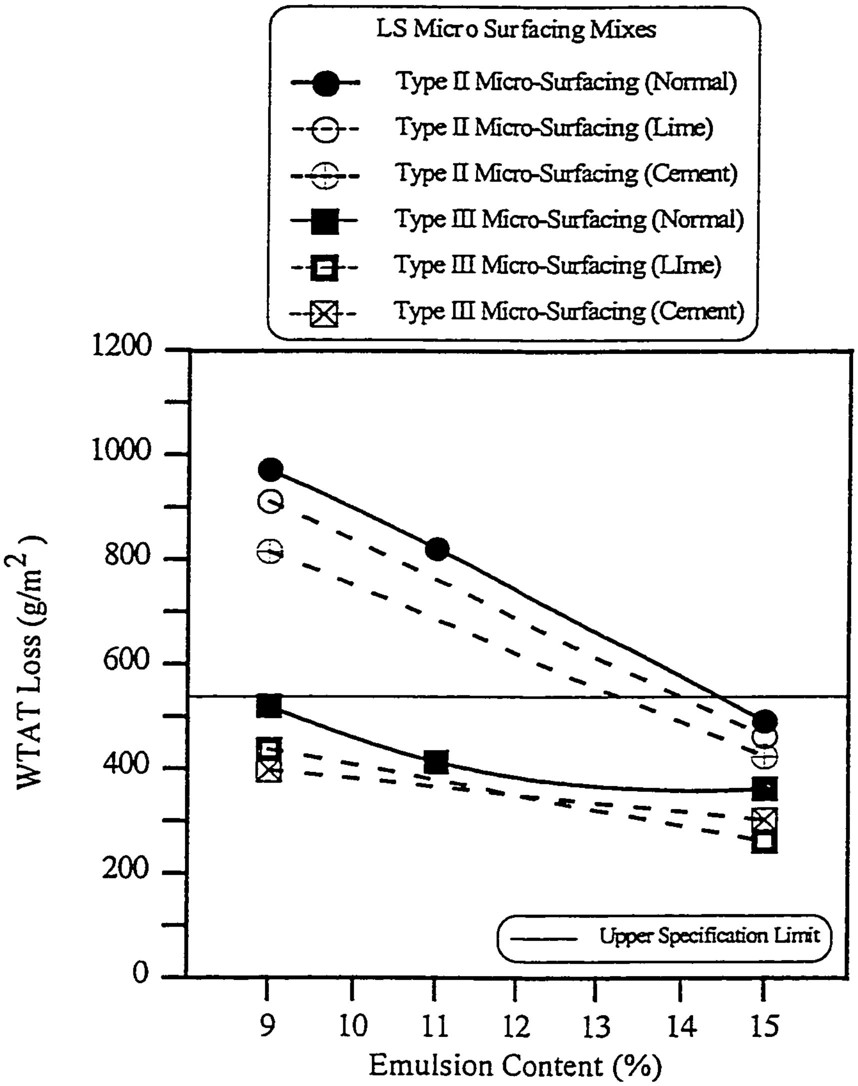


Figure 4.12: WTAT Results For LS Micro Surfacing Mixes

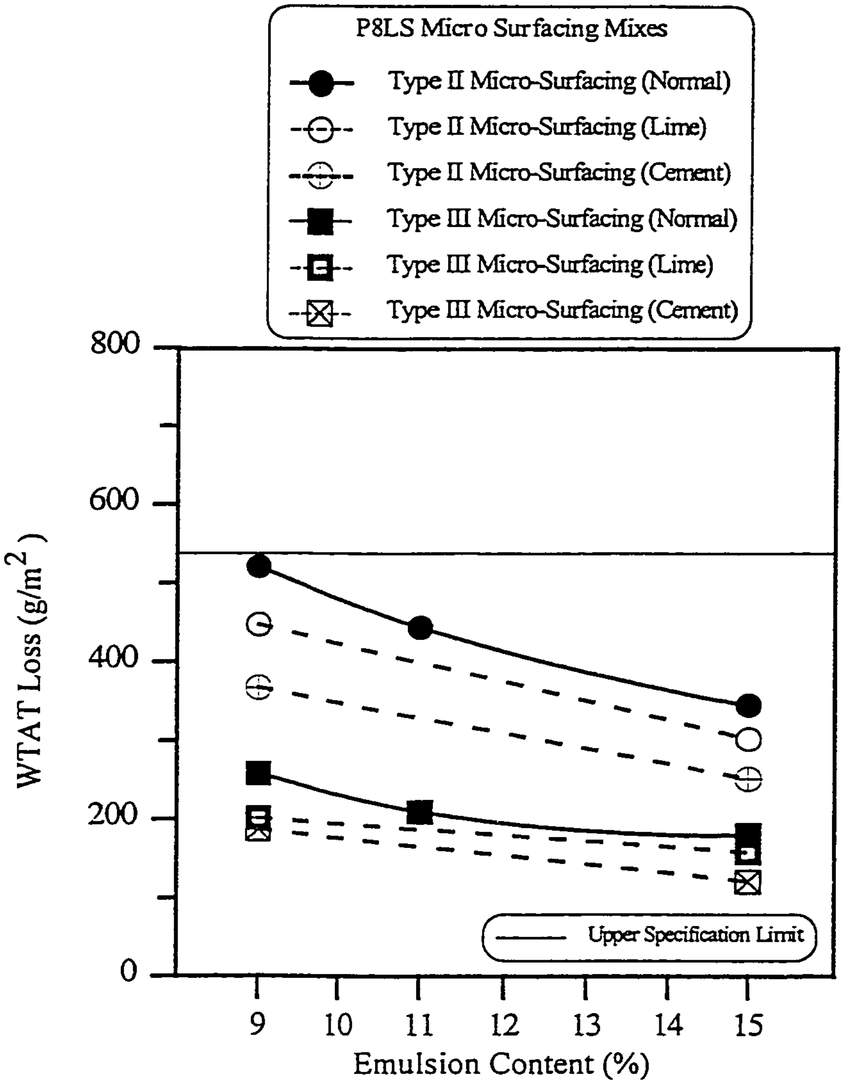


Figure 4.13: WTAT Results For P8LS Micro Surfacing Mixes

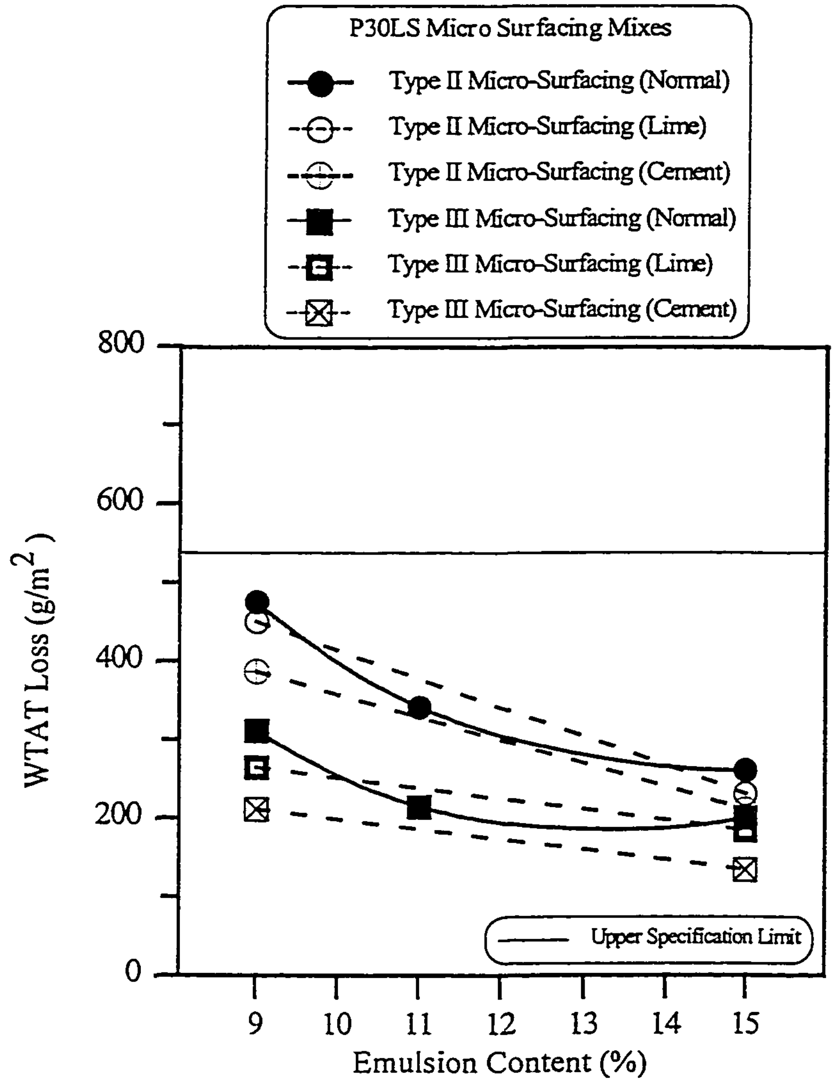


Figure 4.14: WTAT Results For P30LS Micro Surfacing Mixes

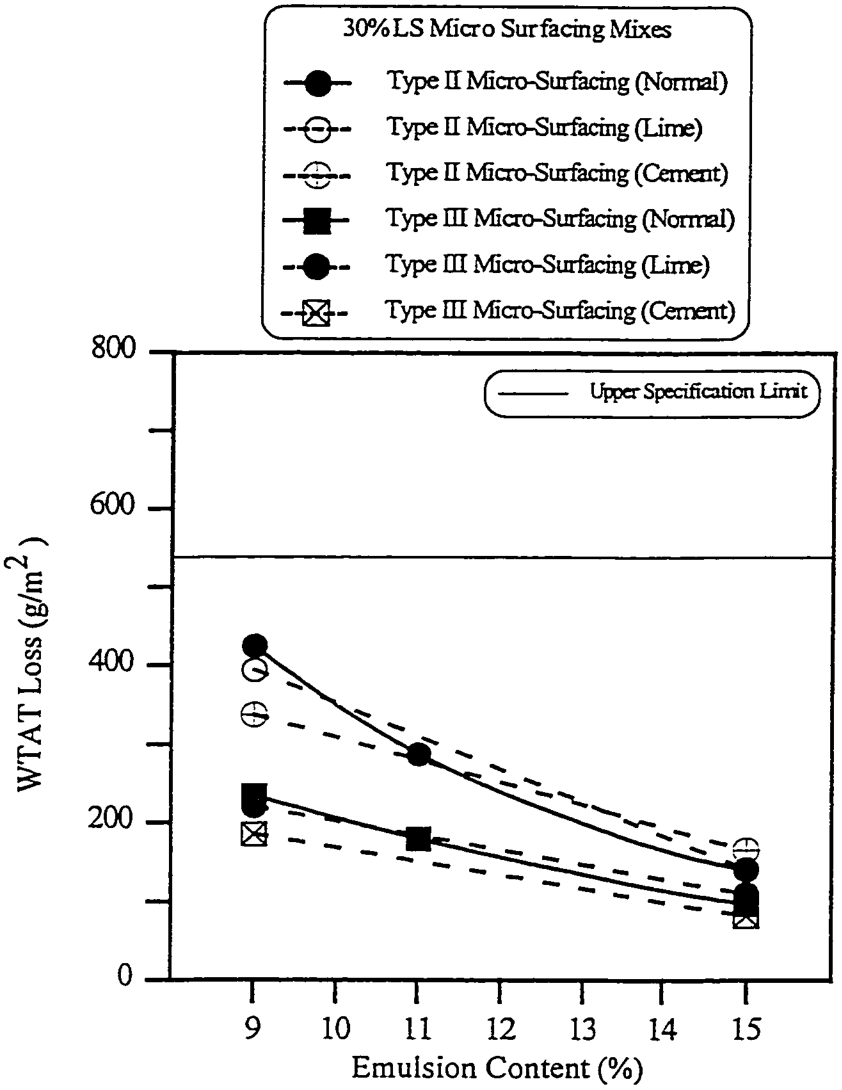


Figure 4.15: WTAT Results For 30%LS Micro Surfacing Mixes

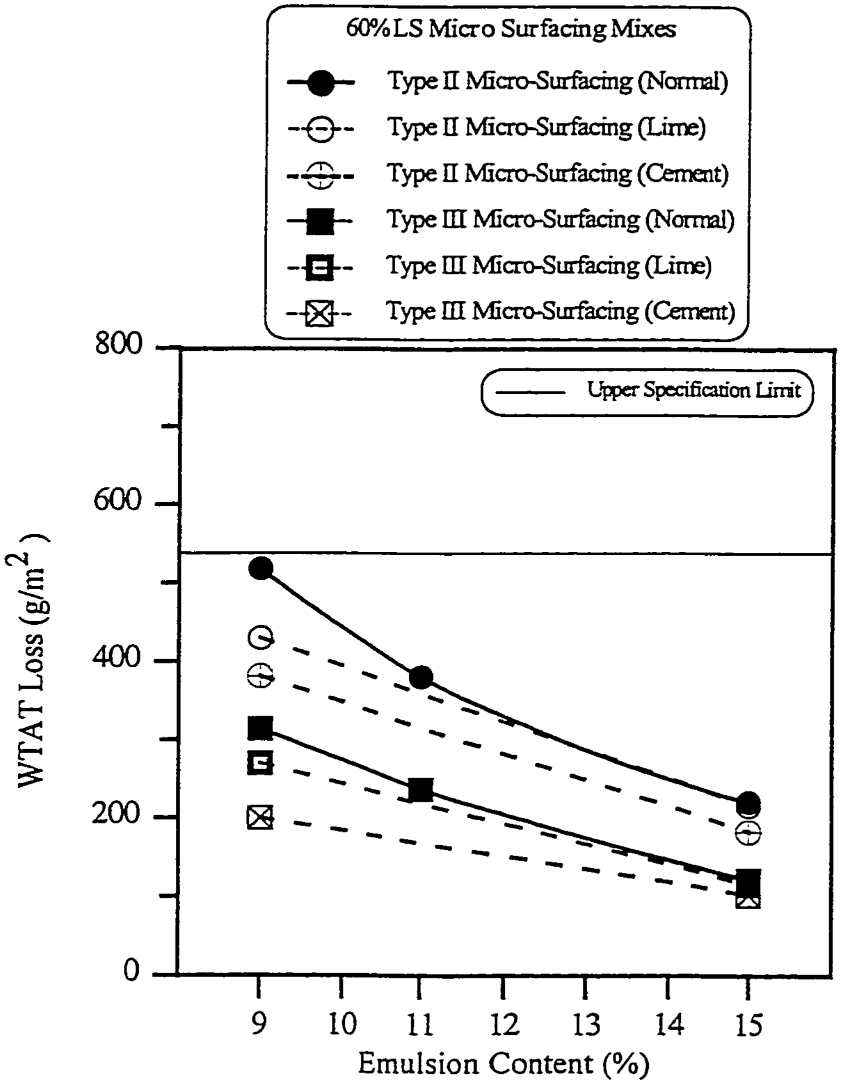


Figure 4.16: WTAT Results For 60%LS Micro SurfacingMixes

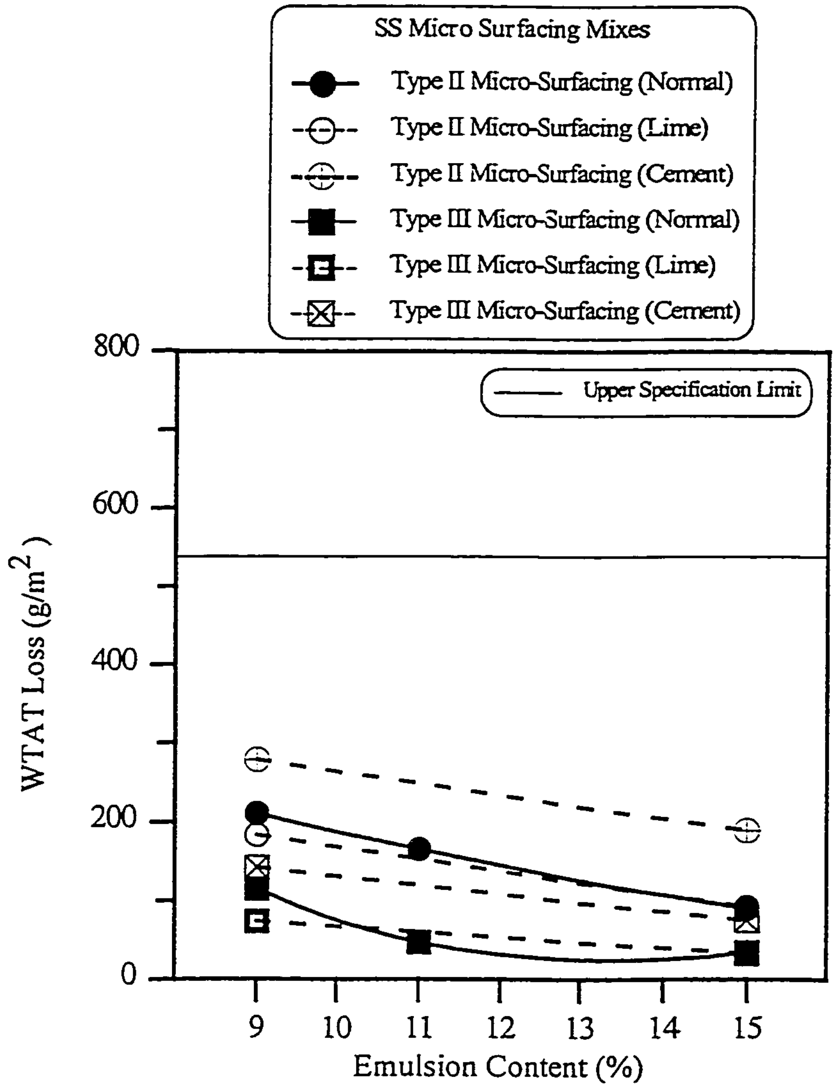


Figure 4.17: WTAT Results For SS Micro Surfacing Mixes

of fine limestone aggregates which poses greater wear loss that cannot be modified successfully. Mixes containing higher slag content have also failed unless modified at higher emulsified asphalt content. This may be related to the fine aggregate gradation failing to get enough binder content, because the larger surface area of the fine aggregates requires more emulsified asphalt content in order to fully coat their surfaces as compared to coarse aggregates. The average reduction in wear loss due to the increase in the emulsified asphalt content (from 9% to 15%) was 28%. It is interesting to note that SS mixes have improved more with lime treatment rather than with Portland cement treatment. In fact, hairline shrinkage cracks were observed on SS samples modified with Portland cement. This phenomenon is attributed to the use of high Portland cement content (total of 6%) with granular material, i.e., steel slag aggregates, which caused shrinkage cracking. Normally, the highest WTAT loss was observed for normal LS mixes (as high as 2100 g/m^2). This is due to the soft and fragile nature of limestone aggregates which pose high abrasion and polishing potential under moving wheel loads. Slag, on the other hand, showed the least abrasion loss (as low as 50 g/m^2) in almost all the conditions indicating its improved polishing and abrasion resistance qualities. Generally, cement modification has produced better results when compared with lime treatment in terms of minimizing wear loss. However, for the case of SS mixes, lime treatment proved more effective.

- *ISSA Type II Slurry Seal mixes:* Although, the wear loss for this gradation was less as compared with Type I, however, only P8LS (cement + 15% emulsion), P30LS (cement + 15% emulsion), P30LS (lime + 15% emulsion), 30%LS (all mixes with 15% emulsion), 60%LS (all mixes with 15% emulsion), and SS (all mixes with 15% emulsion) have passed the specification requirements (maximum 800 g/m^2). Like Type I mixes, the highest wear loss (1600 g/m^2) was observed with normal LS mixes which was, however, 24% less than that of Type I. The average decrease in wear loss only due to the change in gradation (from Type I to Type II) was approximately 26%. This included the effect of aggregate blend, treatment type, and emulsified asphalt content. Generally, cement showed more improvement in performance when compared with lime treatment.
- *ISSA Type III Slurry Seal mixes:* The observed wear loss of this specified gradation was the least in slurry seal mixes. Most of the aggregate blends have passed the maximum wear loss specification of 800 g/m^2, except for LS, P8LS, and P30LS mixes at lower emulsified asphalt content. These failed mixes have all passed the specifications when the emulsified asphalt content was increased. As observed in previous aggregate blends, mixes consisting of higher amounts of steel slag aggregates have shown lower wear loss. In the same way, the increase in emulsified asphalt content, and modification with Portland cement and lime have reduced the wear loss for all the mix types.

Treatment with Portland cement has generally proved more effectiveness as compared to treatment with lime.

- *ISSA Type II Micro Surfacing mixes:* Polymer modification of emulsified asphalt normally yields a physical cross-links between the binder and aggregates which imparts bonding strength to the system thus resulting in increased resistance to stripping and abrasion of aggregate particles (Shuler et al., 1985). This can be confirmed by looking at the test results of Type II micro surfacing which showed significant reduction in wear loss for all the aggregate blends as compared to those of ordinary slurry seal mixes. The average decrease in wear loss due to the use of polymer-modified emulsion only (regardless of other factors) was 65%, as compared to ordinary Type II slurry seal mixes, which is highly significant. All the mixes have passed the specification requirements (maximum 530 g/m^2) except for LS mixes (with 9% emulsified asphalt content) indicating the inferior performance of limestone aggregates. The highest wear loss observed was 980 g/m^2 corresponding to LS mixes and the lowest wear loss was 210 g/m^2 in the case of SS mixes. The average reduction in wear loss within the specific category (Type II micro surfacing mixes) as a result of changing aggregate blend only (from LS to SS) was 78%. The behavior of cement and lime treatment was the same as observed previously. All the treated mixes were qualified according to specification limits.

- *ISSA Type III Micro Surfacing mixes:* ISSA Type III gradation consists of 30-40% coarse (retained on # 4 sieve) materials and is normally used as a new wearing surface for existing pavement structures. The wear loss of this aggregate category was the least (as expected). All of the mixes (regardless of the treatment type) have passed the specified ISSA requirements (maximum 530 g/m^2). The average reduction in wear loss within this specific category as a result of changing the aggregate blend only (from LS to SS) was 86% which is the highest in all the mixes. The average improvement due to the change in aggregate gradation (from Type II micro surfacing to Type III micro surfacing) was 47%. As previously discussed, the highest wear loss (520 g/m^2) was observed for LS mixes and the lowest (30 g/m^2) was observed for SS mixes.

4.6 Loaded Wheel Test (LWT) Results

As described in Chapter 2, the loaded wheel test is mainly used to determine the maximum emulsified asphalt content, in order to avoid asphalt flushing at higher temperatures in any slurry and micro surfacing paving mixes. This is achieved by calculating the amount of sand that is adhered to the excess emulsified asphalt that is present into the mixture. The loaded wheel test system was modified in order to test the specimen at high temperature (50^{0}C in this case), which is likely to be observed most of the time in the harsh eastern Saudi climate. The recommended

ISSA A105 and A143 specification is 530 g/m^2 at room temperature only, which is not applicable at 50^{0}C. Therefore, revision of this specification was important. For this purpose, firstly, the selected trial mixes were tested at room temperature, the trend of sand adhesion was developed, and the amount of emulsified asphalt content producing sand adhesion exactly 530 g/m^2 was determined. Afterwards, this emulsified asphalt content was used for the same trial mixes and modified LWT testing at 50^{0}C was carried out. In this way, maximum sand adhesion of 610 g/m^2 was obtained at 50^{0}C. This revision of specification represents that if the sand adhesion is below this maximum value, mixture bleeding is likely not to occur even at higher temperatures. This gives an indication about the flushing potential of the mixes in the field. Lesser amounts of sand adhesion values represent lesser flushing potential in the field. The LWT on slurry seal and micro surfacing mixes was performed and the amount of sand adhesion for each mix type was recorded and plotted in Figure 4.18 through 4.29. Asphalt stiffness and excess asphalt present into the mix are the two major factors affecting the value of sand adhesion in any slurry seal and micro surfacing mix. Stiffer asphalt results in less amount of sand adhered to the mix. On the contrary, excess amount of asphalt into the mix increases the sand adhesion. It was observed that mixes high in limestone aggregate proportions have lower tendency for flushing (lower sand adhesion values) at elevated temperatures as compared to steel slag mixes. This is due to the higher surface porosity and absorption of limestone aggregates, which leaves little

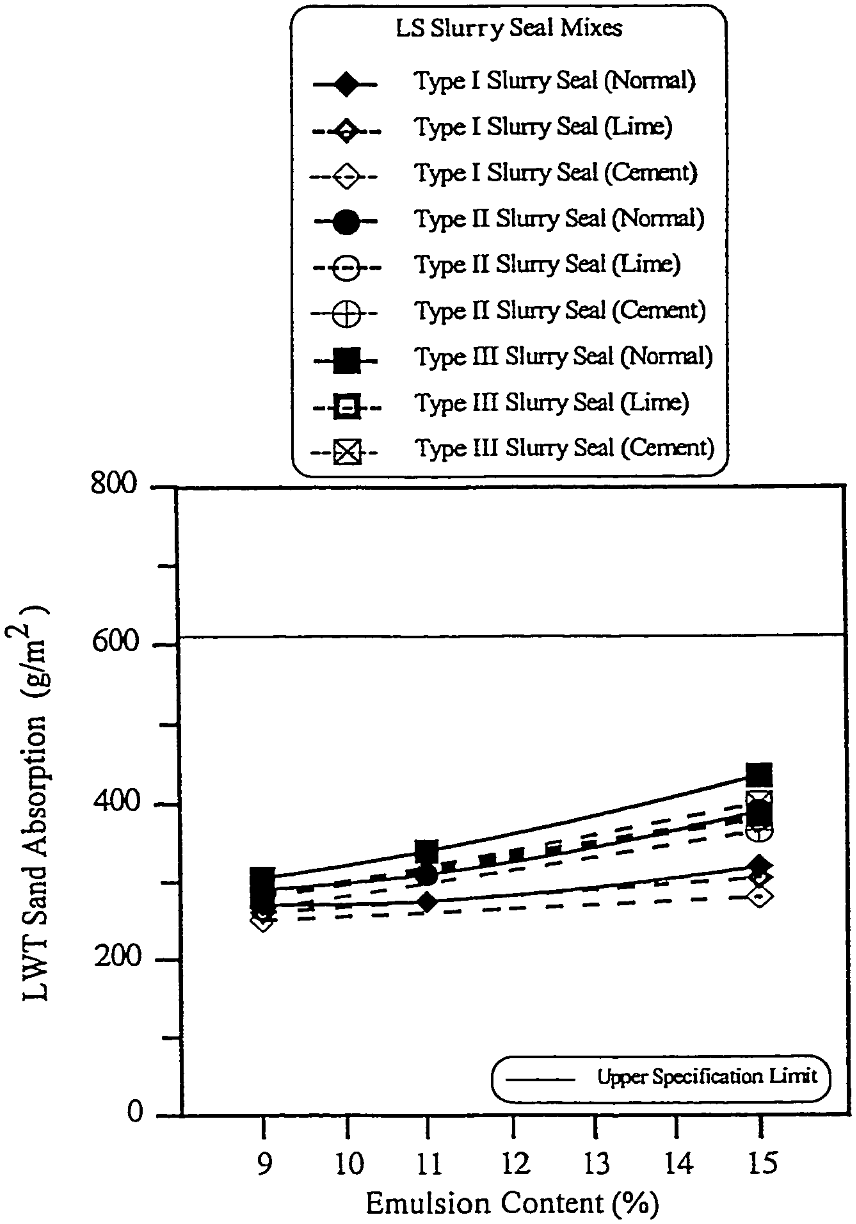


Figure 4.18: LWT Results For LS Slurry Seal Mixes

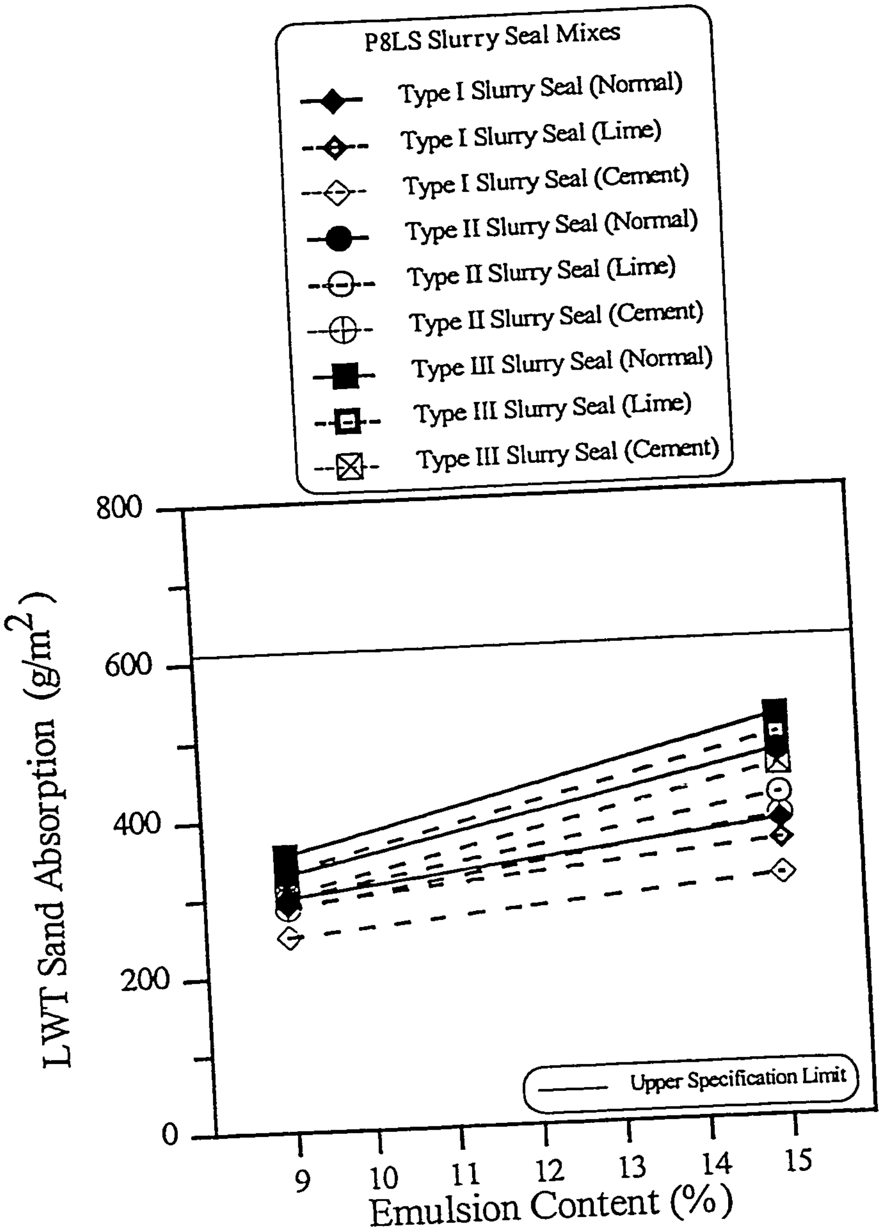


Figure 4.19: LWT Results For P8LS Slurry Seal Mixes

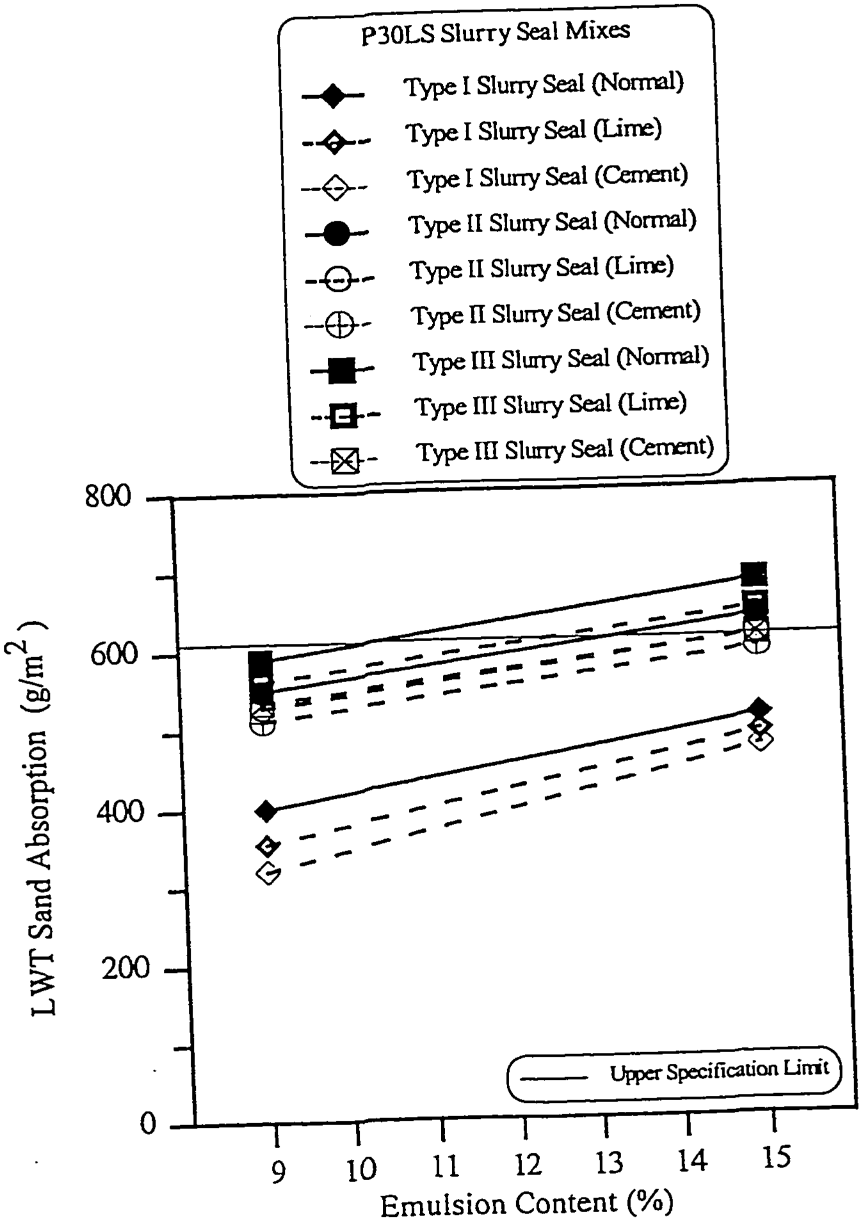


Figure 4.20: LWT Results For P30LS Slurry Seal Mixes

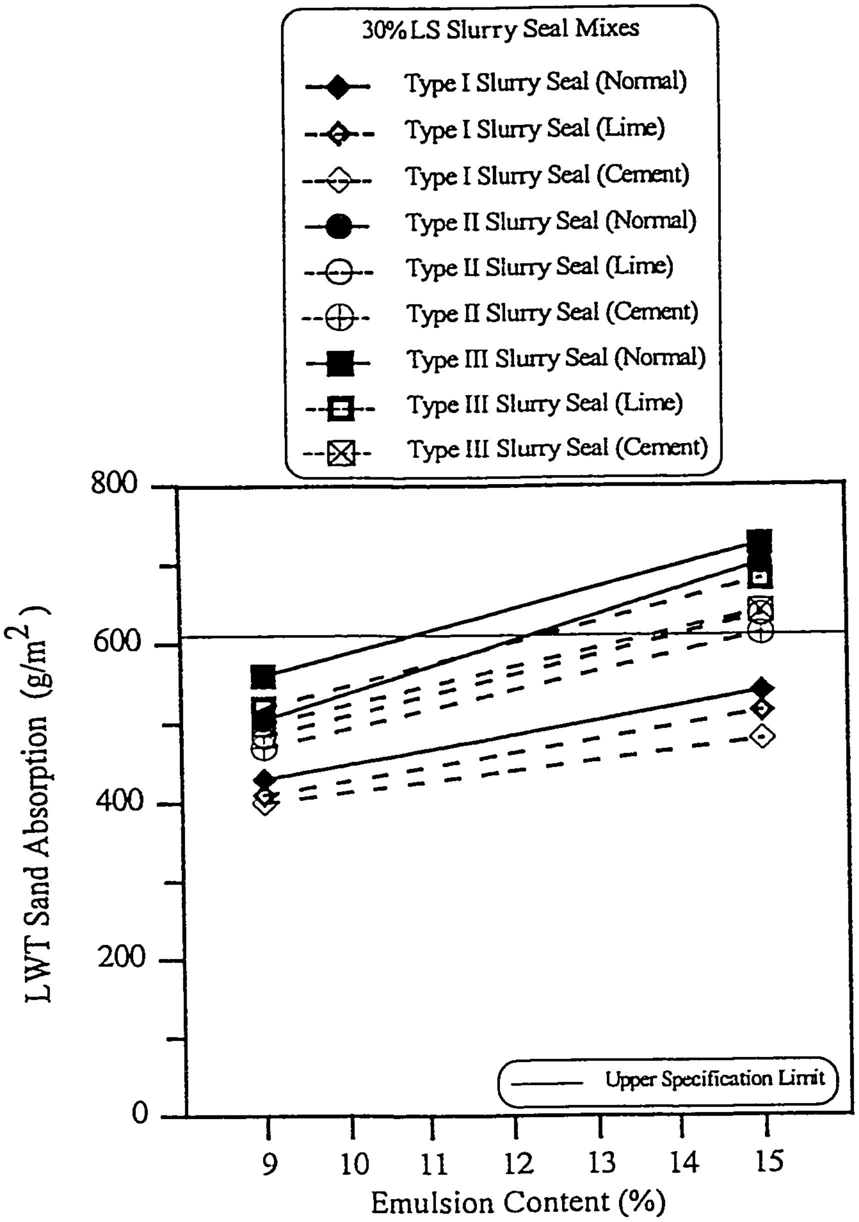


Figure 4.21: LWT Results For 30%LS Slurry Seal Mixes

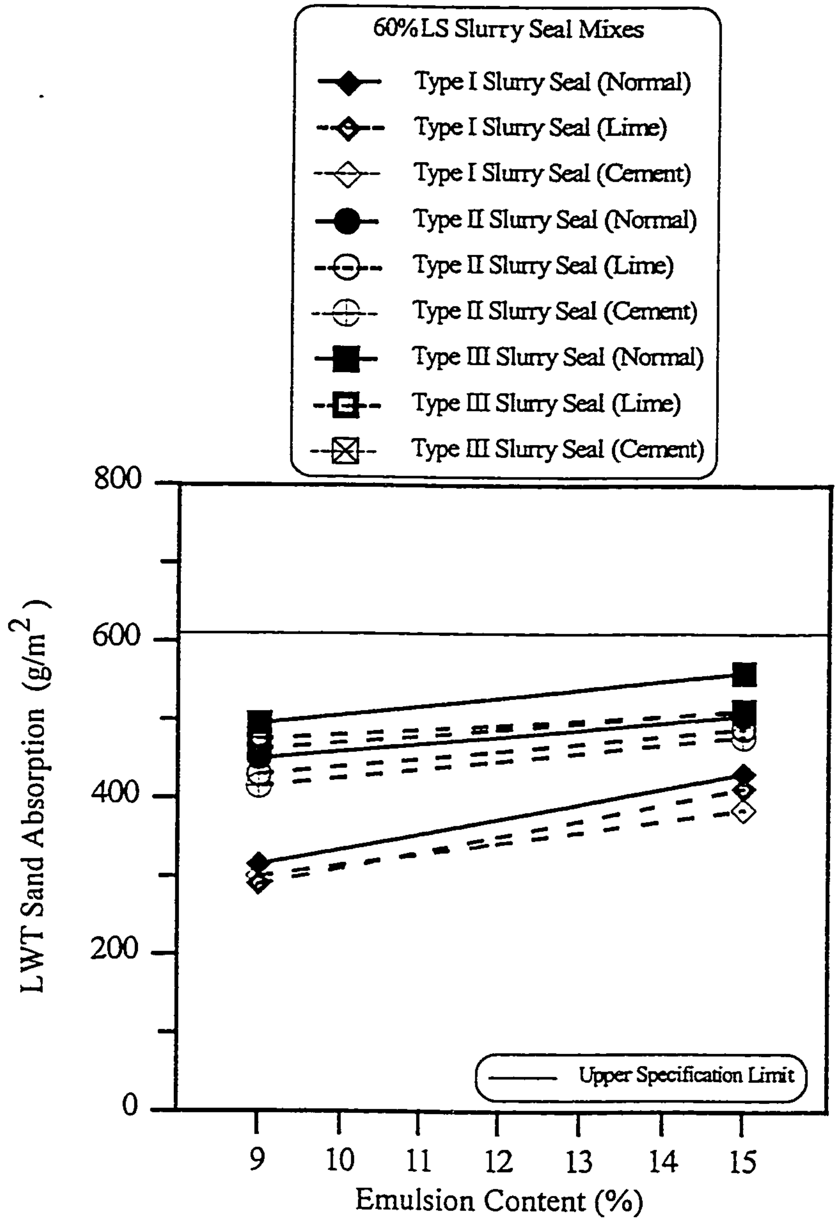


Figure 4.22: LWT Results For 60%LS Slurry Seal Mixes

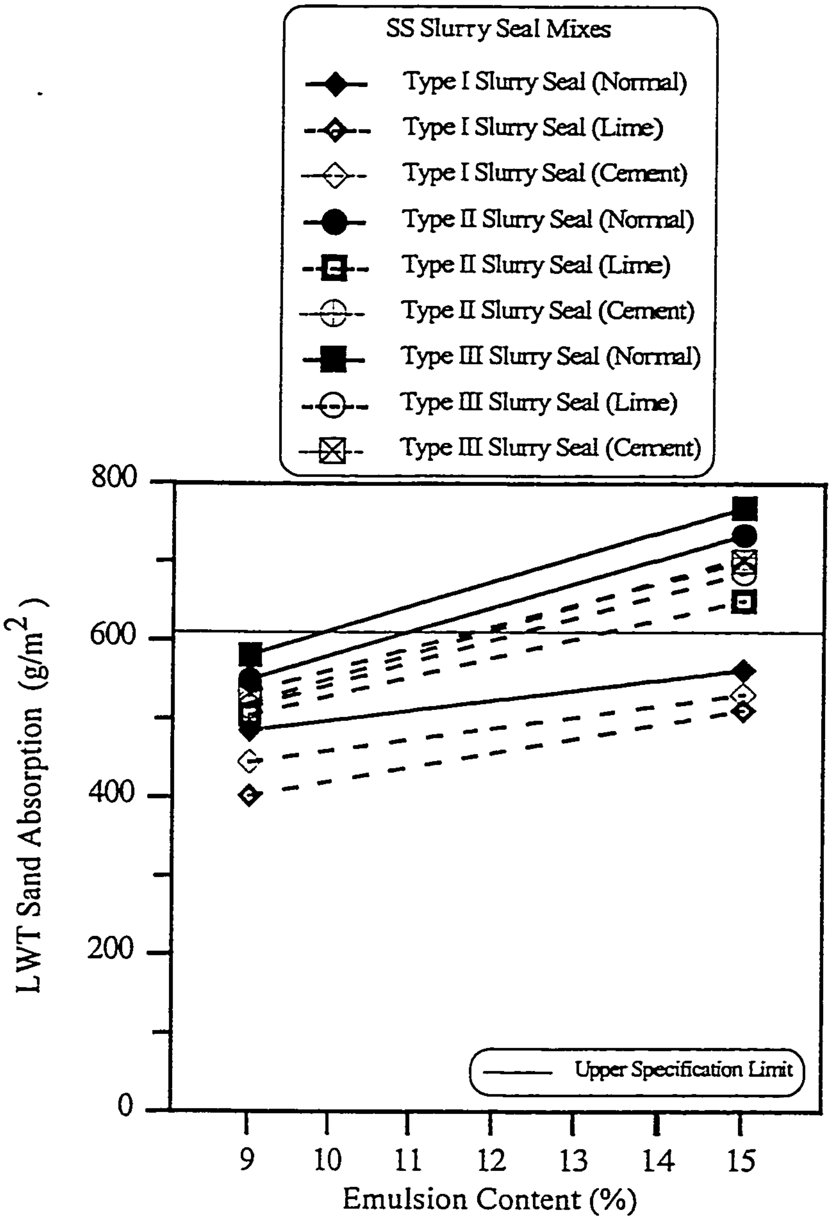


Figure 4.23: LWT Results For SS Slurry Seal Mixes

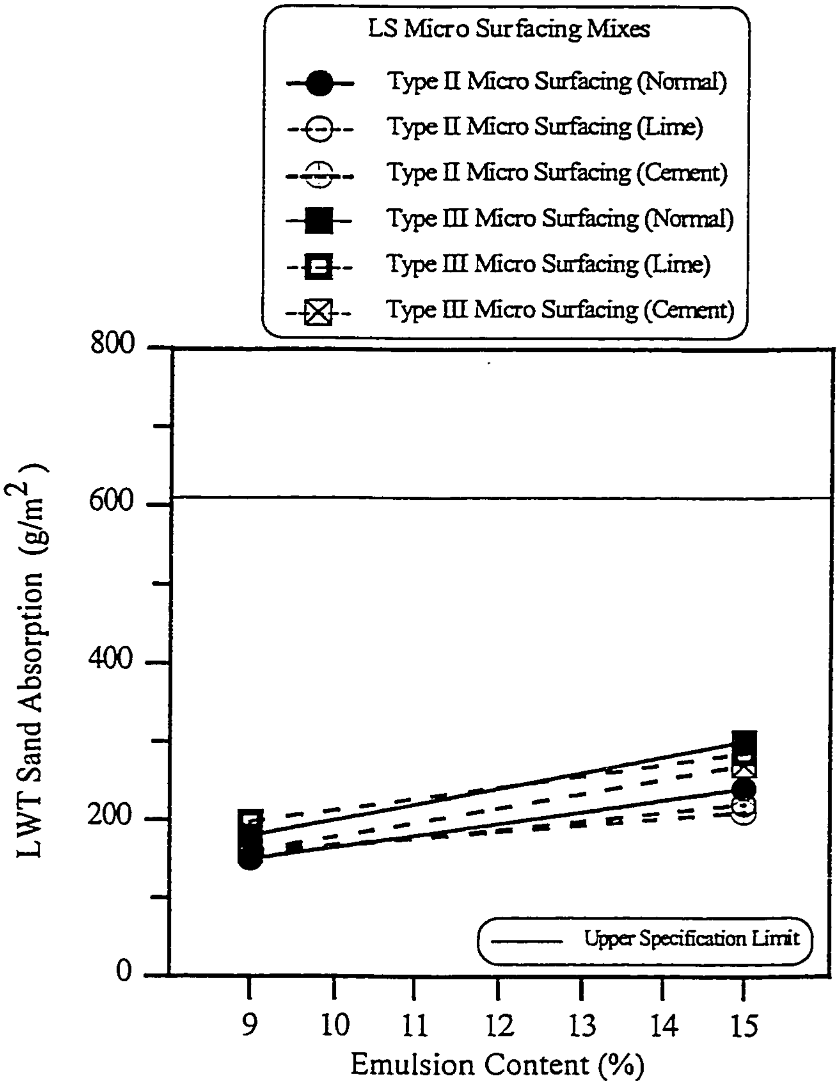


Figure 4.24: LWT Results For LS Micro Surfacing Mixes

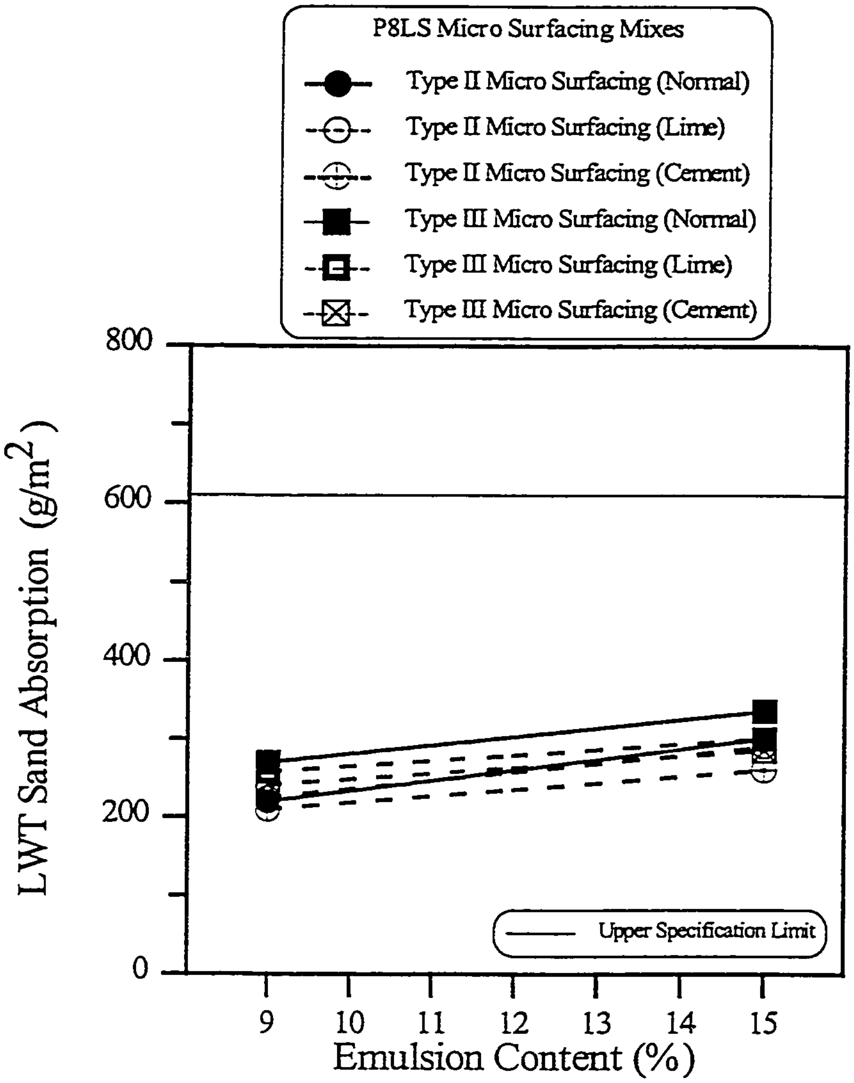


Figure 4.25: LWT Results For P8LS Micro Surfacing Mixes

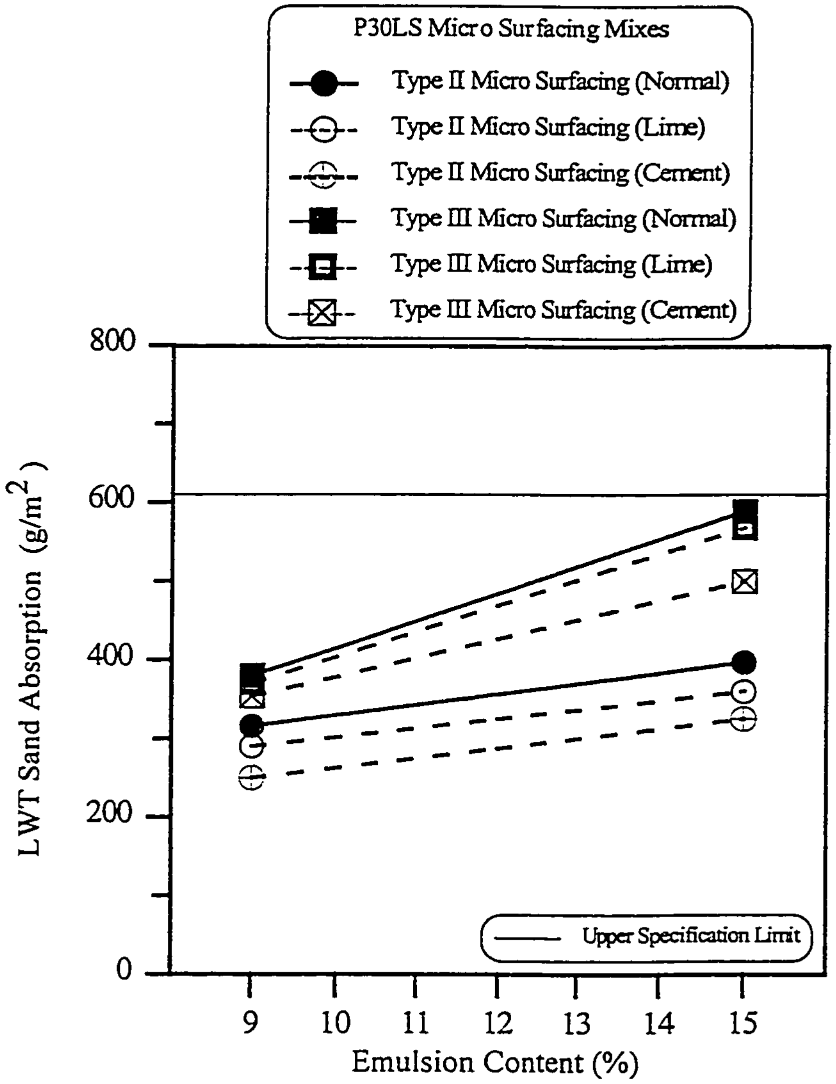


Figure 4.26: LWT Results For P30LS Micro Surfacing Mixes

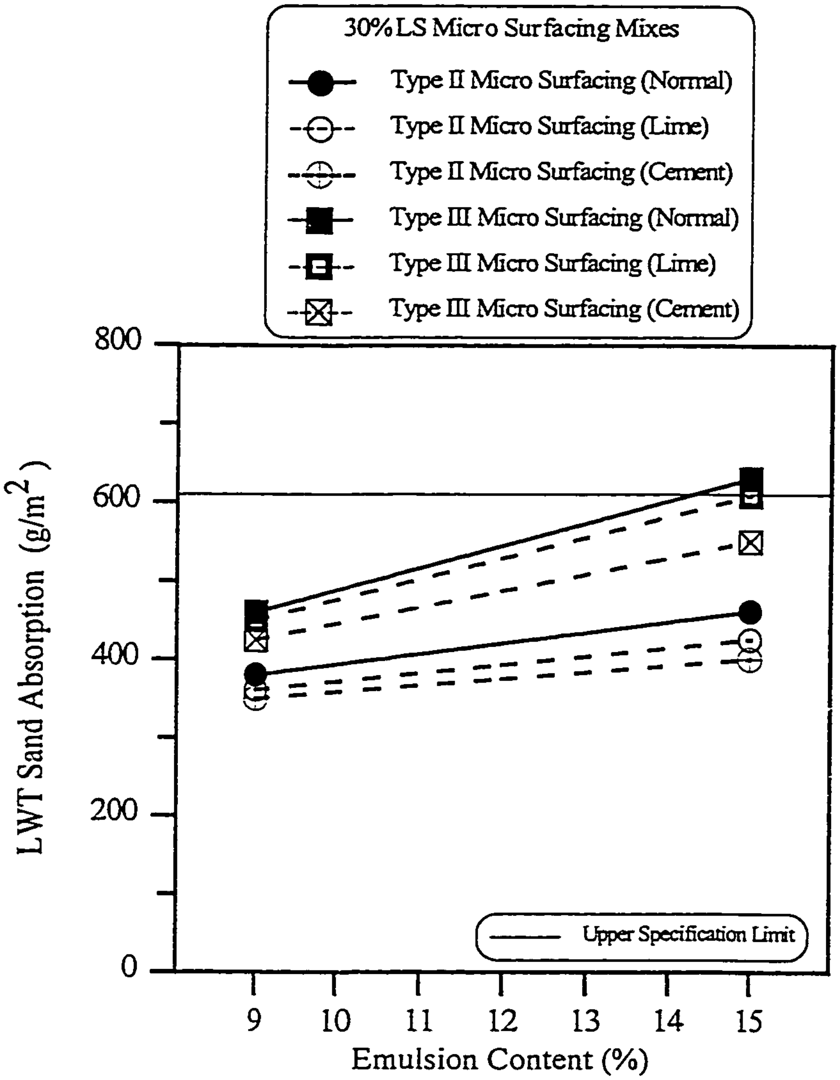


Figure 4.27: LWT Results For 30%LS Micro Surfacing Mixes

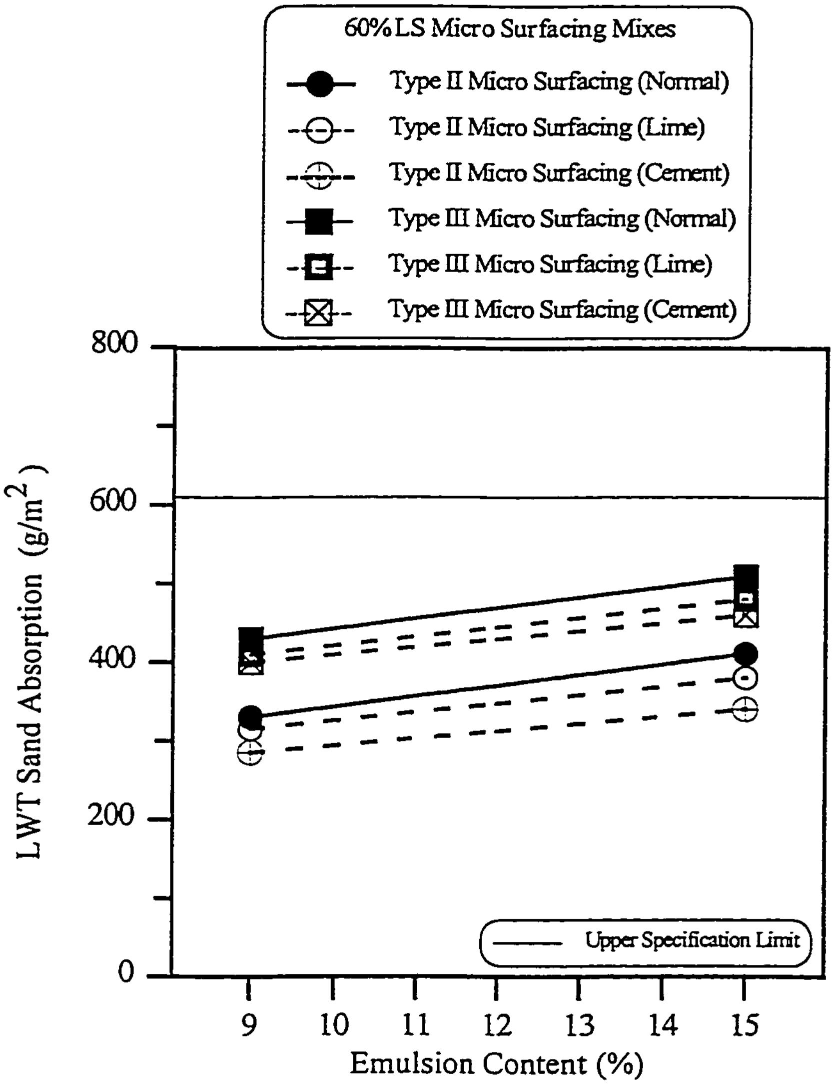


Figure 4.28: LWT Results For 60%LS Micro Surfacing Mixes

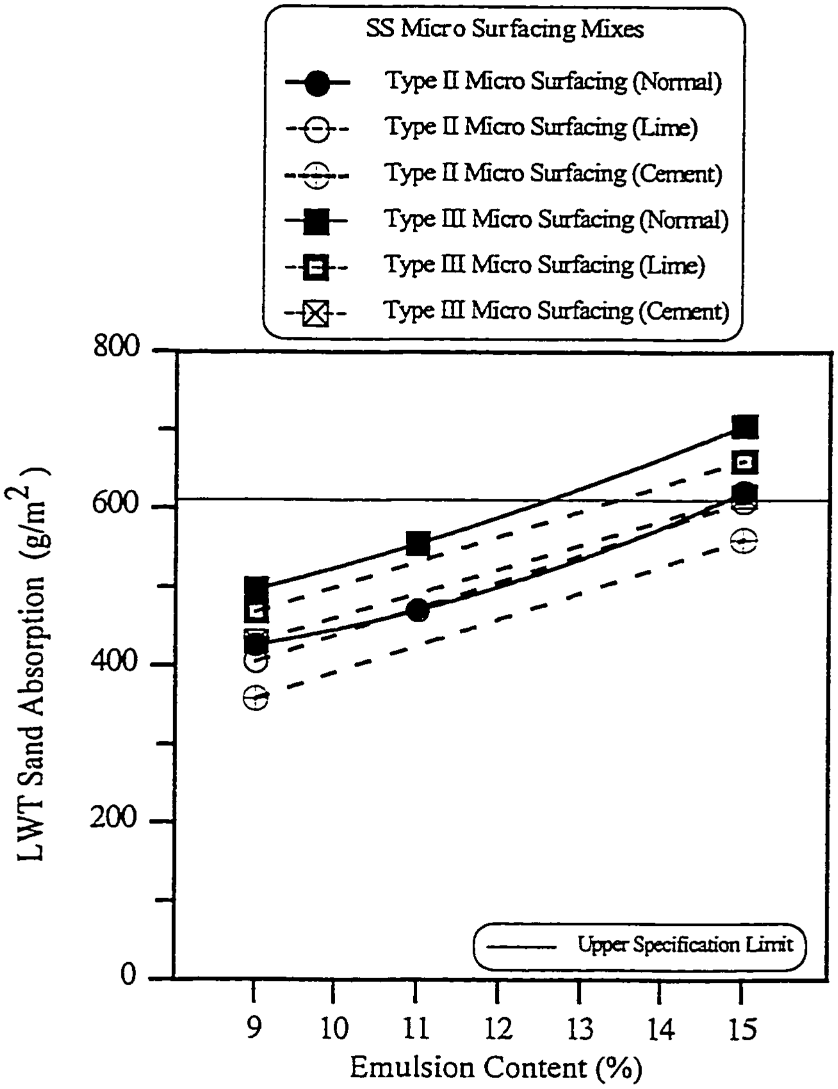


Figure 4.29: LWT Results For SS Micro Surfacing Mixes

or no excess emulsified asphalt to be left behind. Slag, on the other hand, has low surface porosity as well as low surface absorption. This results in higher amounts of useless asphalt to be left behind in the mix, thereby leading towards higher potential of asphalt flushing. In addition, slag aggregates poses higher thermal conduction properties as compared to those of limestone aggregates. This means that mixes containing slag aggregates can absorb and retain more heat and thus results in the softening of asphalt at higher temperatures, which in turn increases flushing potential. That is why pure steel slag aggregates (SS mixes) have shown the highest sand adhesion values (highest asphalt flushing potential). The aggregate gradation also has a pronounced effect on the flushing potential of slurry seal and micro surfacing mixes. For a given emulsified asphalt content, fine aggregates showed less potential for flushing as compared to coarse aggregates. This is because fine aggregates normally absorb higher emulsified asphalt content due of their larger surface areas, leaving behind less excess asphalt for flushing. The LWT test indicated the same behavior regarding aggregate gradation; Type I mixes have shown less sand absorption as compared to Type II as well as Type III mixes, which have shown the highest sand absorption. As expected, the use of micro surfacing emulsions decreased the flushing potential for both limestone and steel slag aggregates. This is due to the presence of chemically cross-linked polymer materials that gave the binder an increased viscosity and desired hardness and stiffness characteristics, even at elevated temperatures. This resulted in decreased temperature susceptibility and reduced potential for asphalt flushing of micro surfacing mixes at higher temperatures. The addition of cement and hydrated lime has also resulted in decreased sand adhesion values. The reason is simple, cement and/or lime treatment result(s) in an increase of binder stiffness as well as decrease in temperature susceptibility. Hence, at higher temperatures and repeated loading, asphalt present into the treated slurry seal and micro surfacing mixes remains stiffer when treated with cement or lime, as compared to that of untreated mixes, and gave lesser values of sand adhesion. The LWT sand adhesion results are summarized in Table 4.6.

4.7 Effect of Additives on the Performance of Slurry Seal and Micro Surfacing Mixes

One of the objectives of this study was to investigate the effect of additives on the performance of both slurry seal and micro surfacing mixes. Wet track abrasion test (WTAT) and loaded wheel test (LWT) were performed on modified slurry seal and micro surfacing samples and the results were evaluated in order to examine the significance of additive modification. All the slurry seal and micro surfacing mixes were evaluated at three levels of modification, i.e., normal, modified with 3% lime, and modified with 3% cement. This was done to study the effect of cement and lime additions on most of the combinations of slurry seal and micro

Table 4.6: LWT Absorption Results for Slurry Seal and Micro Surfacing Mixes

			Slurry Seal Mixes Type						Micro Surfacing Mixes Type					
	Gradation	Treatment	LS	P8 LS	P30 LS	30% LS	60% LS	SS	LS	P8 LS	P30 LS	30% LS	60% LS	SS
9 % Emulsified Asphalt	Type I	Normal	270	300	400	430	315	485	*	*	*	*	*	*
		Lime	260	291	355	410	290	402	*	*	*	*	*	*
		Cement	250	250	320	400	300	445	*	*	*	*	*	*
	Type II	Normal	290	330	550	505	450	550	150	220	316	380	330	426
		Lime	280	300	529	485	430	505	155	258	371	450	410	468
		Cement	265	287	512	470	415	520	160	210	250	350	285	358
	Type III	Normal	305	355	589	560	495	581	180	270	380	460	430	497
		Lime	285	335	562	520	475	515	198	225	290	361	315	405
		Cement	280	305	535	500	462	534	160	241	354	425	400	430
15 % Emulsified Asphalt	Type I	Normal	320	380	510	540	431	562	*	*	*	*	*	*
		Lime	305	355	489	515	412	511	*	*	*	*	*	*
		Cement	280	310	471	480	385	531	*	*	*	*	*	*
	Type II	Normal	390	468	635	700	505	733	240	300	397	461	411	620
		Lime	380	413	612	635	488	650	220	300	568	608	480	660
		Cement	365	385	595	612	478	705	210	260	325	400	340	560
	Type III	Normal	435	512	680	725	560	768	300	335	589	630	509	705
		Lime	385	489	645	680	510	685	285	290	360	425	380	608
		Cement	400	450	611	640	512	700	270	285	500	550	460	615

Cell readings represent LWT sand absorption in g/m^2

* Mixes are not normally used in the field (not recommended by the ISSA)

surfacing mixes in order to develop better understanding of the modification process and improved prediction models. Generally, lime and cement modification have resulted in improvement in mix performance. Cement treatment has generally shown greater improvement as compared to lime treatment. However, in the case of pure steel slag aggregates, lime treatment proved better than cement treatment.

4.7.1 Effect of Additives on WTAT Results

As discussed earlier, the mixes treated with lime and cement showed reduction in WTAT loss values for all the slurry seal and micro surfacing mixes. This is due to the improvement in aggregate bonding characteristics. When lime is added to the aggregate, the lime-asphalt mastic coats the aggregate surface and creates a durable adhesion even in the presence of water, and hence improves the stripping resistance of aggregate. Similarly, the addition of cement increases the aggregate surface roughness and improves the adhesion between the asphalt and aggregates. The test results confirmed that there exists a significant relationship between the performance improvement and additive modification. Generally, the effect of cement modification proved more effective as compared to hydrated lime. Cement modification has resulted in 22% over-all average improvement of WTAT performance as compared to normal mixes for both slurry seal and micro surfacing mixes. In the same way, lime modification has resulted in 11% over-all average improvement in the WTAT performance as compared to normal mixes. Figures

4.30 through 4.34 show the average WTAT loss values of both normal and modified mixes of the different aggregate blends, aggregate gradation, and emulsified asphalt type.

4.7.2 Effect of Additives on LWT Sand Absorption

Additive modification utilizing cement and lime has generally resulted in decreased sand adhesion values when tested by the LWT. This was due to the increase in stiffness and decrease in temperature susceptibility of the binder. As in WTAT, the cement has shown higher improvement levels as compared to lime treatment. Cement treatment has resulted in an overall average of 10% improvement in the LWT performance as compared to non-modified mixes. Similarly, lime treatment has resulted in an over-all average of 6% improvement in the LWT performance as compared to the non-modified mixes. The average LWT sand absorption values of the normal and modified mixes for the different aggregate blends, aggregate gradations, and emulsified asphalt types are shown in Figures 4.35 through 4.39.

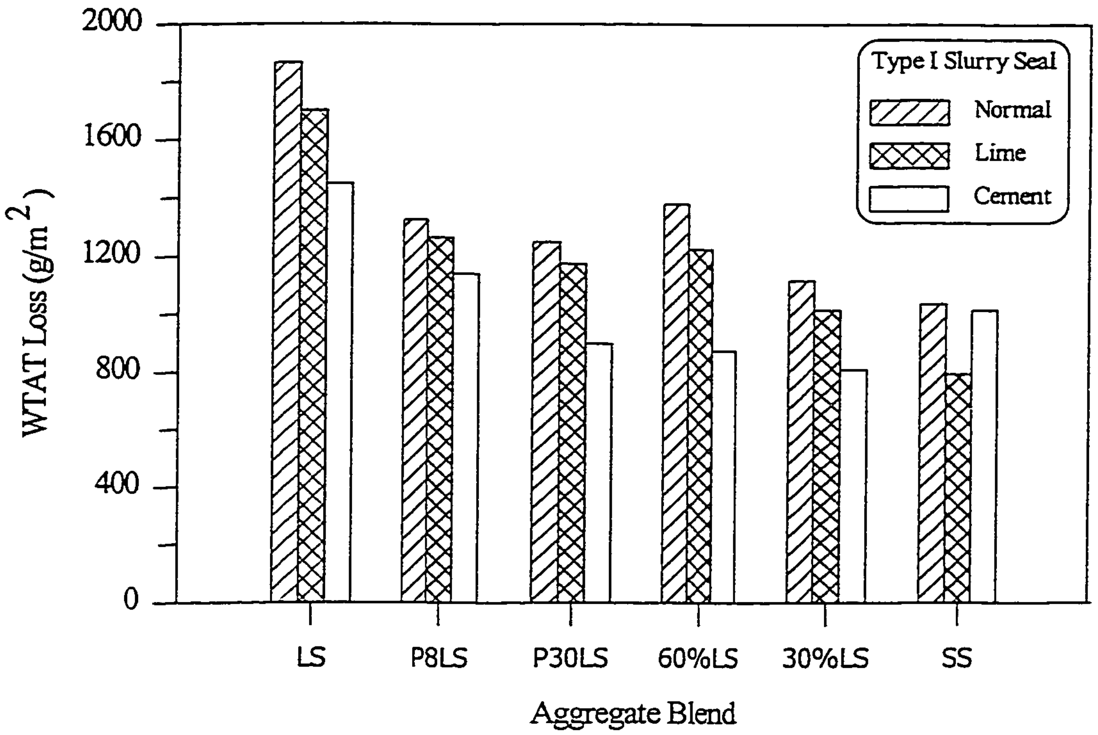


Figure 4.30 : Effect of Additives on WTAT Loss Values for Type I Slurry Seal Mixes

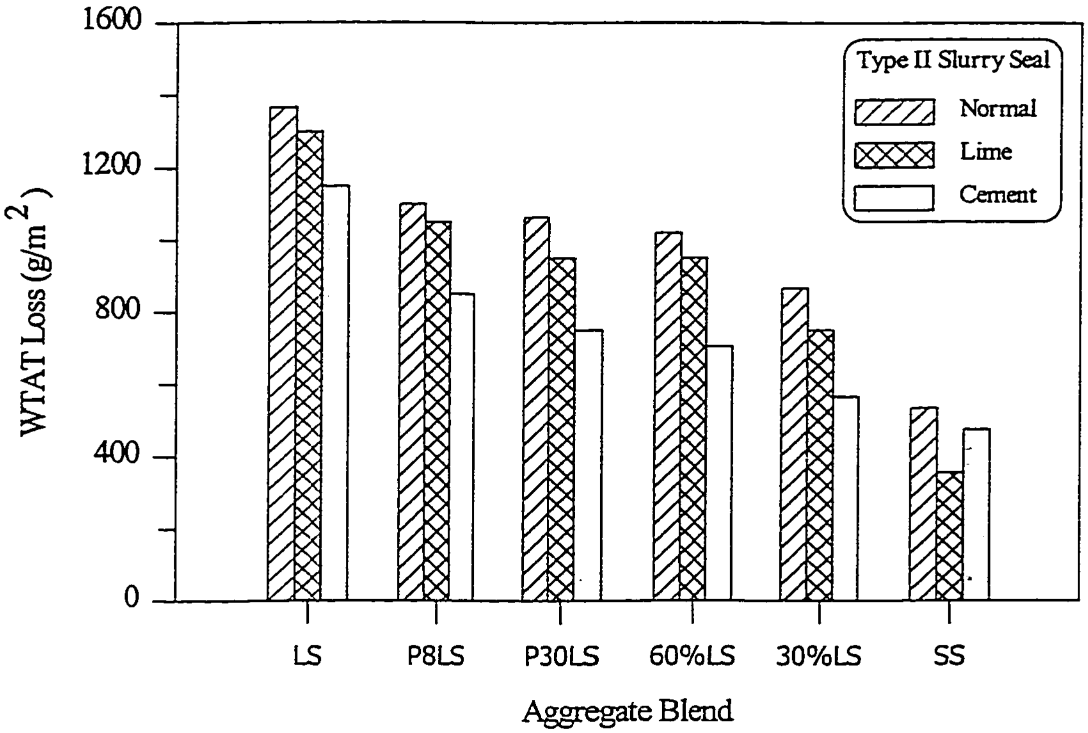


Figure 4.31 : Effect of Additives on WTAT Loss Values for Type II Slurry Seal Mixes

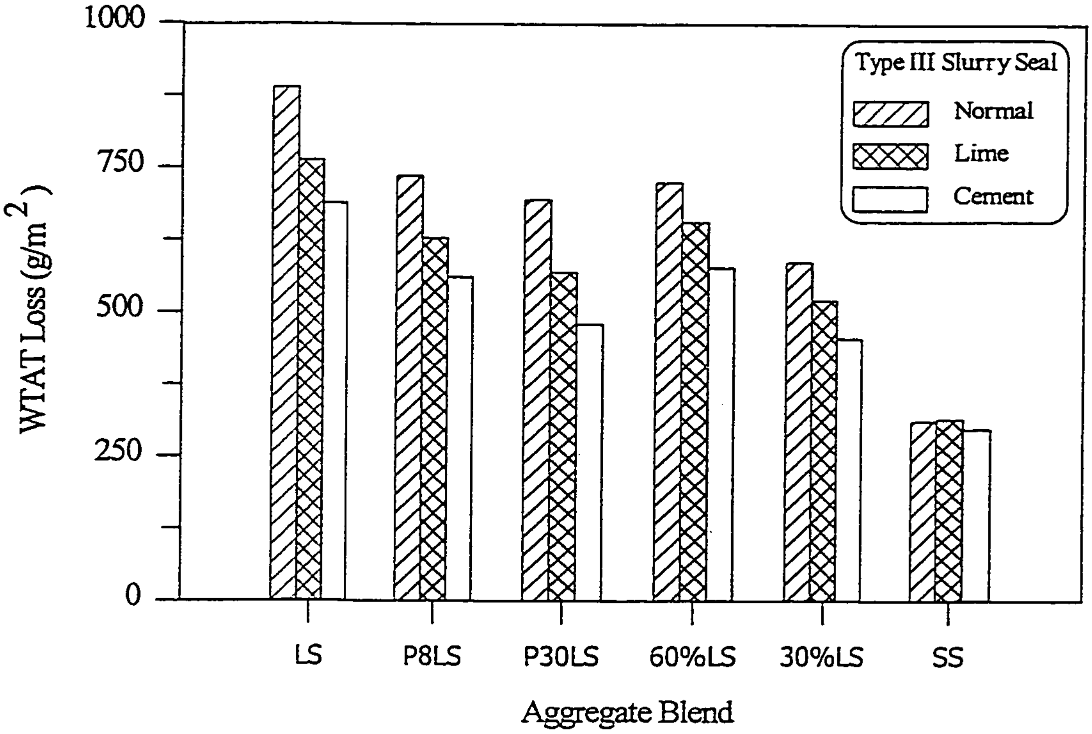


Figure 4.32 : Effect of Additives on WTAT Loss Values for Type III Slurry Seal Mixes

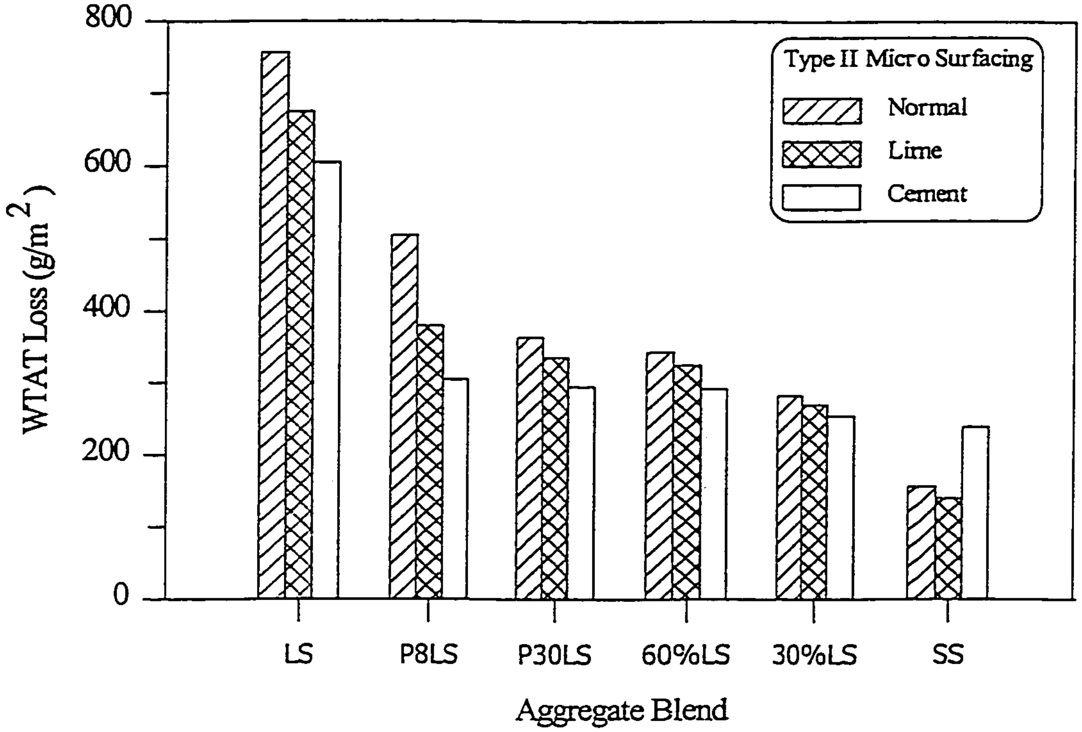


Figure 4.33 : Effect of Additives on WTAT Loss Values for Type II Micro Surfacing Mixes

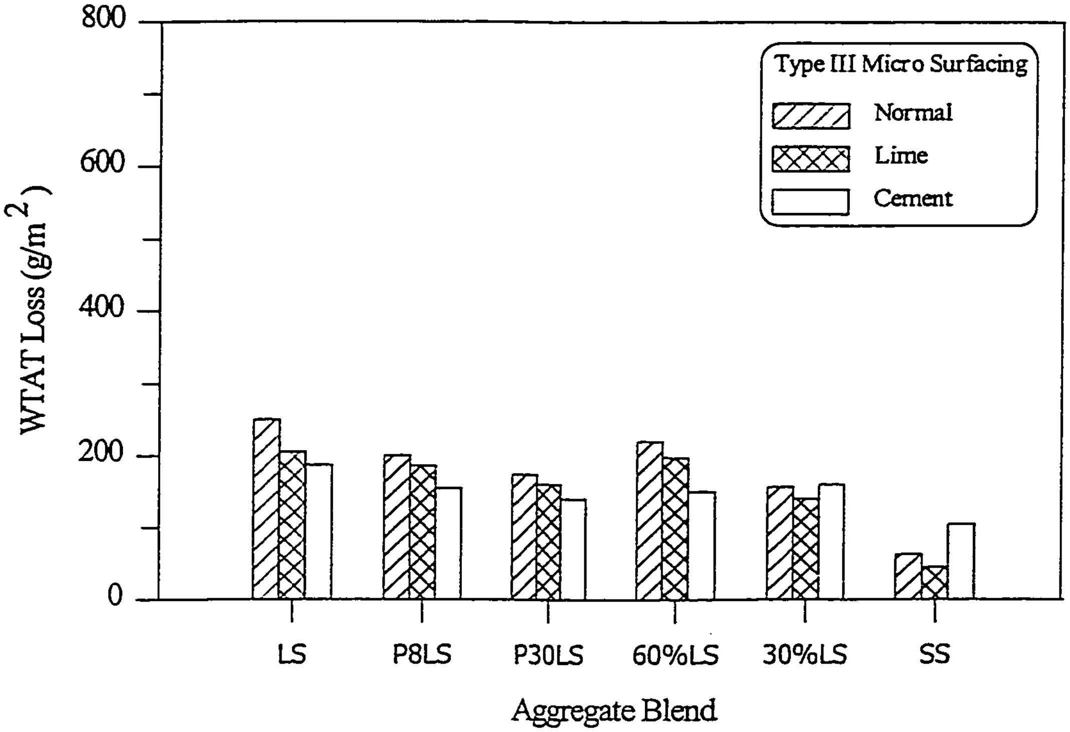


Figure 4.34 : Effect of Additives on WTAT Loss Values for Type III Micro Surfacing Mixes

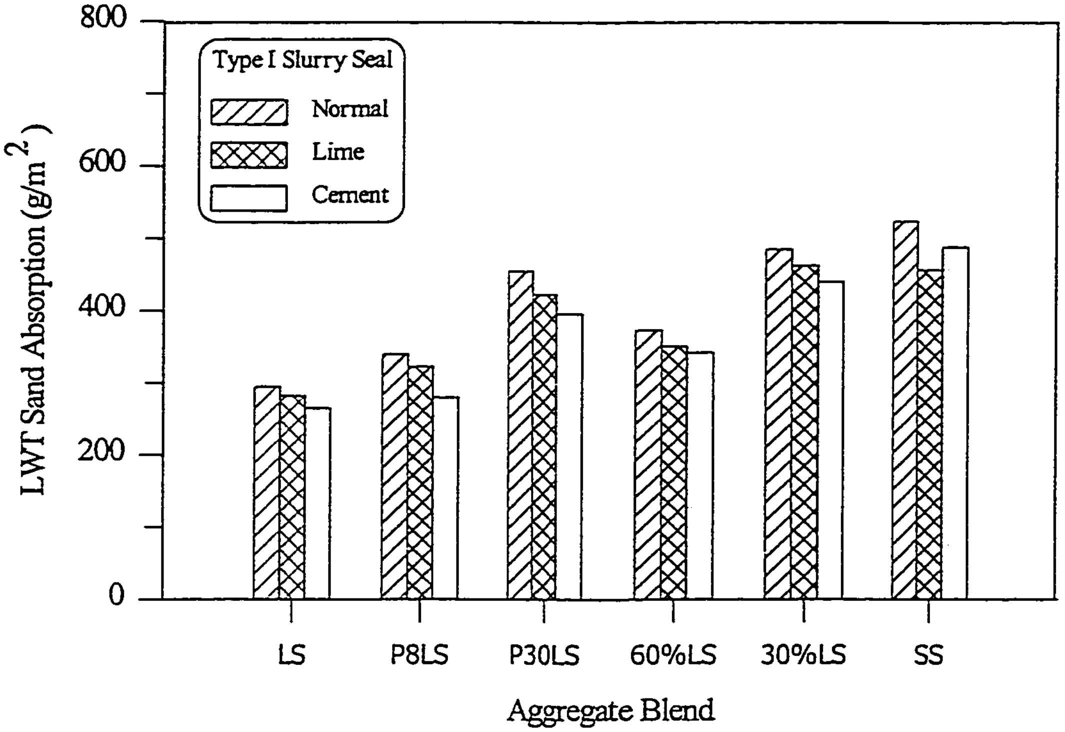


Figure 4.35 : Effect of Additives on LWT Sand Absorption Values for Type I Slurry Seal Mixes

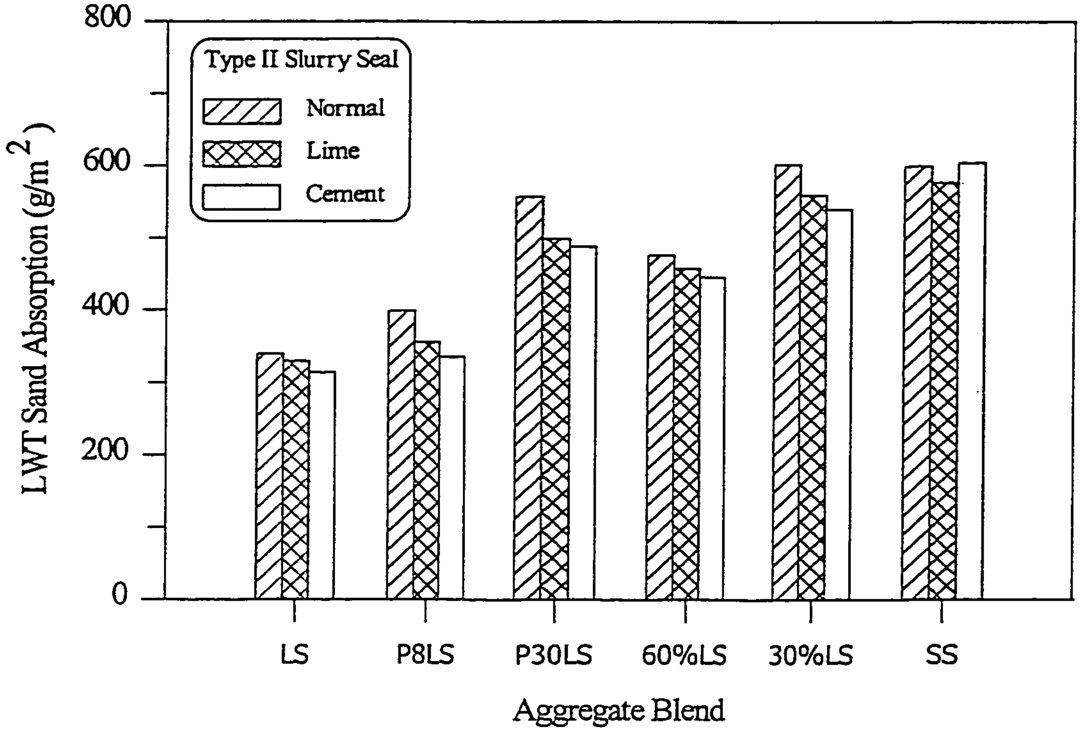


Figure 4.36 : Effect of Additives on LWT Sand Absorption Values for Type II Slurry Seal Mixes

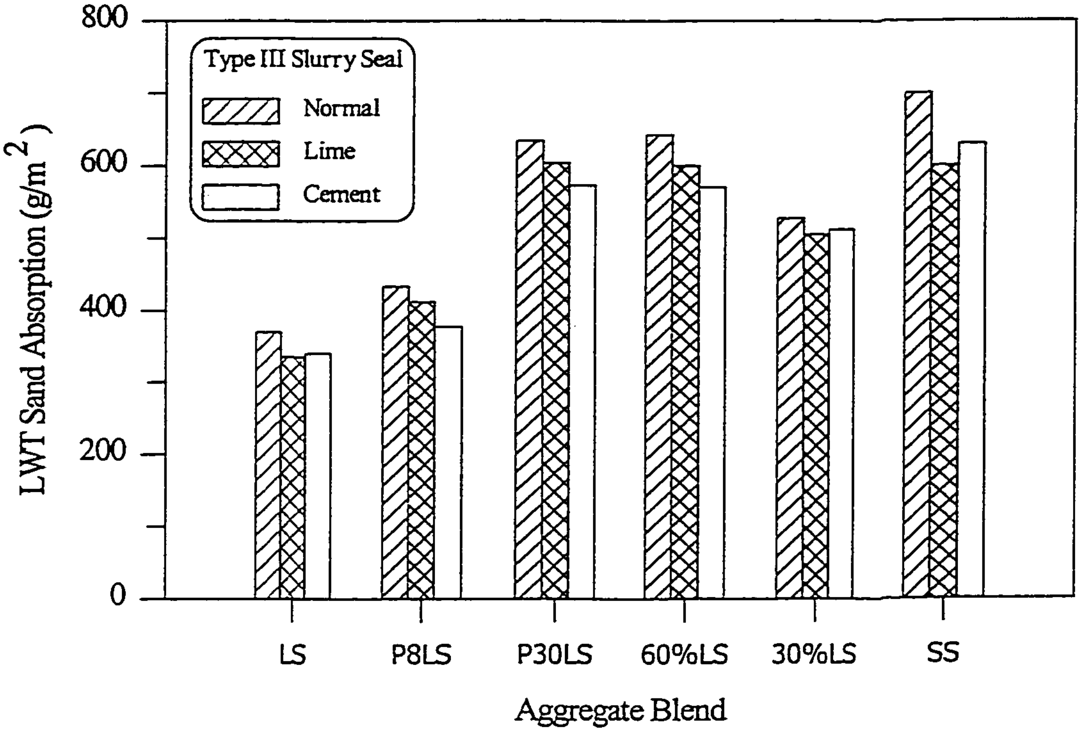


Figure 4.37 : Effect of Additives on LWT Sand Absorption Values for Type III Slurry Seal Mixes

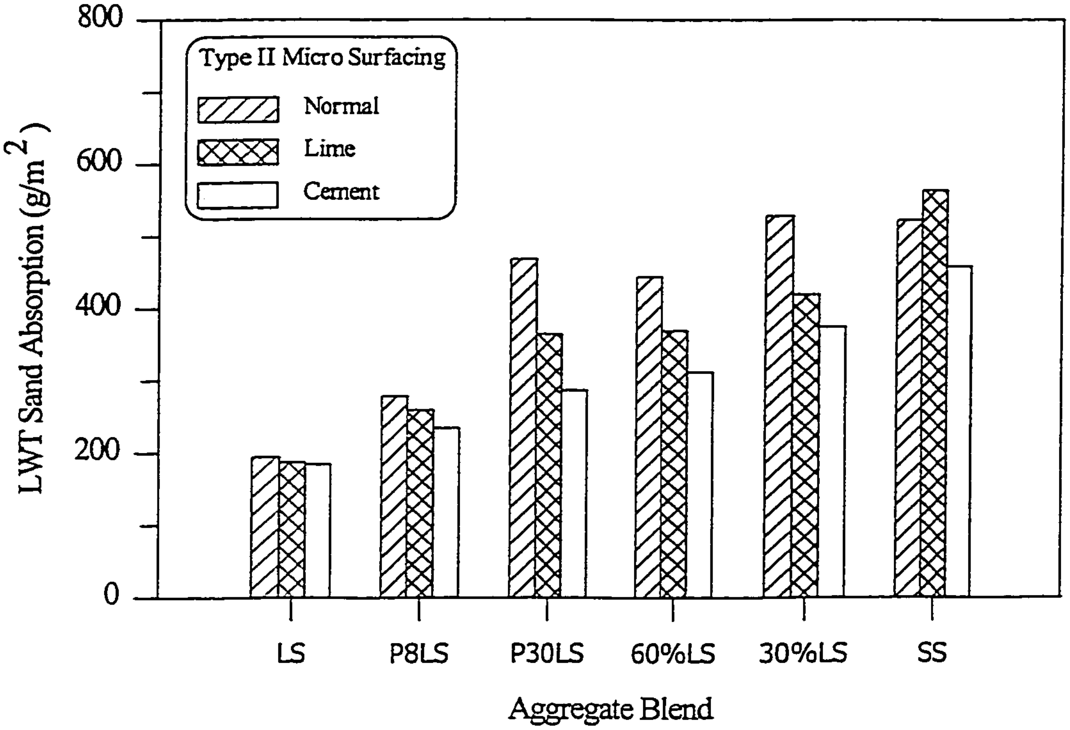


Figure 4.38 : Effect of Additives on LWT Sand Absorption Values for Type II Micro Surfacing Mixes

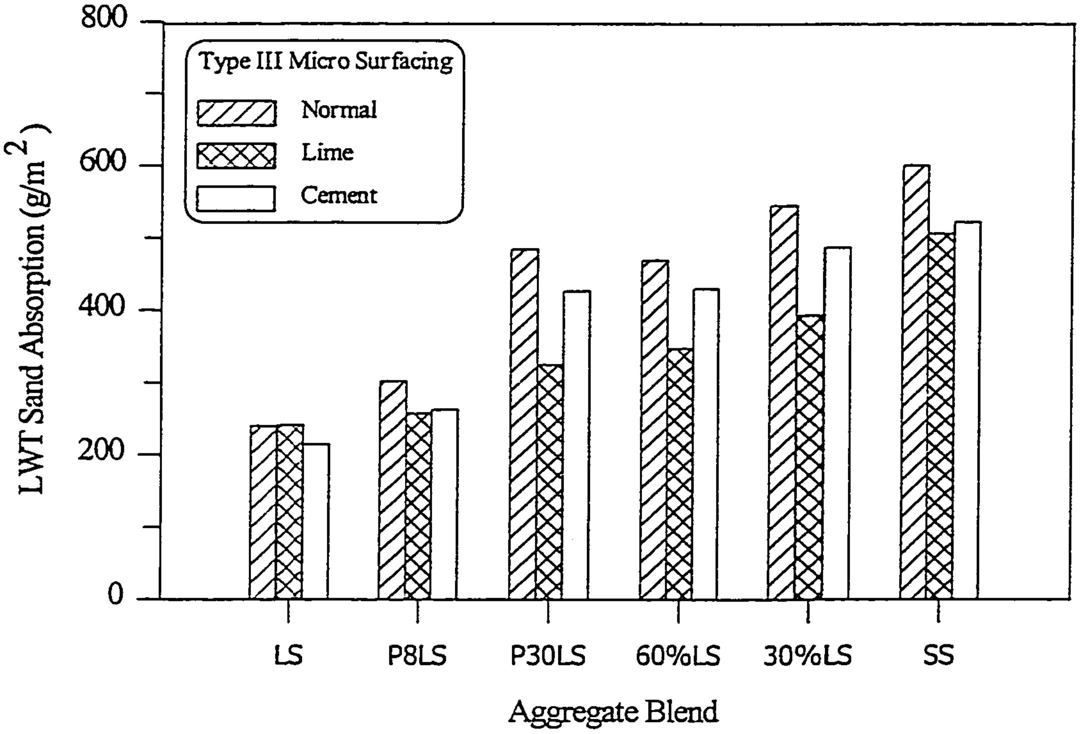


Figure 4.39 : Effect of Additives on LWT Sand Absorption Values for Type III Micro Surfacing Mixes

4.8 Summary

This Chapter provided details about the results of the cone consistency, wet cohesion, wet track abrasion, and loaded wheel tests performed on slurry seal and micro surfacing mixes. The analysis and discussion of these test results were presented. The results indicate that micro surfacing mixes have generally failed to achieve quick traffic requirements when tested for the wet cohesion according to the specifications. Therefore, the reconsideration of wet cohesion test method and test specification should be carried out to suit local environment conditions. The proper blending of steel slag aggregates with limestone aggregates have significantly reduced the wear loss of both the slurry seal and micro surfacing mixes. Lime and cement modifications have also resulted in improvement of mix performance. The use of micro surfacing mixes is preferable over slurry seal mixes due to their improved qualities.

CHAPTER 5

STATISTICAL ANALYSIS AND PERFORMANCE BASED MODELING FOR TEST AND MIX DESIGN PARAMETERS OF SLURRY SEAL AND MICRO SURFACING

5.1 General

One of the major objectives of this study was the generation of models that can be used to predict the test parameters (i.e., consistency, set time, traffic time, final torque, wear loss, and sand adhesion) as well as dosage of binder and the water content so as to achieve an acceptable slurry seal and micro surfacing mix performance. Multiple linear stepwise regression analysis was performed on the test results. The general purpose of multiple regression (the term was first used by Pearson, 1908) is to learn more about the relationship between several independent or predictor variables and a dependent or criterion variable. The independent variables are those that are manipulated whereas the dependent variables are only measured or registered. The terms dependent and independent variables apply mostly to experimental research where some variables are manipulated, and in this sense they are "independent" from the initial reaction patterns, features, intentions, etc. of the subjects.

In this Chapter, the results of stepwise regression analysis are discussed in order to generate prediction models. Two types of models were developed; test parameters models and mix design parameters models. In test parameters models, the dependent variables were taken as consistency, set time, traffic time, final torque, wear loss, and sand adhesion. In the mix design parameters models the dependent variables were considered as the optimum amount of water and emulsified asphalt content required to generate slurry seal and micro surfacing mixes providing acceptable values of consistency, wear loss and sand adhesion values.

For both types of models the test results were grouped into the following six categories after which they were analyzed for regression modeling:

1. Consistency readings for slurry seal mixes.
2. Consistency readings for micro surfacing mixes.
3. WTAT loss readings for slurry seal mixes.
4. WTAT loss readings for micro surfacing mixes.
5. LWT absorption readings for slurry seal mixes.
6. LWT absorption readings for micro surfacing mixes.

5.2 Statistical Analyses and Test Parameters Modeling

In this study, statistical technique involving step wise regression analysis was utilized in order to study the effects of factors (i.e., aggregate blend, aggregate gradation, emulsified asphalt type and content, and treatment type) on the mix performance (e.g., consistency, set time, cure time, WTAT loss, and LWT sand absorption). The forward stepwise regression analysis was employed. Models were obtained as regressor variables were added one by one depending on their respective significance to the dependent variables.

In this study, statistical analysis was performed to study the significance of the five main effects included in the experiments. It was assumed that interactions within the factors themselves are insignificant. These factors are:

- Aggregate blend at six levels (slag, limestone, and four other slag-limestone blends)
- Aggregate gradation at three levels (Type I, II and III)
- Emulsified asphalt content at three levels (9%, 11%, and 15%)
- Emulsified asphalt type at two levels (Slurry seal and micro surfacing)
- Treatment type at three levels (Normal, lime, and cement)
- Total water content, which entered as a random variable.

Table 5.1 shows the used properties for regression analysis as well as their significance on the various test results.

Table 5.1 : Used Properties and Their Significance

Used Symbol	Property	Expected Significant Effect on the Following
AGGT	Aggregate blend	Consistency, Cohesion, WTAT, and LWT
GRAD	Aggregate Gradation	Consistency, Cohesion, WTAT, and LWT
EML%	Emulsion Content	Consistency, Cohesion, WTAT, and LWT
EMLTYP	Emulsion Type	Consistency, Cohesion, WTAT, and LWT
TREAT	Treatment Type	WTAT, and LWT
WATER	Water Content	Consistency

Regression variables called DUMMY, INDICATOR and BINARY are used primarily to include the qualitative and categorical variables in the regression analysis. In dummy variables, different classes or categories are identified by the use of dummy variables that take finite, discontinuous scores. The use of dummy variables allows the regression model (s) to change only its intercept for each category where its slope remains the same. As most of the factors in this study are qualitative, rather than quantitative, dummy variables were assigned instead of text characters to the required ones, and the coding is presented in Table 5.2.

5.3 Discussion of Analysis Results

From the results of statistical analysis utilizing *STATISTICA* software facility (developed by the SatSoft Inc., 1997) with forward stepwise regression procedure. The regression results are given in Appendix A. The following section discusses the generated models for the different variables.

5.3.1 Factors Affecting Cone Consistency Values

The analysis has revealed that all factors have shown significant effect (p-level > 0.05) on the consistency value. The highest correlation was observed between the slump value and the total water content for both slurry seal and micro surfacing mixes. As can be seen from the Table 5.3, the factor "WATER" has entered first because of its highest significance level (t-statistic = 23.67 >> 1.65) with a

Table 5.2 : Dummy Variable Coding for the Stepwise Regression Modeling

Factor Code	Description	Levels	Dummy Number	
AGGT	Aggregate blend	LS	1	
		P8LS	2	
		P30LS	3	
		60%LS	4	
		30%LS	5	
		SS	6	
GRAD	Aggregate Gradation	ISSA Type I	1	
		ISSA Type II	2	
		ISSA Type III	3	
EML%	Emulsion Content (%)	9%	Original Values	9
		11%		11
		15%		15
EMLTYP	Emulsion Type	Slurry Seal	1	
		Micro Surfacing	2	
TREAT	Treatment Type	Normal	1	
		Lime	2	
		Cement	3	
WATER	Total Water Content (%)	Random	Original Values	

Table 5.3: Summary of Consistency Model

(Factors in order of Significance)

Variable	Intercept	WATER	AGGT	GRAD	EMLTYP
Coeff	-36.893	2.129508	2.66227	8.2646	-3.56248
t-statistic	-15.3139	23.67672	14.86097	13.18586	-3.92746

R= .87475252
R^2= .76519197

Table 5.4 : Summary of Set Time Model

(Factors in order of Significance)

Variable	Intercept	EMLTYP	EML%	GRAD	AGGT
Coeff	5.510486	-1.49722	0.137054	-0.10972	-0.02393
t-statistic	23.79185	-13.7923	8.907558	-1.42942	-1.06477

R= .84708103
R^2= .71754627

Table 5.5 : Summary of Traffic Time Model

(Factors in order of Significance)

Variable	Intercept	GRAD	AGGT	EMLTYP	EML%
Coeff	14.86445	-1.53508	-0.33562	-1.25854	0.110096
t-statistic	15.56926	-5.56467	-3.99676	-3.50696	2.037697

R= .83308865
R^2= .69403670

coefficient of determination (R^2) of 29%. This means that only the water content explains 29% of the variability involved in consistency values, which is highly significant. Its regression coefficient estimate is highly significant (probability > F = 0) which means that the probability of exceeding its test statistic is almost zero. This shows the fact that water is an integral part for producing workable flow. The higher the water content, the higher is the flow. The next highly correlated factor is the aggregate blend, which showed an increase of 26.66% in the R^2 value. The regression coefficient of estimate of aggregate blend is also significant with a probability exceeding its test statistic of 1.34×10^{-33}. Aggregate gradation has also played a highly significant role on the slump value (p-level as low as 1.41×10^{-28}) and showed an improvement of 18.88% in the R^2 value of the model. This confirms that aggregate gradation and type are normally considered as major factors influencing the flow of emulsified asphalt mixes. Fine aggregates absorb relatively more water, because their surface areas are larger than those of coarse aggregates. Hence, at any given water content, fine aggregates exhibit less flow as compared to that of coarse aggregate. On the other hand, porous aggregates (limestone for example) normally absorb more water than non-porous aggregates (steel slag). Hence, higher water content is required for limestone aggregates to produce the desired flow. The least significant factor (as compared to others) turned out to be related to the emulsified asphalt type. The improvement in R^2 value due to the addition of this factor was only 1.9% with a p-level of 0.00012 which is, however, still significant enough (at least statistically) to be included in the model. It means that polymer modification of emulsions do not produce very significant effect on their slump values. This phenomenon can be confirmed by looking at the cone consistency results in which the use of micro surfacing emulsion has not increased the required total water content very significantly. An analysis of variance (ANOVA) was run on the consistency model. The probability of getting a model better than this is almost zero. The parameter estimates for the consistency model are shown in Table 5.3. The signs of these parameters are in complete similarity with the actual observations. Water content, aggregate blend, and aggregate gradation are directly proportional to the consistency readings of the mixes. However, emulsified asphalt type is inversely proportional to the consistency values. The regression summaries, model-fitting results are shown in Table A1 through Table A3 and various probability plots are shown in Figure A1, in Appendix A.

5.3.2 Cohesion Test Results

Stepwise regression was also performed on the data obtained for the modified cohesion testing sequences. The independent variable list included the emulsified asphalt type, emulsified asphalt content, aggregate blend, and aggregate gradation. Three runs of regression analysis were performed. The first run was made in order to check the significance of factors affecting the set time (the set time taken as the dependent variable). Another run was carried out in order to check the significance levels of various factors affecting the traffic time values of the slurry seal and micro surfacing mixes. The third run was performed to identify significant factors affecting the final torque values of slurry seal and micro surfacing mixes. The following observations were made:

Factors Affecting Set Time Values

The emulsified asphalt type has shown the highest significance level with set time values. It has entered the regression model with a coefficient of determination of 60.3% meaning that only the emulsified asphalt type can explain 60.3% of the variability occurred in the set time values of slurry seal and micro surfacing mixes. This means that changing the emulsified asphalt type from normal (slurry seal) emulsions to polymer modified (micro surfacing) emulsions will significantly reduce the time required for the mix to set. This is true in practice because micro surfacing emulsions have known to achieve higher cohesion torque in less time due to the addition of polymer materials. This increases the viscosity of the binder and produces a mesh-like structure that hinders the lateral as well as sliding movements of the aggregate particles resulting in an increase in cohesion torque values at a given time. The next highest significance was shown by the emulsified asphalt content, which entered at second step into the regression model. The R^2 change (10.9%) was however not very high. In reality, the increase in emulsified asphalt content also increases the set time of slurry seal and micro surfacing mixes. This is due to the extra emulsion droplets, which are not used to cover the aggregate surface. These extra emulsion droplets act as lubricants and pose slipping of aggregates onto each other as well as slipping of the torque measurement head on top of the sample mat. This results in decreased torque values at a given time. It takes long time for these extra droplets to dry out and, thus, the set time is increased. On the other hand, mixes with less emulsified asphalt content require less time to set. It is interesting to note that both aggregate gradation and aggregate blend have not shown any statistical significance towards the set time values. This is because both their p-levels and t-statistic values are exceeding the minimum required criteria (p-level should be less than 0.05 and t-statistic should be greater than 1.65 at 95% significance level) for entry into the significant factors list. This means that both aggregate gradation and aggregate blend have no statistical effect on the time required to set for the emulsified asphalt mixes. However, it is not reasonable to drop these variables from the model because they are theoretically known to affect the set time (in statistical analysis essential variables can be forced to enter the models). Hence, these two factors were forced to enter the regression model. The summary of stepwise regression analysis as well as probability plots are shown in Appendix A (Tables A4 through A6 and Figure A2). Table 5.4 shows the parameter estimates of each factor with their corresponding t-statistic values. The statistical model suggests that emulsified asphalt content is directly proportional to the set time (higher emulsion content will lead more set time), and the aggregate blend, aggregate gradation and emulsion type being inversely proportional to the set time. Hence, no violations are observed in this model as this behavior is in accordance with the theory.

Factors Affecting Traffic Time Values

As mentioned previously, traffic rolling time is the time required for any slurry seal or micro surfacing mix to reach a cohesion value of 20 kg.cm. Statistical analysis of obtained data showed that the aggregate gradation is the most significant factor influencing the traffic time of any emulsified asphalt mix with explaining about 52.3% of the total variability. The next significant factor was aggregate blend. Unlike set time in which initial phase of the slurry seal and micro surfacing is important, traffic time happens after the set time has actually occurred. This means that the relative importance of emulsified asphalt type and content has become less significant because the initial setting of the mix has now taken place. The remaining factors, which are aggregate gradation and aggregate blend, become more significant at this stage. In theory, aggregate gradation and aggregate blend affect the cohesion torque values. Coarse as well as rough surface textured aggregates poses higher cohesion torque values at a given stage than that of fine and smooth surface textured aggregates. This was exactly what the analysis of data revealed. Emulsified asphalt type has also shown statistical significance ($p\text{-level} < 0.05$, and $t\text{-statistic} > 1.65$). This tells us that the use of polymer-modified emulsion does reduce the traffic time required by the mixes. This phenomenon can be attributed towards the addition of rubberized (polymer) materials, which tend to improve both the cohesion as well as adhesion properties of the binder and the aggregates. Emulsified asphalt content has barely shown any statistical significance ($p\text{-level} = 0.046$) with the traffic time because its p-level is very close to the borderline. Thus, changing emulsified asphalt content will not change the traffic time very significantly. This statement is also valid in practice because, normally, most of the emulsified asphalt content is dried out before the initial traffic rolling time can be achieved. The stepwise regression analysis results as well as probability plots are given in Appendix A (Tables A7 through A9 and Figure A3). The regression model is briefly described in Table 5.5. According to this model, aggregate gradation, aggregate blend, and emulsified asphalt type are inversely proportional to the traffic time of mixes. However, the emulsified asphalt content is directly proportional to the traffic time.

Factors Affecting Final Torque Values

Final torque represents the skid resistance characteristics of the end-product surface. Obviously, the goal is to achieve higher skid resistant surface in order to promote safety while driving. The stepwise analysis revealed that the most significant factor effecting the final torque values (skid resistance) of any slurry seal and micro surfacing mixes is the aggregate gradation. Aggregate gradation alone explains up to 60.8% of the variability involved in the final torque values. The next highly significant factor is the aggregate blend that entered the model with R^2 value of 15.4% (making, 76.2% out of 79.3%). This observation is as expected. As in all asphalt mixes, the surface properties of emulsified asphalt mixes (specifically slurry seal and micro surfacing) depends mainly upon the aggregate gradation and type. Coarse aggregates provide higher skid resistant surface as compared to fine aggregates mainly because of their raised and visible edges in the mixed gradation, which increases the rubber-tire to aggregate friction. In the same way, aggregates having rough and angular surface properties also increases this friction considerably resulting in an increase in the final torque values when measured with the wet cohesion device. Emulsified asphalt type as well as content has also shown statistically significant effect (t-statistic > 1.65) on the final torque values. Polymer-modified emulsion provide better bonding characteristics with the aggregate and hence can increase the skid resistance properties of the surface. In the same way, increase in emulsion type can also increase the bonding characteristics of the mix resulting in an increase in the final torque values. However, this increase is not highly significant. An analysis of variance (ANOVA) was performed on the obtained model, which indicated that the possibility of obtaining a better model is nearly zero. Table 5.6 presents the

Table 5.6 : Summary of Final Torque Model

(Factors in order of Significance)

Variable	Intercept	GRAD	AGGT	EMLTYP	EMLP%
Coeff	4.734444	4.711111	1.205238	2.138889	0.215476
t-statistic	2.672306	8.095637	7.074145	2.598968	1.847267

R= .89082175
R^2= .79356339

Table 5.7 : Summary of WTAT Loss Model

(Factors in order of Significance)

Variable	Intercept	EMLTYP	AGGT	GRAD	EML%	TREAT
Coeff	2952.255	-523.87	-99.8556	-239.889	-44.8338	-72.9514
t-statistic	45.2428	-18.6289	-17.1524	-12.0639	-11.2483	-5.99096

R= .95299189
R^2= .90819354

Table 5.8 : Summary of LWT Absorption Model

(Factors in order of Significance)

Variable	Intercept	AGGT	EML%	EMLTYP	GRAD	TREAT
Coeff	100.6433	54.72571	18.0963	-116.306	58.05556	-23.26
t-statistic	3.593237	21.06884	12.23818	-12.1368	9.25411	-4.282

R= .90532043
R^2= .81960508

summary of final torque stepwise regression results. The model fitting results and graphic plots are shown in Appendix A (Tables A10 through A12 and Figure A4).

5.3.3 Wet Track Abrasion Test (WTAT) Results

Wet track abrasion test (WTAT) is one of the two most important field performance measures of any slurry seal or micro surfacing mix design. The other one is Loaded Wheel Test (LWT). In this research, these two tests were considered as decisive criterion for evaluating slurry seal and micro surfacing mixes for field applications. The test results of WTAT loss of various mixes were evaluated statistically. Factors list included the aggregate blend, aggregate gradation, treatment type, emulsified asphalt type, and emulsified asphalt content. The analysis disclosed that the most determining factor towards the explanation of WTAT loss is emulsified asphalt type. Only this factor explains around 62.3% of the variability involved in the WTAT results. This means that changing emulsified asphalt type from slurry seal to micro surfacing reduces the WTAT loss highly significantly. In theory, polymer modification of binder is well known to impart improved adhesion properties as well as stripping resistance characteristics to the paving mixes. The test observations revealed similar behavior. The aggregate blend also proved another very significant factor in reducing the WTAT loss. Hence, according to the analysis results, increase in slag content will significantly reduce the WTAT loss. Theoretically, this is due to the rough and angular surface texture of steel slag aggregates that provide greater interlocking between particles that in turn resist particle displacement under wet track conditions. This results in significant reduction of WTAT loss. Aggregate gradation entered the significant factor list on the third place. Generally, the increase in coarse size particles reduces the wear loss of any paving mix. This is because, unlike fine aggregates, the points of contact between rubber tire and paving surface reduces significantly whenever coarse particles are used. This tends to reduce the wear loss as, under normal conditions, only polishing of aggregates occurs in such case. In addition, the particle interlocking increases with increase in aggregate size resulting in a reduced potential for aggregate stripping out of the mix. The analysis showed that both the emulsified asphalt content and treatment type has statistically significant effect on WTAT loss of any slurry seal and micro surfacing mixes. In short, for a given set of aggregate blend, aggregate gradation, emulsion type and content, and treatment type, all of which play a significant role. Careful design of any slurry seal or micro surfacing mixes by optimizing these factors can greatly reduce the WTAT loss. The regression model is summarized in Table 5.7 with the coefficient of determination (R^2) value of 90.82%, which is very high. The summaries of stepwise regression results and probability plots are depicted in Appendix A (Tables A13 A15 and Figure A5)

5.3.4 Loaded Wheel Test (LWT) Results

As discussed earlier, loaded wheel test is used to determine the maximum limit of emulsified asphalt content in order to achieve a slurry seal or micro surfacing mix that have little tendency for flushing at higher temperatures. LWT was performed on all the slurry seal and micro surfacing mixes and the results were analyzed statistically. Variables, as in the WTAT, included the aggregate blend and gradation, emulsified asphalt type and content, and treatment type. Stepwise regression analysis revealed that the most significant factor towards the determination of LWT absorption values is aggregate blend. Aggregate blend has entered the model with R^2 value of 46% and a t-statistic of 21.06, which is highly significant. This shows that the change in material type (from mixes high in limestone to mixes high in slag aggregates) can significantly increase the LWT sand absorption. This observation is valid in practical terms because the low surface porosity and low absorption of steel slag aggregates lead to higher excess asphalt in the mix. In addition, the high thermal conductivity of steel slag can significantly increase the flushing potential of emulsified asphalt mixes at high temperatures. Emulsified asphalt content and type have entered as the next two significant, which implies that the increase in emulsified asphalt content can also significantly increase the flushing potential. On the other hand, the use of micro surfacing emulsion can significantly reduce the same. This proves the importance of proper mix design with optimized emulsified asphalt content for any given type of emulsion, which means that the criteria for both minimum as well as maximum emulsified asphalt content should be maintained in order to achieve an effective slurry seal or micro surfacing mix design in terms of both WTAT loss and LWT absorption values ranging within ISSA specification limits. Aggregate gradation and treatment type have also played a statistically significant role in determining the LWT sand absorption values (or flushing potential of mixes). Use of coarse aggregate can increase the sand absorption values. This is due to the use of coarser sized particles that require lesser amounts of emulsified asphalt for proper bonding characteristics as compared to finer particles, which have larger surface areas and require much higher quantities of emulsified asphalt. On the contrary, treatment order (Normal-Lime-Cement) can significantly increase the asphalt stiffness and viscosity and thus reduce LWT sand absorption. The regression model, which have a R^2 value of 81.9% is summarized in Table 5.8 and the fitting results as well as probability plots are shown in Appendix A (Tables A16 through A18 and Figure A6). According to this model, the aggregate blend, gradation and emulsified asphalt content are directly proportional to the LWT absorption of the mixes. However, the treatment type and emulsified asphalt type are inversely proportional to the LWT absorption of the same mixes.

The various models obtained for the prediction of consistency, set time, traffic time, final torque values, WTAT loss values, and LWT sand adhesion values are summarized with their R^2 values as well as P-levels in Table 5.9.

5.4 Mix Design Parameters Modeling

Models regarding the performance of slurry seal and micro surfacing mixes in terms of providing acceptable consistency, wear loss, and sand absorption readings were developed and tested for reasonable reliability and adequacy. This is because these characteristics (consistency, wear loss, and sand absorption) directly reflect the field performance of slurry seal and micro surfacing mixes. In the developed prediction models, the independent variables were the mix characteristics (aggregate blend, aggregate gradation, and treatment type). The dependent variable list contains the optimum emulsified asphalt and water content required achieving a slurry seal or micro surfacing mix that meets the specification requirement of consistency, WTAT loss, and LWT absorption as well. Validation mixes were selected randomly as P30LS Type I and LS Type II for consistency and P8LS Type III (Cement) and 30% LS Type III (Cement) for required emulsion content in the case of slurry seal and micro surfacing, respectively. These validation samples were not included in the model development process. The A-priori hypothesis for the model is given in Table 5.10. The A-priori hypothesis reflects the initial

Table 5.9 : Summary of Test Performance Prediction Models

Property	Suggested Performance Prediction Model	R^2	P-level
Consistency (mm)	CONST = -36.893 + 2.129508 WATER + 2.66227 AGGT + 8.2646 GRAD - 3.56248 EMLTYP	0.76	0
Set Time (hours)	SET = 5.510486 - 1.49722 EMLTYP + 0.137054 EML% - 0.10972 GRAD - 0.02393 AGGT	0.71	0
Traffic Time -(hours)	TRAFFIC = 14.86445 - 1.53508 GRAD - 0.33562 AGGT - 1.25854 EMLTYP + 0.110096 EML%	0.69	4.54E-13
Final Torque (kg.cm)	FTORQ = 4.734444 + 4.711111 GRAD + 1.205238 AGGT + 2.138889 EMLTYP + 0.215476 EML%	0.79	3.06E-22
WTAT Loss (g/m^2)	WTAT = 2952.255 - 523.87 EMLTYP - 99.8556 AGGT - 239.889 GRAD - 44.8338 EML% - 72.9514 TREAT	0.90	0
LWT Sand Absorption (g/m^2)	LWT = 100.6433 + 54.72571 AGGT + 18.0963 EML% - 116.306 EMLTYP + 58.05556 GRAD - 23.2667 TREAT	0.81	0

Table 5.10 : A-Priori Hypothesis for the Prediction Models

Factor Code	Hypothesis for Required Water Content	Hypothesis for Required Emulsion Content	Explanation
AGGT	Inversely Proportional	Inversely Proportional	Increase in slag percentage reduces required water & emulsion content
GRAD	Inversely Proportional	Inversely Proportional	Coarse gradation reduces required water & emulsion content
EMLTYP	Directly Proportional	Inversely Proportional	Micro surfacing emulsion increases required water & decreases required emulsion content
TREAT	N.A*	Directly Proportional	Treatment order (Normal-Lime-Cement) decreases required emulsion content

*N.A = No Significance Observed

assumptions (based upon theory) about the behavior of any mixture by changing any of its material properties.

To have a preliminary idea about the relationship between the variables used in the models, correlation matrices were obtained. Correlation coefficients provide a normalized and scale-free measure of the association between two variables. A positive correlation coefficient indicates that the variables vary in the same direction, whilst a negative coefficient indicates that the variables vary in the opposite direction. Statistically independent variables have an expected correlation coefficient of zero. These correlation matrices are shown in Appendix B for all the categories of slurry seal and micro surfacing mixes.

Firstly, the possibility of improving the fit through transformation was investigated. To do this, the relationship between the dependent variables and the independent variables were drawn. The shapes of these graphs were studied to check if the relationship was linear or non-linear. Several transformations (normally natural logarithms proved most useful) were made for either the dependent variable(s) or independent variable(s) or both in order to improve the regression fit. The required transformations were then carried out and the models were rebuilt and evaluated for practicality.

The stepwise regression analysis was performed utilizing *STATISTICA* software facility at 95% confidence interval ($\alpha = 0.05$). The confidence intervals for the mean give us ranges of values around the mean where we expect the "true" (population) mean is located (with a given level of certainty, say 95%). Note that the width of the confidence interval depends on the sample size and the variation of data values. The calculation of confidence intervals is based on the assumption that the variables are normally distributed in the population. It is important to assume in multiple regression that the residuals (predicted minus observed values) are distributed normally (i.e., follow the normal distribution).

The variables were coded according to the dummy numbers assigned as given in Table 5.2. The criteria for including any factor (independent variable) in the regression model was set to be 1.0, i.e., the variable will be included in the model if it adds to the significance level of F-ratio a value of 1.0 or greater. After the addition of each factor, starting with the one that contributed the most to the F-value, the contribution of each factor to the F-value of the model was recalculated. If the value of the contribution for any of the included factors dropped under 1.0, it was dropped from the model. The selection procedure continued until the contribution of all factors inside the model was greater than or equal to one and the contribution of the factors not included in the model was less than 1.0 (Hines and Montgomery, 1990).

The quantity, R^2 that is called the coefficient of determination, was used to judge the adequacy of the prediction regression models. R^2 often refer to as the amount of variability in the data explained or accounted for by the regression model. Hence, a higher R^2 value indicates better prediction capability by the model

(Montgomery, 1991). All R^2 values for all the models were found to be over 0.6 and all suggested models had a p-level significantly less than 0.05, which is considered as the significance borderline (Brownlee, 1960).

5.5 Modeling Results for Required Water Content

The stepwise regression modeling was performed on the optimum values of total water content corresponding to the design cone consistency results (20-30 mm) shown in Table 5.11. The independent list of variables contains aggregate blend, aggregate gradation, emulsified asphalt type, and desired consistency value. The dependent variable on the other hand was the amount of water required to produce the desired consistency at any specified combination of materials as given in the independent variable list. Some transformations were required to improve the model fitting results since the relationship between some of the dependent and independent variables were not essentially linear. The coefficient of determination (R^2) of the model came out to be 81.3%, which was quite satisfactory. The confidence levels for all independent factors as well as the whole model itself were greater than 99.99% indicating their high significance with the dependent variable.

This regression model predicts the total amount of water required in order to achieve a desired consistency value (specification ranging between 20-30 cm) with any given combination of aggregate blend, aggregate gradation, and emulsified asphalt type. The coding of independent factors is based on Table 5.2

Table 5.11 : Cone Consistency Test Results

		Slurry Seal Mixes Type						Micro Surfacing Mixes Type					
		LS	P8 LS	P30 LS	30% LS	60% LS	SS	LS	P8 LS	P30 LS	30% LS	60% LS	SS
Aggregate Gradation	Type I	27.5	23	22	21	23.5	17	*	*	*	*	*	*
	Type II	22	19.5	17.5	17.7	21	15	23	21	20.5	21	22.5	16
	Type III	18.7	15.5	14	14.8	15.5	11.5	20	15.8	14.5	16	16.2	12.2

Cell readings represent total water content to acquire a design slump of 25 mm
* Mixes are not normally used in the field (not recommended by the ISSA)

and must be used in order to achieve the required prediction. Table 5.12 gives the linear model and Table 5.13 gives the transformed model for the estimation of optimum water content with their t-statistic and R^2 values. The model fitting results as well as the residual analysis are shown in Appendix B (Tables B1 through B6 and Figures B1 and B2).

5.6 Modeling Results for Required Emulsified Asphalt Content

WTAT loss and LWT sand absorption results were evaluated to obtain those emulsified asphalt contents that gave the specified wear loss (800 for slurry seal and 530 for micro surfacing mixes, in g/m^2) as well as maximum allowable sand absorption values (610 g/m^2). The models were generated using the optimum values of emulsified asphalt content conforming to the specification limits of both WTAT and LWT as shown in the Table 5.14. The independent variables were aggregate blend, gradation, and treatment type. The dependent variable was the optimum amount of required emulsified asphalt. Two separate models were generated, each for slurry seal and micro surfacing mixes in order to reduce the variability due to the increase in one independent factor, i.e., emulsified asphalt type. Preliminary observations revealed that this separate grouping has significantly improved the model fitting capabilities. Logarithmic transformations were carried out for some dependent and independent variables in order to improve the regression fit. Both transformed and linear models are presented so

Table 5.12 : Summary of Linear Model with Water Content as Dependent Variable (Factors in order of Significance)

Variable	Intercept	GRAD	CONST	AGGT	EMLTYP
Coeff.	19.369633	-3.147455	0.32071	-1.04994	0.929190
t-statistic	32.6601697	-18.13793	18.1553	-13.6080	2.971233

R= .90294985
R^2= .81531843

Table 5.13: Summary of Transformed Model with LN-Water Content as Dependent Variable (Factors in order of Significance)

Variable	Intercept	GRAD	LN-CONST	AGGT	EMLTYP
Coeff.	2.27415	-0.1874	0.364046	-0.0634	0.05682
t-statistic	46.7931	-22.850	23.03559	-17.523	3.86120

R= .91910866
R^2= .84476074

Table 5.14 : Optimized Slurry Seal and Micro Surfacing Mixes Conforming To Both WTAT and LWT Specifications

			Slurry Seal Mixes Type						Micro-Surfacing Mixes Type					
		Treat	LS	P8 LS	P30 LS	60 % LS	30 % LS	SS	LS	P8 LS	P30 LS	60 % LS	30 % LS	SS
Aggregate Gradation	Type I	Normal	28	19.5	17.6	25.1	17.1	18.9	*	*	*	*	*	*
		Lime	25	19.2	16.3	21	15.9	16	*	*	*	*	*	*
		Cement	23	16.3	13.5	13	12	12	*	*	*	*	*	*
	Type II	Normal	19.5	16.7	14.3	13.5	11.8	7.3	10.5	8.3	7.8	7.5	7	6.5
		Lime	18.5	15	14	13.3	11.5	5.8	8.5	6.5	6.8	6	6	5.5
		Cement	17.5	13	11	11	7.8	6	7	6	5.5	5.8	5.5	5.9
	Type III	Normal	12.8	10	9.5	10	8.5	7	7.8	7.5	6.4	6.5	6.6	6.3
		Lime	11	9.4	7.8	8.5	6.9	6.7	6.5	6.3	5.75	5.7	5.4	5.1
		Cement	10.5	8.3	6.4	7	6.6	6.3	6.45	6.4	5.5	5.3	5.2	5.8

Cell readings represent optimized values of emulsified asphalt content
(Optimum Emulsion Content required for passing both WTAT & LWT Specification)
* Mixes are not normally used in the field (not recommended by the ISSA)

that the relative improvements can be easily visualized. Generally, model fittings were greatly improved with the required transformation. In all models, the R^2 was found greater than 63.6%, which is quite adequate for general purposes. The confidence level of all the models exceeds the value of 99.99%.

The developed models predict the optimum required amount of emulsified asphalt in order to generate slurry seal or micro surfacing mixes that pass the specification limits of both wear loss and sand adhesion values when tested with WTAT and LWT. Obviously, the description of materials (aggregate blend, gradation, and treatment type) is the required input. Tables 5.15 through 5.18 present the generated models along with the corresponding t-statistic and R^2 values. The model fitting results as well as residual plots are depicted in Appendix B (Tables B7 through B18 and Figures B3 through B6).

The summary of the recommended prediction models along with their respective R-square and P-values is given in Table 5.19.

5.7 Measures of Model Adequacy

A number of techniques can be used to measure the adequacy of a multiple regression model. Some of the most practical techniques were used to test the developed prediction models for adequacy (Hines and Montgomery, 1990).

Table 5.15 : Summary of Linear Model for Slurry Seal Mixes with Emulsion Content as Dependent Variable (Factors in order of Significance)

Variable	Intercept	GRAD	AGGT	TREAT
Coeff.	32.40672	-4.973685	-1.55639	-1.95
t-statistic	27.60141	-14.25670	-9.27301	-5.67383

R= .91348408
R^2= .83445316

Table 5.16: Summary of Transformed Model for Slurry Seal Mixes with Emulsion Content as Dependent Variable (Factors in order of Significance)

Variable	Intercept	LN-GRAD	LN-AGGT	TREAT
Coeff.	27.27669	-8.917892	-4.481685	-1.95
t-statistic	26.32904	-13.447114	-9.0033623	-5.35641

R= .92368765
R^2= .85319888

Table 5.17 : Summary of Linear Model for Micro Surfacing Mixes with Emulsion Content as Dependent Variable (Factors in order of Significance)

Variable	Intercept	TREAT	AGGT	GRADT
Coeff.	10.55706	-0.69642	-0.2909	-0.62578
t-statistic	17.04338	-5.56849	-4.9196	-3.08744

$R = .79737069$
$R^2 = .63580002$

Table 5.18 : Summary of Transformed Model for Micro Surfacing Mixes with LN-Emulsion Content as Dependent Variable (Factors in order of Significance)

Variable	Intercept	LN-TREAT	LN-AGGT	LN-GRAD
Coeff.	2.308329	-0.18419	-0.124854	-0.207871
t-statistic	38.22884	-7.034350	-6.407375	-3.560002

$R = .87173562$
$R^2 = .75992299$

Table 5.19 : Summary of Transformed Generated Models

Property		Suggested Mix Design Prediction Model	R^2	P-value
* WATER (Transformed)	All Mix Type	LN (WATER) = 2.27415 - 0.1874 GRAD + 0.364046 LN (CONST) - 0.0634 AGGT + 0.05682 EMLTYP	0.84	0
EML% (Transformed)	Slurry Seal	EML% = 27.27669 - 8.9179 LN (GRAD) - 4.4816 LN (AGGT) - 1.950 TREAT	0. 85	2.02E-20
EML% (Transformed)	Micro Surfacing	LN (EML%) = 2.3083 - 0.1842 LN (TREAT) - 0.1249 LN (AGGT) - 0.208 LN (GRAD)	0. 75	9.95E-10

Transformed models showed significant improvement in R^2 values as compared to the linear, they should be used instead.

5.7.1 Sign Testing and Model Validation

The sign test was carried out to check if the parameter signs in the developed models were according to the ones set in the priori hypothesis. It was observed that all model parameters were in accordance with the A-priori hypothesis and no violations of sign were detected. Some of the general observations about the used signs in the developed models are as follows:

- WATER content, for all the mixes, is negatively related to aggregate blend, and gradation and positively related to desired consistency and emulsion type
- EML%, for all the mixes, is negatively related to aggregate blend, gradation, and treatment type

The above mentioned observations are all according to the A-priori hypothesis.

In addition to the sign testing, it was decided to visually check the ability of prediction performance of the model by comparing the observed with the predicted values for validation samples that were selected earlier and not included in the model development. For this purpose, the samples were randomly selected and the independent variables concerning these samples were entered into the prediction model. The results of this comparison have been shown in Table 5.20. It can be seen from the Table 5.20 that the accuracy of these models was quite adequate in predicting the dependent variables as in all the cases the percent error of the

Table 5.20 : Prediction of the Generated Models for Randomly Selected Samples

Model Type		Sample I.D.	Observed	Predicted	Model R^2
WATER (Transformed)	Slurry Seal	P30LS Type I	21	22.76	84.47 %
	Micro Surfacing	LS Type II	23	22.68	84.47 %
EML% (Transformed)	Slurry Seal	P8LS Type III (Cement)	8.3	8.52	85.32 %
	Micro Surfacing	30% LS Type III (Cement)	5.2	5.34	75.6 %

prediction is well under the 1- R^2 limits. Furthermore, F-Test for variance was performed on the observed and predicted values and the results are summarized in Table 5.21. These results of F-Test revealed that there was no significant variance between observed and predicted values (P-value = 0.4806 >> 0.05). Hence, it can be concluded that the predicted values are not significantly different from observed values and the model can be considered valid for prediction.

5.7.2 The Coefficient of Multiple Determination (R^2)

R^2 is a measure of the amount of reduction in the variability of any dependent variable obtained using the regressor variables (independent variables). A higher R^2 value normally indicates higher explained variability, which is involved in the model. More specifically, an R^2 value of 0.85 (for example) means that this model can explains up to 85% of the variability involved in the data set. However, a large value of R^2 does not necessarily imply that the regression model is a good one. Adding a variable to the model will always increase the R^2, regardless of whether the additional variable is statistically significant or not (Hines and Montgomery, 1990). In the current study, as it is obvious that the variables involved are both highly significant and fewer in number. Hence, the increase in R^2 value is mostly due to the improvement of regression fit.

5.21 : F-Test on Observed and Predicted for Variances

Property	Observed	Predicted
Mean	14.375	14.825
Variance	79.78917	84.7945
Observations	4	4
Degrees of Freedom	3	3
F-Value	0.940971	
P-Value	0.480642	
F Critical	0.107798	

All the R^2 values of the predicted models were exceeding 64.6% reaching as high as 83.3%. This means the accuracy of the prediction based upon these models will be higher than 64.6%.

5.7.3 Residual Analysis

In fitting any model, analysis of the residuals from a regression model is necessary to determine the adequacy of the least squares fit. One of the main assumptions that must be satisfied when using the ordinary least square method is that the error has constant variance. This implies that there should be a scatter of errors around all points of the independent variables. This assumption is called homoscedasity. To check for homoscedasity of the used variables, plots of predicted values of dependent variables against residuals (difference between measured and predicted values) will reveal any violation of this assumption (Montgomery and Peck, 1982). The plots of predicted values versus residuals, observed versus residuals, and predicted versus observed for the estimation of the water and emulsion content is shown in Appendix B (Figures B1 through B6). As can be seen, the residual plots do not reveal any major difficulty as no outliers are observed. Also, the residuals are very randomly distributed around the mean line and have no detectable patterns. Hence, it can be concluded that the regression model is an adequate fit for the dependent variables.

5.7.4 Normality Testing

In multiple regression, it is assumed that the residuals (predicted minus observed values) are distributed normally (i.e., follow the normal distribution). In multiple regression, normality is part of the significance testing (Montgomery, 1991). Normal probability plots were drawn and shown in Appendix B for the residuals to ensure that the errors were normally distributed with the means. These plots do not indicate any serious violation of the normality assumption as the residuals form nearly a linear pattern. Hence, the assumption of normality distribution remains valid.

The assumption of normally distributed error terms implies that the histogram of the residuals should be approximately symmetric and bell-shaped. Skewness to the left or right represents deviation from normality. The histograms of these models are shown in Appendix B and no obvious violations are detectable.

5.7.5 Autocorrelation Testing (Durbin-Watson Test)

It was assumed in the regression models that the model error components are uncorrelated random variables (Hines & Montgomery, 1990). Several statistical procedures can be used to determine if the error terms in the model are uncorrelated among which the Durbin-Watson test is widely used. The value of the

Durbin-Watson test statistic (d) was obtained using *STATISTICA* software. Table 5.22 shows the values of Durbin-Watson statistics along with the lower and upper limits (d_L & d_U) at both 0.05 and 0.01 significance level. A small d value indicates a positive autocorrelation, while a large d value indicates a negative autocorrelation. The limits of the d value follow (Montgomery and Peck, 1982):

- If $d < d_L$ then reject the null hypothesis of non-autocorrelated error terms in favor of the hypothesis of positive autocorrelation.
- If $d > d_U$ then do not reject the null hypothesis, this means that there is no significant autocorrelation present into the error terms.
- If $d_L < d < d_U$ then the test is inconclusive.

When $d > 2$, the test statistic becomes $4 - d$, and the same criteria as in positive autocorrelation was used to reject or accept the null hypothesis. Results show that for all the models at both 0.05 and 0.01 significance levels the test is conclusive and the null hypothesis cannot be rejected indicating the non-presence of autocorrelation among error terms.

In summary, when d is close enough to 2 (as determined by the STATISTICA software), there is no significant evidence of autocorrelation. But if its value is close to 0 or 4, there is probably an autocorrelation problem. Table 5.22 shows the results of hypothesis testing regarding autocorrelation. The results of Durbin-Watson test indicate that the null hypothesis cannot be rejected (non-presence of autocorrelation.

Table 5.22 : Durbin-Watson Test for Autocorrelation

Property		$\alpha = 0.05$		$\alpha = 0.01$		# Reg.	# Obs.	d (+ve)	d (-ve)	H_0 (0.05)	H_0 (0.01)
		d_L	d_U	d_L	d_U						
WATER Transformed	All Mixes	1.59	1.76	1.45	1.63	4	114	1.9436	2.0564	N.R*	N.R
EML% Transformed	Slurry Seal	1.42	1.67	1.24	1.49	3	54	2.0936	1.9064	N.R	N.R
EML% Transformed	Micro Surfacing	1.30	1.66	1.10	1.45	3	36	1.7814	2.2186	N.R	N.R

*N.R = Don't reject Null Hypothesis (H_o)

5.7.6 Multicolinearity Testing

Multicolinearity occurs whenever the independent or regressor variables are highly intercorrelated. Multicolinearity can have serious effects on the estimates of the regression coefficients and on the general applicability of the estimated model. There are several ways to detect the presence of multicolinearity. Some of the important tests are (Hines and Montgomery, 1990):

- If the F-test for significance of regression is significant, but the tests on the individual regression coefficients are not significant, then multicolinearity might be present
- Inspection of the individual elements of the correlation matrix can be helpful in detecting multicolinearity. If an element is close to one, then the two factors may be strongly multicolinear.

The F-tests on the model and the individual regression coefficient revealed p-levels far less than 0.05. This shows the non-presence of multicolinearity between regressors. In addition, the inspection of the correlation matrices revealed no highly intercorrelated factors. Hence, the multicolinearity does not seem to be a problem. The F-test results and the correlation matrices are shown in Appendix B (Tables B1 through B18).

One of the advantages of using STATISTICA software is that it issues a matrix ill conditioned message to let the user know that he is trying to include multicolinear independent variables. As no such warning messages were observed, there seems to be no multicolinearity associated within the independent (regressor) variables.

5.8 Summary

The obtained test data was analyzed statistically utilizing Forward step-wise regression procedure and the results were shown in this Chapter. Models with reasonable reliability and validity were generated for the test parameters and mix design parameters prediction. These models were discussed for specific implementations.

CHAPTER 6

ECONOMIC ANALYSIS OF SLURRY SEAL AND MICRO SURFACING MAINTENANCE TECHNIQUES

6.1 General

This Chapter deals with the economic analysis of pavement maintenance strategies utilizing slurry seal and micro surfacing mixes. The principles of engineering economy as well as common sense were used to identify the best slurry seal or micro surfacing mix type under a specified criterion for a required pavement maintenance program. A considerable amount of literature is available on the principles of engineering economy and methods of economic evaluation. However, a review of the literature suggests that the best method for measuring economic worth of pavement maintenance alternatives is that of present worth or present value, which is basically the accumulation of the future recurring costs in terms of present cost (Epps, 1982). The present worth of a required maintenance strategy can be viewed as the amount of money that must be available at the present time in order to have sufficient funds to pay for not only the immediate maintenance that is required but also the anticipated future rehabilitation and maintenance operations needed through some selected period in the future.

In order that the present worth of rehabilitation and maintenance can be determined, several important items of information need to be determined and/or established. These factors include definition of costs, selection of a discount rate, selection of an analysis life, development of a methodology for determination of salvage value and establishment of the life of various maintenance alternatives (Haas, 1978).

6.2 Definition of Costs

The initial and recurring costs that an agency may consider in the economic evaluation of alternative rehabilitation strategies are summarized below:

- Initial capital costs of maintenance alternative (these include materials, equipment, labor, and all other project associated costs)
- Future capital costs of reconstruction or maintenance
- Salvage value

Salvage or residual value is used by some agencies in economic evaluation. It can be significant in the case of major rehabilitation or overlay design because it involves the value of reusable materials at the end of the design period (Epps, 1982). However, for slurry seal and micro surfacing projects which involve a minimal thickness (a maximum of 3/8 inches) of wearing layers, the reusability of old materials is not practical and hence the concept of salvage value is not normally applied to such projects.

The current prices were obtained from Al-Binali & Sons, Sand-Fix Company, and Saudi ARAMCO. These prices have been unitized in Riyals for each square meter laying of slurry seal or micro surfacing layers (Riyals/m^2). The prices of Type III mixes are high as compared to those of Type II or Type I because more material and other costs are associated with its use. Similarly, the prices of micro surfacing emulsions are higher than those of slurry seal emulsions. The cost of steel slag aggregates are also higher than those of limestone mixes due to their increased transportation charges as the unit weight of steel slag aggregates are higher (approximately 7 Riyals/m^3 for limestone and 9 Riyals/m^3 for steel slag aggregates). These companies refused to disclose their mix design so the exact idea about the amount of used aggregate and emulsified asphalt for each type of mix couldn't be obtained. This resulted in difficulty to split the unit prices over the constituent materials (i.e., costs of aggregate and emulsified asphalt). However, Sand Fix company suggested that the price split (i.e., separate prices for emulsion, labor, and equipment) are on fixed percentage basis of the total unit price for each square meter, which means that these prices depends mainly upon the aggregate gradation (i.e., Type I, II, or III) and type of emulsified asphalt. Another problem was the gathering of the total unit price for each square meter, as it is somewhat a relative term that depends upon the location, contractor, and size of project. Nevertheless, attempts were made to collect a range of average practical prices for each mix type. Although mixes containing steel slag aggregates are likely to utilize less amount of emulsified asphalt than those of pure limestone mixes making the use of steel slag aggregates more economical, it was assumed that both mixes are prepared at fixed emulsified asphalt content, as suggested by the companies. The obtained initial capital costs (split for each category) of maintenance utilizing slurry seal and micro surfacing mixes are shown in Table 6.1 for the different aggregate gradations as well as aggregate blends.

6.3 Discount Rate

A discount rate is used to reduce the future-expected costs or benefits to present-day terms. It provides the means to compare alternatives uses of funds, but it should not be confused with the interest rate, which is associated with borrowing money.

The actual rate to be used in the agency's calculations is a policy-decision question. In addition, this rate could vary with the factor being evaluated to reflect the associated degree of uncertainty. Most agencies, however, use a single rate. In the pavement field, discount rates between 4 and 10 percent have often been used, with 4 percent suggested by most of the agencies (Epps, 1982).

Table 6.1 : Initial Capital Costs of Slurry Seal and Micro Surfacing Mixes

		Slurry Seal Type			Micro Surfacing Type	
	Aggregate Blend	Type I	Type II	Type III	Type II	Type III
Aggregate Cost (12% of Total)	LS	0.40	0.43	0.49	0.55	0.62
	P8LS	0.40	0.43	0.50	0.56	0.62
	P30LS	0.41	0.44	0.50	0.56	0.63
	60%LS	0.40	0.44	0.50	0.56	0.63
	30%LS	0.41	0.44	0.50	0.56	0.63
	SS	0.41	0.45	0.51	0.57	0.64
Emulsion Cost (38% of Total)	LS	1.25	1.35	1.54	1.73	1.92
	P8LS	1.25	1.35	1.56	1.74	1.94
	P30LS	1.27	1.37	1.57	1.76	1.95
	60%LS	1.27	1.36	1.55	1.75	1.94
	30%LS	1.28	1.38	1.57	1.76	1.95
	SS	1.29	1.39	1.58	1.77	1.97
Labor Cost (20% of Total)	LS	0.65	0.70	0.80	0.90	1.00
	P8LS	0.65	0.70	0.81	0.90	1.01
	P30LS	0.66	0.71	0.82	0.91	1.02
	60%LS	0.66	0.71	0.81	0.91	1.01
	30%LS	0.67	0.72	0.82	0.92	1.02
	SS	0.67	0.72	0.82	0.92	1.02
Equipment Cost (30% of Total)	LS	0.95	1.02	1.17	1.32	1.46
	P8LS	0.95	1.03	1.18	1.32	1.48
	P30LS	0.96	1.04	1.19	1.34	1.48
	60%LS	0.96	1.03	1.18	1.33	1.47
	30%LS	0.97	1.05	1.19	1.34	1.48
	SS	0.98	1.06	1.20	1.35	1.49
Total Cost	LS	3.25	3.50	4.00	4.50	5.00
	P8LS	3.26	3.52	4.05	4.52	5.05
	P30LS	3.30	3.57	4.08	4.57	5.08
	60%LS	3.29	3.54	4.04	4.54	5.04
	30%LS	3.33	3.58	4.08	4.58	5.08
	SS	3.36	3.61	4.11	4.61	5.11

*Cell readings represent unit cost in Riyals/m^2
Total Prices obtained from Al-Binali & Sons, Sand-Fix Company, and Saudi ARAMCO,
% Price split obtained from Sand-Fix Company

6.4 Analysis Life

In economic studies, projects under consideration are defined as having a service life, an economic life and an analysis life. Service life estimates the actual total usage of a facility. It is the time span from installation of a facility to retirement from service. The ending of service life of a pavement (except by a disaster) is by man-made decision.

The economic life is the life in which a project is economically profitable or until the service provided by the project can not be provided by another facility at lower costs. The economic life may be less than the service life. Shortage of capital often extends a project service life beyond the end of its economic life (Epps, 1982).

Analysis life may not be the same as the service life or economic life of a project, but it represents a realistic estimate to be used in economic analysis. The analysis period utilized should be long enough to include the time for the various maintenance activities under study. However, the analysis period should not be excessive, as the analysis becomes more uncertain due to the change in technology and/or events not occurring as predicted. An analysis period of 20 years is normally suggested by most of the agencies for use when evaluating pavement rehabilitation and maintenance alternatives unless the life of a selected alternative is expected to exceed 20 years (Epps, 1982). As in slurry seal and micro surfacing mixes, the service life is well below 20 years, the analysis period was taken as 20 years.

6.5 Life of Maintenance Alternatives

The expected life of rehabilitation alternatives must be based on the engineer's or, more practically, on the agency's experience with consideration given to local materials, environmental factors and contractor capability. For example, the practical expected service lives of slurry seal layers, in eastern Saudi Arabia range between 3 to 7 years depending on the material type, gradation and quality as well as adopted mix design. For this study, the service lives of different slurry seal and micro surfacing mixes containing full limestone were obtained by the experiences of various contracting and consulting agencies (i.e., Al-Binali & Sons, Sand-Fix Company, and Saudi ARAMCO). As no previous experience regarding the utilization of steel slag aggregate in slurry seal or micro surfacing mixes is available for eastern Saudi Arabia, the service lives of mixes containing steel slag aggregates were estimated utilizing the laboratory WTAT test results by comparing them to those of full limestone mixes. For example, consider the case of 30%LS mixes of Type III gradation. The average wear loss of this mix under WTAT was observed as 586 g/m^2, and that of pure limestone mixes (LS) was observed for the same category as 890 g/m^2 and having an expected service life of 5 years. Therefore, by applying ratio method, one can estimate the expected service life of 30%LS mixes as approximately 8 years. However, the maximum service life of any slurry seal layer is taken as 7 years (ISSA, 1991). Therefore, the service life of Type III 30%LS was taken as 7 years. The same methodology was adopted for all the mixes. The service lives of the different slurry seal and micro surfacing mixes are shown in Table 6.2.

6.6 Analysis Procedure

Based on the information presented above, the present worth or present value economic evaluation methods appear to be the best techniques to utilize for pavement maintenance strategies. A discount rate of 4 percent was used in this study with an analysis period of 20 years, which is normally used by most of the agencies. The unit prices of the various slurry seal and micro surfacing aggregate blends are shown in Table 6.1, which were obtained from various contracting companies in eastern Saudi Arabia.

The basic equation for determining present worth of maintenance for a given facility is (Epps, 1982):

Table 6.2 : Estimated Service Lives of Slurry Seal and Micro Surfacing Mixes

	Slurry Seal Type			Micro Surfacing Type	
Aggregate Blend	Type I	Type II	Type III	Type II	Type III
*LS	3	4	5	5	6
P8LS	4	5	6	6	7
P30LS	4	5	6	6	7
60%LS	4	5	6	7	8
30%LS	5	6	7	8	9
SS	6	6	7	9	10

* Service lives of LS aggregate blend were obtained from Al-Binali & Sons, Sand-Fix Company, and Saudi ARAMCO. Service lives of rest of the aggregate blends were estimated according to their relative laboratory test performances.

$$\mathrm{PW} = C + M_1\left[\frac{1}{1+r}\right]^{n1} + \ldots\ldots\ldots\ M_i\left[\frac{1}{1+r}\right]^{ni} - S\left[\frac{1}{1+r}\right]^{Z} \quad (6.1)$$

Where:

PW = Present worth or present value

C = Present cost of initial maintenance activity

M_i = Cost of the i – th maintenance alternative in terms of present costs

r = discount rate (4 percent as suggested)

n_i =Number of years from the present to the i – th maintenance activity

S = Salvage value at the end of the analysis period (0 in this case)

Z = Length of analysis period in years (20 years as suggested)

The present worth of costs method is usually used and preferred by most of the agencies because it is directly comparable to the uniform annual cost method and presents the summation of all costs into present worth form. Hence, a better understanding of all outstanding costs during the analysis life can be achieved at the beginning of any maintenance project using the present worth method (Hicks, 1977).

For this study, various slurry seal and micro surfacing mixes were grouped into the following categories:

- Emulsion type with two levels, i.e., slurry seal and micro surfacing
- Aggregate gradation with three levels, i.e., Type I, Type II, and Type III

- Aggregate blend with six levels, i.e., LS, P8LS, P30LS, 30%LS, 60%LS, and SS

Initial capital costs and estimated service lives of these mixes are given, respectively, in Tables 6.1 and 6.2. The calculation forms of present worth life cycle costing for each of the mix type are given in Appendix C (Tables C1 through C5). The analysis results are presented in Table 6.3.

6.7 Discussion of Analysis Results

It can be seen from Table 6.3 that the proper selection of aggregate blend (increase in slag percentage) for a given aggregate gradation and emulsified asphalt type can greatly reduce the present worth of the project. Although, the initial costs of such mixes are greater, fewer life cycle costs are expected due to the increase in the service lives of these mixes. The LS mixes have shown the highest present worth as compared to those of the others because of their reduced expected service life, which requires frequent maintenance during the analysis period of 20 years. For example, the life cycle present worth of LS mixes for Type I slurry seal mixes was calculated as 16.43 Riyals/m^2 which is at least 6.66 Riyals higher than SS mixes for the same category. The initial capital costs and the life cycle present worth of the different slurry seal and micro surfacing mixes are given in Table 6.3.

Table 6.3 : Summary of Economic Analysis of Different Aggregate Blends for Slurry Seal and Micro Surfacing Mixes

	Aggregate Blend	Initial Total Cost, Riyals/m^2	Life Cycle PW, Riyals/m^2
Type I Slurry Seal	LS	3.25	16.43
	P8LS	3.26	13.67
	P30LS	3.30	13.86
	60%LS	3.29	13.83
	30%LS	3.33	11.67
	SS	3.36	9.77
Type II Slurry Seal	LS	3.50	14.71
	P8LS	3.52	12.36
	P30LS	3.57	10.36
	60%LS	3.54	12.43
	30%LS	3.58	8.359
	SS	3.61	8.43
Type III Slurry Seal	LS	4.00	14.03
	P8LS	4.05	11.76
	P30LS	4.08	9.53
	60%LS	4.04	9.45
	30%LS	4.08	9.53
	SS	4.11	9.60
Type II Micro Surf.	LS	4.50	15.79
	P8LS	4.52	13.15
	P30LS	4.57	13.28
	60%LS	4.54	10.61
	30%LS	4.58	10.36
	SS	4.61	10.12
Type III Micro Surf.	LS	5.00	14.54
	P8LS	5.05	11.80
	P30LS	5.08	11.87
	60%LS	5.04	11.41
	30%LS	5.08	11.15
	SS	5.11	10.89

In summary, careful selection and combination of aggregate blend, aggregate gradation, and emulsified asphalt type should be carried out for any project in order to ensure reduction in present worth.

6.8 Summary

This Chapter presented the results of economic analysis that was performed on various slurry seal and micro surfacing mixes utilizing steel slag and limestone aggregates. Present worth method was used to calculate the life cycle costs of the different mixes. Generally, the use of steel slag aggregates has resulted in decreased life cycle costs. In the same way, the use of coarser sized particles has also reduced the associated life cycle costs of the various slurry seal and micro surfacing mixes.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this study, steel slag aggregate was blended with limestone into different ratios and the resulting slurry seal and micro surfacing mixes were tested for performance evaluation. In addition, the effect of adding cement and hydrated lime on mix performance was also investigated. The tests used were cone consistency, wet cohesion, wet track abrasion, and loaded wheel. The test results were utilized to generate the test parameter models and the mix design parameter models. Economic analysis was also performed so as to determine the relative feasibility of using the different slurry seal and micro surfacing mixes. This study has fulfilled the objectives based on a comprehensive analysis of the collected data from the tests. The following conclusions can be drawn:

1. The pure limestone mixes have shown significantly higher wear loss as compared to those of others. This means that these mixes are likely to fail in the field.
2. The blending of steel slag aggregates with limestone aggregates has significantly improved the test properties for both slurry seal and micro surfacing mixes. As these test properties directly reflect the mix performance in the field, it can safely be assumed that these mix blends will perform better as compared to pure limestone mixes. However, pure steel slag aggregates have shown deficient resistance to asphalt flushing when tested with the loaded wheel at high temperatures as the higher amount of sand adhesion was observed for such mixes. This was due to the high temperature susceptibility and low absorption capability of steel slag aggregates. Hence, lesser amounts of emulsified asphalt should be used for mixes with increased proportions of steel slag aggregates.
3. The use of polymer modified (micro surfacing) emulsion has greatly reduced the wear loss as well as asphalt flushing potential as compared to those of slurry seal mixes. This was due to the addition of polymers present into the emulsion that imparts greater resistance to wear and asphalt flushing as well.
4. The aggregate gradation has effected the wear loss and the asphalt flushing potential. Type III aggregate, which is the coarsest, has shown the lowest wear loss, but simultaneously, the highest asphalt flushing potential. This

phenomenon is associated with the increased resistance to wear and decreased absorption of emulsified asphalt of coarser particles.

5. Emulsified asphalt content has also shown significant effect on mix performance. The reduction in wear loss is observed with higher emulsion content due to the increase in the aggregate binding characteristics. On the other hand, the increase in flushing potential is noted for mixes with a higher emulsion content due to the increase in excess asphalt, which leads to flushing. Therefore, optimization of emulsified asphalt content is mandatory for the proper mix design in order to reduce both the wear loss and flushing potential of slurry seal and micro surfacing mixes.
6. Treatments with cement and lime have generally resulted in an improved resistance to both wear loss and flushing potential. This was due to the improvement in bonding characteristics between aggregates and increased stiffness of the asphalt itself. In general, the cement treatment has shown better improvement in mix performance as compared to lime treatment.
7. Models were developed for the prediction of test parameters, i.e., consistency, set time, traffic time, final torque, wear loss, and sand adhesion. These models have adequate coefficient of determination (R^2 values ranging between 0.69 and 0.908, which is quite adequate) and high levels of significance (P-levels ranging between 0 and 4.54×10^{-13}).

8. Mix design parameters models were also generated in order to come up with the optimum percentages of water for the desired consistency and optimum emulsified asphalt content conforming to the design limits of both wear loss and sand adhesion values. These models were tested and validated for adequacy.
9. Economical analysis of slurry seal and micro surfacing mixes has revealed that the blending of steel slag aggregate with limestone can significantly reduce the life cycle costs.
10. The over-all optimum aggregate blend in terms of giving simultaneously lower abrasion loss, lower sand adhesion values, and lower life cycle costs was identified as **30%LS** (30% Limestone and 70% Steel Slag Aggregates by weight).

7.2 Recommendations

The primary objective of this study was to optimize the performances of slurry seal and micro surfacing mixes utilizing steel slag aggregates. For this purpose, laboratory test procedures were employed throughout this research program. The actual field performance evaluation with trial sections is however recommended as a follow-up of this study before any full-scale construction. For this purpose, aggregate blend 30%LS (optimum blend) can be selected and the required aggregate gradation (i.e., ISSA Type I, II, or III) can be determined through field surveys for a given functionally deteriorated pavement. The type of emulsified asphalt can also be selected according to available resources (polymer modified emulsions are recommended for improved performance). The models that were developed in this study can be used to determine the approximate required water and emulsion contents. However, at least three percentages of emulsion content (optimum obtained from models, and ± 1%) should be tested in the laboratory in order to develop and study the performance trends.

The wet cohesion test needs to be revised. Either the sample curing and wet cohesion test should be performed in fresh air to simulate actual field conditions or the specification limits should be adjusted for laboratory conditions.

In practice, the slurry seal and micro surfacing layers are normally compacted after laying down. However, the ISSA does not specify any compaction of the test specimen in the laboratory. This means that the laboratory test specimens do not essentially reflect the properties of the field slurry seal and micro surfacing layers. Therefore, laboratory compaction effects should be studied on the slurry seal and micro surfacing mix performances.

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APPENDICES

APPENDIX A

Model Fitting Results and Probability Plots for the Test Parameters Modeling

Table A1: Regression Summary for Dependent Variable: “CONSISTENCY” For All Mixes

R= .87475252 R^2= .76519197 Adjusted R^2= .76022249

F(4,189)=153.98 p<0.0000 Std.Error of estimate: 3.0172

	BETA	St. Err. of BETA	B	St. Err. of B	t(189)	p-level
Intercpt			-36.893	2.409123	-15.3139	5.97E-35
WATER	1.01864	0.043023	2.129508	0.089941	23.67672	0
GRAD	0.774553	0.058741	8.2646	0.626778	13.18586	1.41E-28
AGGT	0.575217	0.038707	2.66227	0.179145	14.86097	1.34E-33
EMLTYP	-0.21435	0.054576	-3.56248	0.90707	-3.92746	0.00012

Summary of Stepwise Regression; DV: CONST

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variables included
WATER	1	0.538946	0.290463	0.290463	78.59903	5.65E-16	1
GRAD	2	0.692287	0.479262	0.188799	69.24884	1.7E-14	2
AGGT	3	0.863729	0.746028	0.266767	199.5723	2.12E-31	3
EMLTYP	4	0.874753	0.765192	0.019164	15.42496	0.00012	4

Table A2: Analysis of Variance; DV: CONSTISTENCY

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	5606.937	4	1401.734	153.9782	0
Residual	1720.554	189	9.103459		
Total	7327.491				

Table A3: Correlation Matrix

	AGGT	GRAD	EMLTYP	WATER	CONST
AGGT	1	-0.01963	0.006078	-0.35984	0.19216
GRAD	-0.01963	1	0.761732	-0.43528	0.156591
EMLTYP	0.006078	0.761732	1	-0.30067	0.072881
WATER	-0.35984	-0.43528	-0.30067	1	0.538946
CONST	0.19216	0.156591	0.072881	0.538946	1

Table A4: Regression Summary for Dependent Variable: "SET-TIME" For All Mixes

R= .84708103 R^2= .71754627 Adjusted R^2= .71203498

F(4,205)=130.20 p<0.0000 Std.Error of estimate: .32566

	BETA	St. Err. of BETA	B	St. Err. of B	t(205)	p-level
Intercpt			5.510486	0.231612	23.79185	0
EMLTYP	-0.72402	0.052494	-1.49722	0.108555	-13.7923	4.79E-31
EMLP%	0.33064	0.037119	0.137054	0.015386	8.907558	2.84E-16
GRADT	-0.07504	0.052494	-0.10972	0.07676	-1.42942	0.154405
AGGT	-0.03952	0.037119	-0.02393	0.022473	-1.06477	0.288233

Summary of Stepwise Regression; DV: SET (torque1.sta)

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
EMLTYP	1	0.777075	0.603846	0.603846	317.0485	1.75E-43	1
EMLP%	2	0.844493	0.713169	0.109323	78.896	3.34E-16	2
GRADT	3	0.846158	0.715984	0.002815	2.041919	0.154538	3
AGGT	4	0.847081	0.717546	0.001562	1.133735	0.288233	4

Table A5: Analysis of Variance; DV: SET-TIME

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	55.2329	4	13.80822	130.1956	0
Residual	21.74179	205	0.106058		
Total	76.97469				

Table A6: Correlation Matrix

	AGGT	GRADT	EMLP%	EMLTYP	SET
AGGT	1	3.6E-16	2.19E-16	1.73E-16	-0.03952
GRADT	3.6E-16	1	6.88E-16	0.707107	-0.58699
EMLP%	2.19E-16	6.88E-16	1	4.39E-16	0.33064
EMLTYP	1.73E-16	0.707107	4.39E-16	1	-0.77708
SET	-0.03952	-0.58699	0.33064	-0.77708	1

Table A7: Regression Summary for Dependent Variable: "TRAFFIC TIME" For All Mixes

R= .83308865 R²= .69403670 Adjusted R²= .67094513
F(4,53)=30.056 p<.00000 Std.Error of estimate: 1.0205

	BETA	St. Err. of BETA	B	St. Err. of B	t(53)	p-level
Intercpt			14.86445	0.954731	15.56926	2.02E-21
GRADT	-0.54711	0.098318	-1.53508	0.275862	-5.56467	8.84E-07
AGGT	-0.31073	0.077745	-0.33562	0.083973	-3.99676	0.0002
EMLTYP	-0.34627	0.098737	-1.25854	0.358869	-3.50696	0.000932
EMLP%	0.155233	0.076181	0.110096	0.05403	2.037697	0.046586

Summary of Stepwise Regression; DV: TRAFFIC (torque1.sta)

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
GRADT	1	0.722678	0.522263	0.522263	61.21932	2.14E-10	1
AGGT	2	0.773657	0.598545	0.076282	10.4507	0.002111	2
EMLTYP	3	0.818576	0.670066	0.071522	11.70592	0.001207	3
EMLP%	4	0.833089	0.694037	0.02397	4.152211	0.046586	4

Table A8: Analysis of Variance; DV: TRAFFIC TIME

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	125.1968	4	31.2992	30.05585	4.55E-13
Residual	55.19251	53	1.041368		
Total	180.3893				

Table A9: Correlation Matrix

	AGGT	GRADT	EMLP%	EMLTYP	TRAFFIC
AGGT	1	-0.1738	-0.00586	-0.20262	-0.14639
GRADT	-0.1738	1	-0.06999	0.631611	-0.72268
EMLP%	-0.00586	-0.06999	1	-0.0473	0.211727
EMLTYP	-0.20262	0.631611	-0.0473	1	-0.63621
TRAFFIC	-0.14639	-0.72268	0.211727	-0.63621	1

Table A10: Regression Summary for Dependent Variable: "FINAL TORQ" For All Mixes

R= .89082175 R²= .79356339 Adjusted R²= .78123881

F(4,67)=64.389 p<.00000 Std.Error of estimate: 2.4689

	BETA	St. Err. of BETA	B	St. Err. of B	t(67)	p-level
Intercpt			4.734444	1.77167	2.672306	0.00945
GRADT	0.635509	0.0785	4.711111	0.581932	8.095637	1.62E-11
AGGT	0.392672	0.055508	1.205238	0.170372	7.074145	1.12E-09
EMLTYP	0.20402	0.0785	2.138889	0.822976	2.598968	0.01149
EMLP%	0.102538	0.055508	0.215476	0.116646	1.847267	0.069124

Summary of Stepwise Regression; DV: TORQ (torque1.sta)

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
GRADT	1	0.779773	0.608046	0.608046	108.5924	1.18E-15	1
AGGT	2	0.873062	0.762237	0.154191	44.74713	5.43E-09	2
EMLTYP	3	0.884901	0.783049	0.020812	6.523214	0.012928	3
EMLP%	4	0.890822	0.793563	0.010514	3.412396	0.069124	4

Table A11: Analysis of Variance; DV:FINAL TORQ

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	1569.954	4	392.4884	64.38871	3.06E-22
Residual	408.4058	67	6.095609		
Total	1978.359				

Table A12: Correlation Matrix

	AGGT	GRADT	EMLP%	EMLTYP	TORQ
AGGT	1	1.46E-16	-1.7E-17	5.42E-17	0.392672
GRADT	1.46E-16	1	-1.4E-17	0.707107	0.779773
EMLP%	-1.7E-17	-1.4E-17	1	2.47E-17	0.102538
EMLTYP	5.42E-17	0.707107	2.47E-17	1	0.653393
TORQ	0.392672	0.779773	0.102538	0.653393	1

Table A13: Regression Summary for Dependent Variable: "WTAT" For All Mixes

R= .95299189 R^2= .90819354 Adjusted R^2= .90600767

F(5,210)=415.48 p<0.0000 Std.Error of estimate: 146.12

	BETA	St. Err. of BETA	B	St. Err. of B	t(210)	p-level
Intercpt			2952.255	65.25358	45.2428	0
EMLTYP	-0.55084	0.029569	-523.87	28.12139	-18.6289	0
AGGT	-0.35863	0.020909	-99.8556	5.82168	-17.1524	8.23E-42
GRAD	-0.35672	0.029569	-239.889	19.88482	-12.0639	8.34E-26
EML%	-0.23519	0.020909	-44.8338	3.985832	-11.2483	2.79E-23
TREAT	-0.12526	0.020909	-72.9514	12.17692	-5.99096	8.95E-09

Summary of Stepwise Regression; DV: WTATT (wtat22222.sta)

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
EMLTYP	1	0.803085	0.644946	0.644946	388.7256	0	1
AGGT	2	0.879525	0.773564	0.128618	120.9863	1.62E-22	2
GRAD	3	0.914981	0.83719	0.063625	82.84849	7E-17	3
EML%	4	0.944724	0.892503	0.055313	108.5707	9.26E-21	4
TREAT	5	0.952992	0.908194	0.015691	35.89157	8.95E-09	5

Table A14: Analysis of Variance; DV: WTAT

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	44356948	5	8871390	415.4842	0
Residual	4483906	210	21351.93		
Total	48840854				

Table A15: Correlation Matrix

	AGGT	GRAD	TREAT	EML%	EMLTYP	WTAT
AGGT	1	-3.8E-16	2.48E-16	2.45E-16	-7.6E-16	-0.35863
GRAD	-3.8E-16	1	2.34E-17	2.76E-16	0.707107	-0.74623
TREAT	2.48E-16	2.34E-17	1	7.88E-17	1.94E-17	-0.12526
EML%	2.45E-16	2.76E-16	7.88E-17	1	3.91E-16	-0.23519
EMLTYP	-7.6E-16	0.707107	1.94E-17	3.91E-16	1	-0.80309
WTAT	-0.35863	-0.74623	-0.12526	-0.23519	-0.80309	1

Table A16: Regression Summary for Dependent Variable: “LWT” For All Mixes

R= .90532043 R^2= .81960508 Adjusted R^2= .81442132

F(5,174)=158.11 p<0.0000 Std.Error of estimate: 59.516

	BETA	St. Err. of BETA	B	St. Err. of B	t(174)	p-level
Intercpt			100.6433	28.0091	3.593237	0.000425
AGGT	0.678388	0.032199	54.72571	2.597471	21.06884	0
EMLS%	0.394053	0.032199	18.0963	1.478676	12.23818	3.04E-25
EMLTYP	-0.41357	0.034076	-116.306	9.582913	-12.1368	5.94E-25
GRADT	0.315342	0.034076	58.05556	6.273489	9.25411	7.85E-17
TREAT	-0.13789	0.032199	-23.2667	5.433001	-4.28247	3.05E-05

Summary of Stepwise Regression; DV: LWT (lwt.sta)

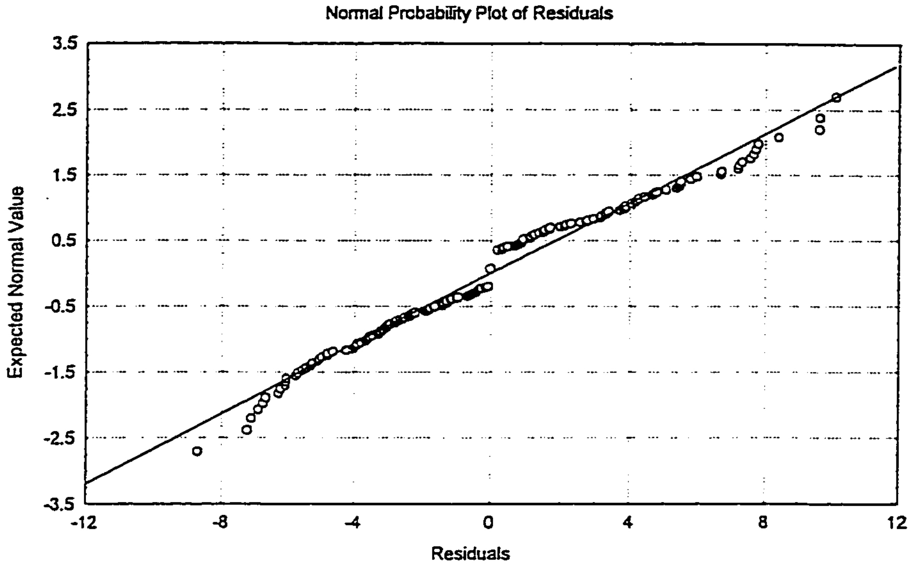
	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
AGGT	1	0.678388	0.46021	0.46021	151.7581	1.78E-25	1
EMLS%	2	0.78453	0.615488	0.155278	71.47794	1.1E-14	2
EMLTYP	3	0.843686	0.711806	0.096318	58.821	1.17E-12	3
GRADT	4	0.894758	0.800592	0.088786	77.91817	1.12E-15	4
TREAT	5	0.90532	0.819605	0.019014	18.33956	3.05E-05	5

Table A17: Analysis of Variance; DV: LWT

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	2800208	5	560041.7	158.1101	0
Residual	616325.3	174	3542.1		
Total	3416534				

Table A18: Correlation Matrix

	AGGT	GRADT	TREAT	EMLS%	EMLTYP	LWT
AGGT	1	1.31E-15	3.07E-16	2.92E-18	-2.1E-16	0.678388
GRADT	1.31E-15	1	1.35E-16	-3.5E-18	0.327327	0.179969
TREAT	3.07E-16	1.35E-16	1	1.66E-17	2.56E-17	-0.13789
EMLS%	2.92E-18	-3.5E-18	1.66E-17	1	4.2E-18	0.394053
EMLTYP	-2.1E-16	0.327327	2.56E-17	4.2E-18	1	-0.31035
LWT	0.678388	0.179969	-0.13789	0.394053	-0.31035	1



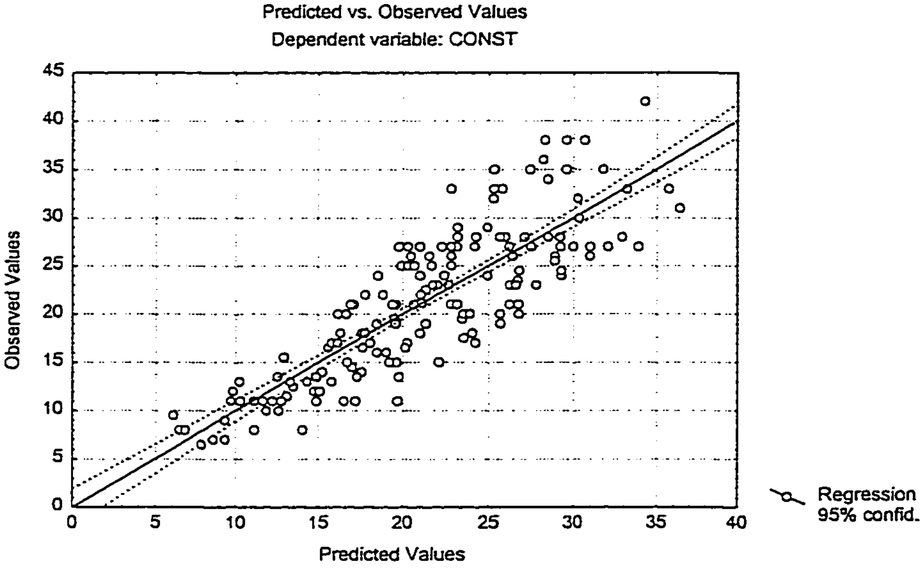
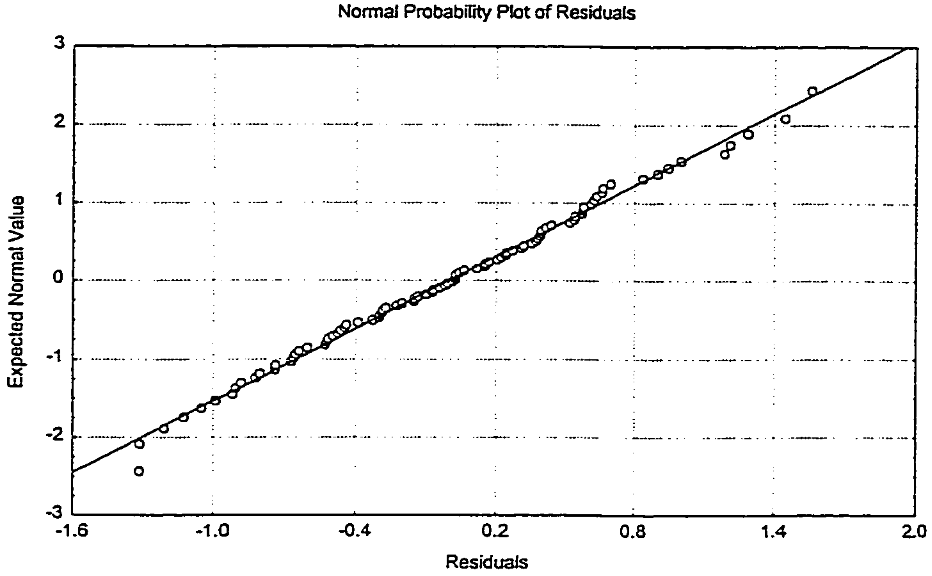


Figure A1: Probability Plots of Residuals and Predicted Values For Consistency Model



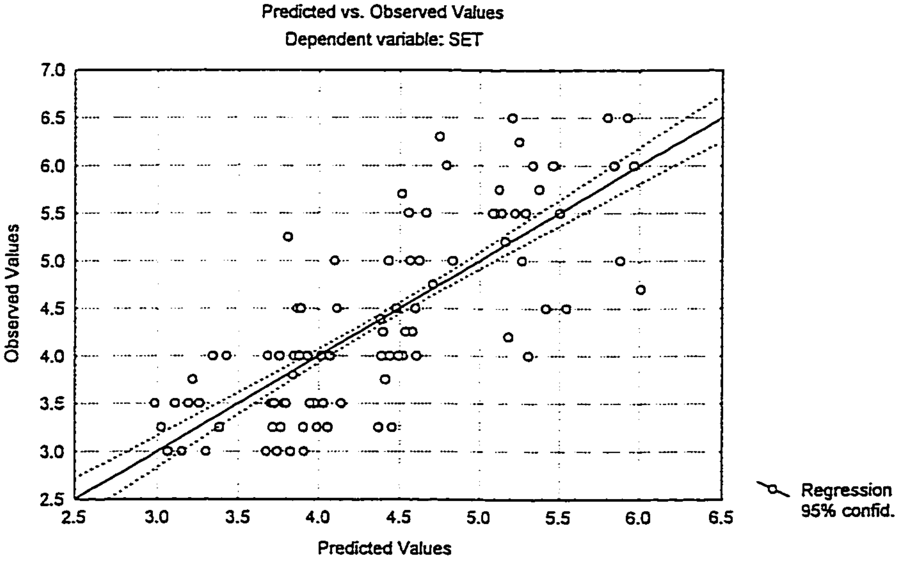


Figure A2: Probability Plots of Residuals and Predicted Values For Set Model

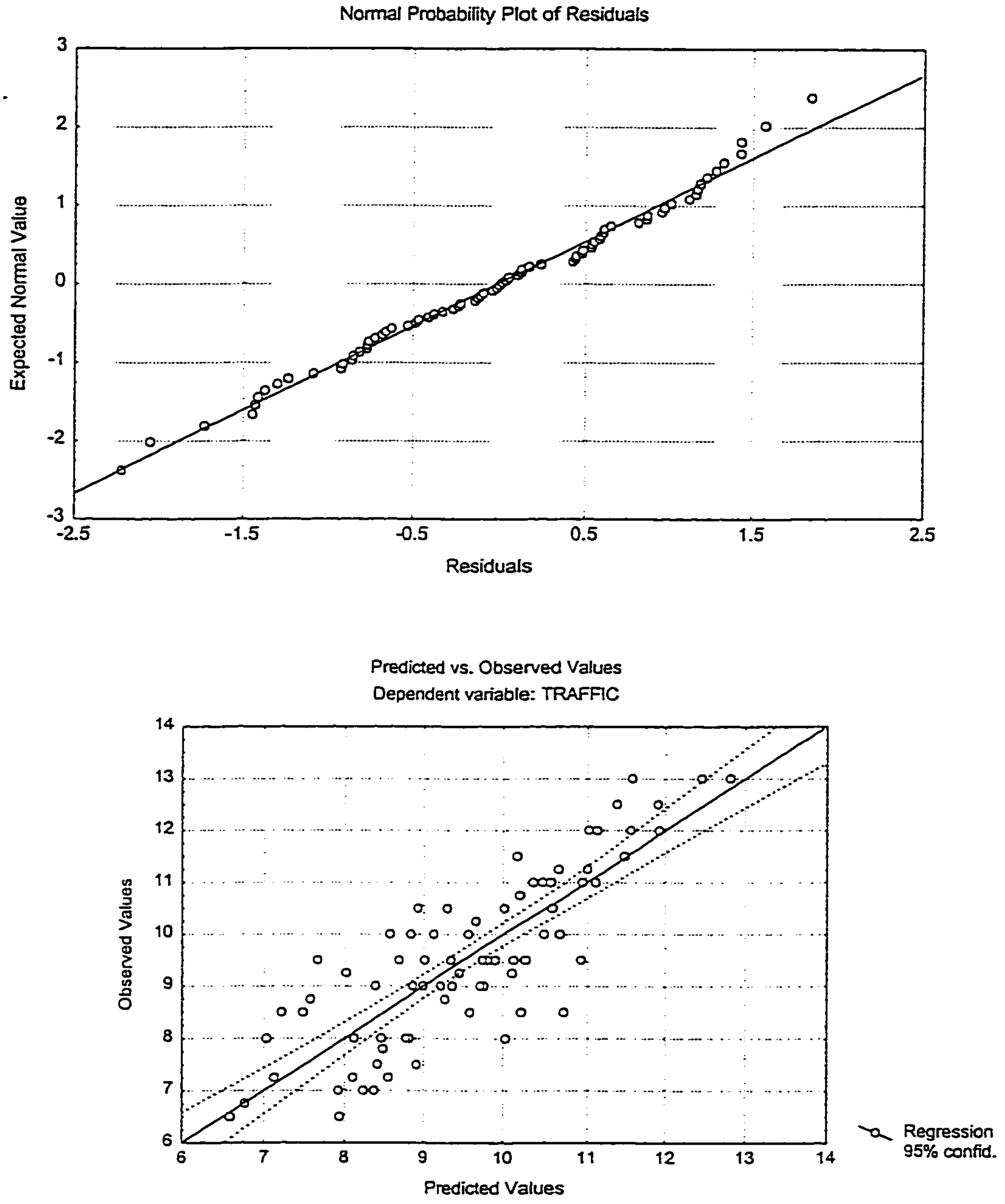


Figure A3: Probability Plots of Residuals and Predicted Values For Traffic Model

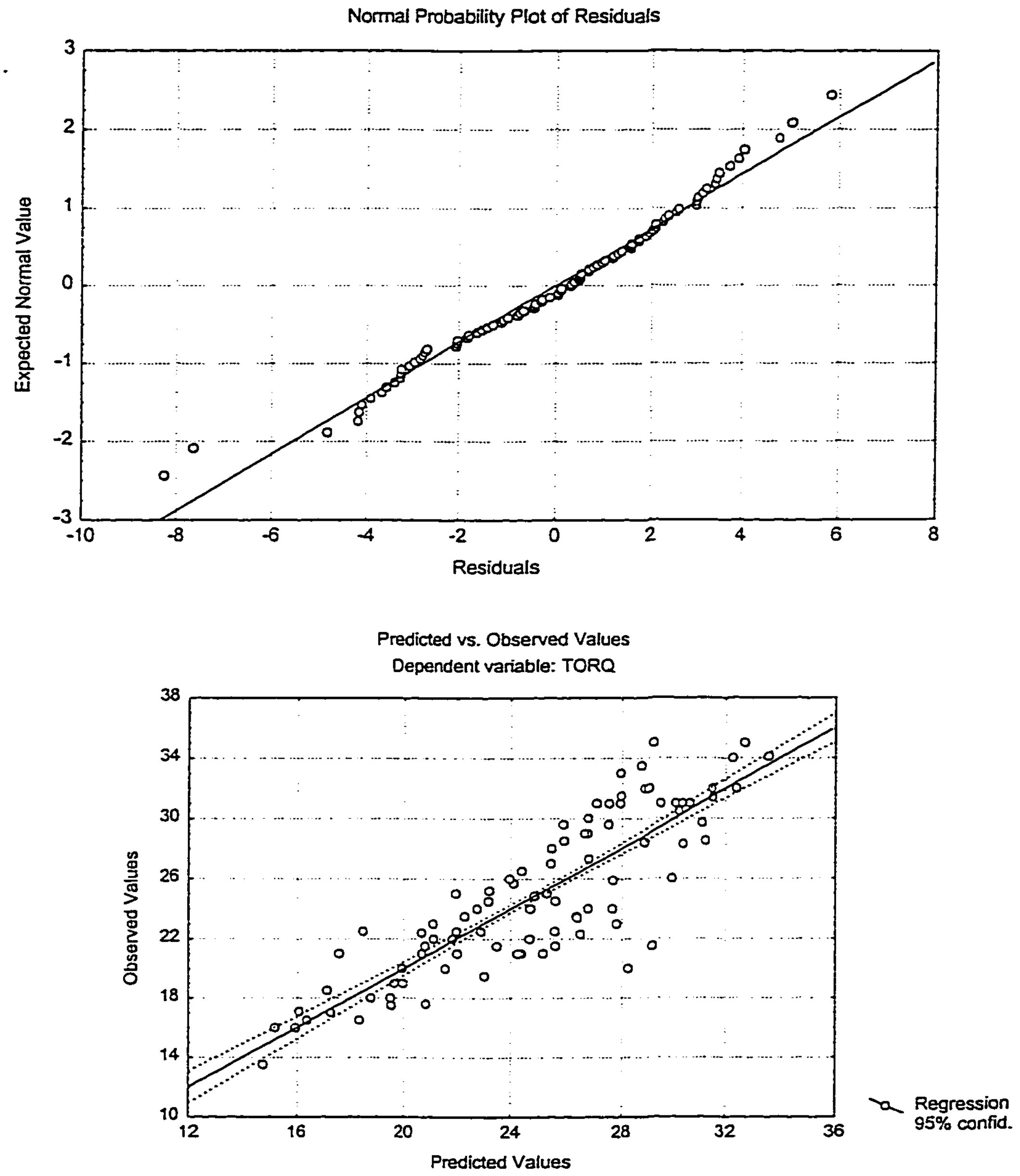


Figure A4: Probability Plots of Residuals and Predicted Values For Torque Model

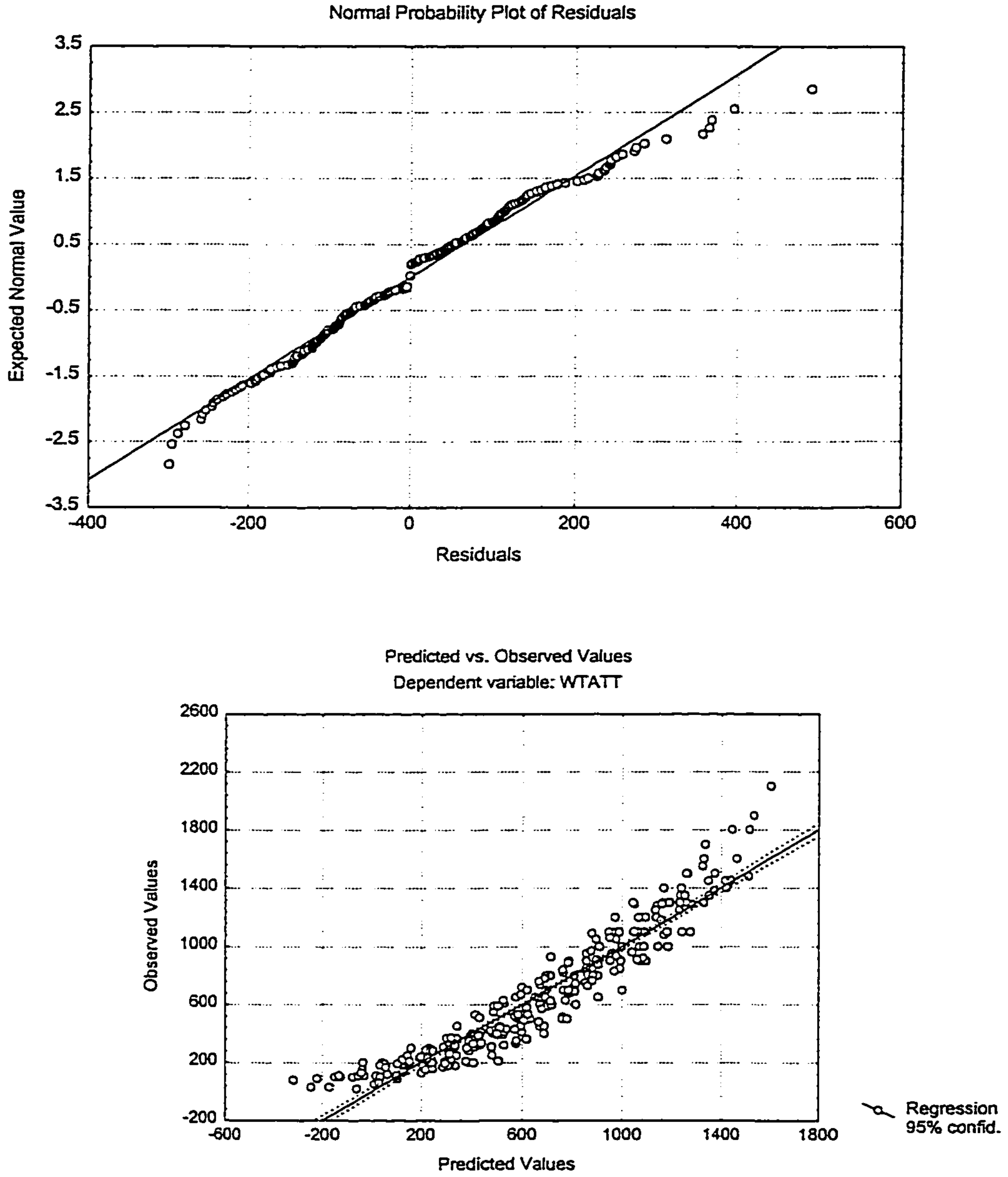


Figure A5: Probability Plots of Residuals and Predicted Values For WTAT Model

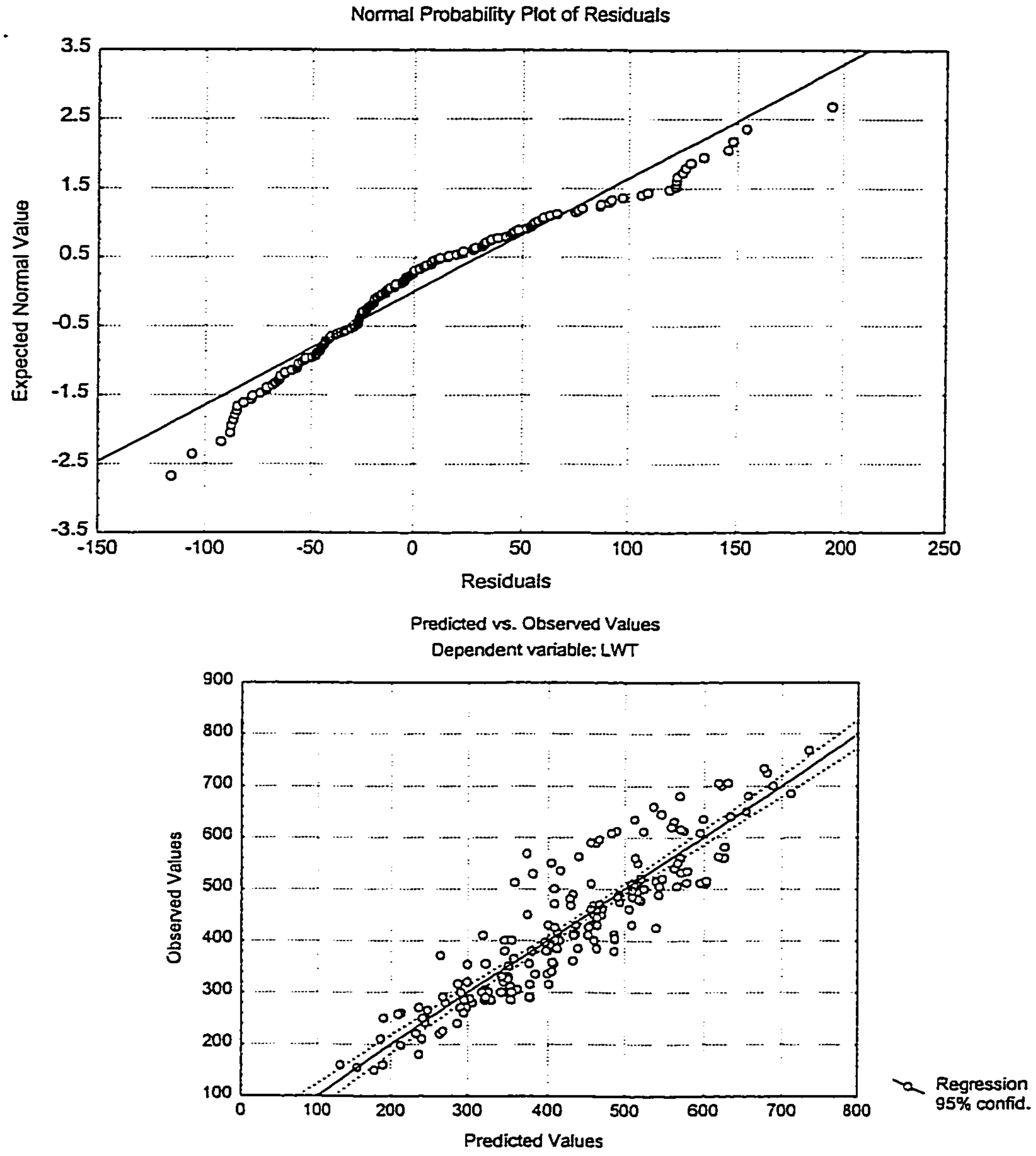


Figure A6: Probability Plots of Residuals and Predicted Values for LWT Model

APPENDIX B

Model Fitting Results and Probability Plots for the Mix Design Parameters Modeling

Table B1: Regression Summary for Dependent Variable: "WATER CONTENT" For All Mixes Linear

R= .90294985 R^2= .81531843 Adjusted R^2= .81025866

F(4,187)=194.41 p<0.0000 Std.Error of estimate: 1.4989

	BETA	St. Err. of BETA	B	St. Err. of B	t(187)	p-level
Intercpt			19.36963	0.593066	32.66017	0
GRAD	-0.70773	0.039019	-3.14746	0.173529	-18.1379	3.15E-39
CONST	0.680301	0.037471	0.320715	0.017665	18.15538	2.85E-39
AGGT	-0.49165	0.03613	-1.04995	0.077156	-13.6081	9.46E-28
EMLTYP	0.112225	0.03777	0.92919	0.312729	2.971233	0.00347

Summary of Stepwise Regression; DV: WATER

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
GRAD	1	0.504057	0.254074	0.254074	50.75166	4.44E-11	1
CONST	2	0.755054	0.570107	0.316033	108.8011	2.21E-19	2
AGGT	3	0.896745	0.804151	0.234045	175.669	8.03E-27	3
EMLTYP	4	0.90295	0.815318	0.011167	8.828226	0.00347	4

Table B2: Analysis of Variance; DV: WATER CONTENT

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	1747.009	4	436.7523	194.4051	0
Residual	420.116	187	2.24661		
Total	2167.125				

Table B3: Correlation Matrix

	AGGT	GRAD	EMLTYP	CONST	WATER
AGGT	1	0.006634	-0.00644	0.162396	-0.37597
GRAD	0.006634	1	0.326915	0.238646	-0.50536
EMLTYP	-0.00644	0.326915	1	-0.01517	-0.12793
CONST	0.162396	0.238646	-0.01517	1	0.426484
WATER	-0.37597	-0.50536	-0.12793	0.426484	1

Table B4: Regression Summary for Dependent Variable: "LN-WATER CONTENT" For All Mixes Transformed

R= .91910866 R^2= .84476074 Adjusted R^2= .84147525
F(4,148)=190.35 p<0.0000 Std.Error of estimate: .08969

	BETA	St. Err. of BETA	B	St. Err. of B	t(148)	p-level
Intercpt			2.274159	0.0486	46.79314	0
GRAD	-0.72289	0.031635	-0.18748	0.008204	-22.8509	0
LN-CONST	0.69932	0.030358	0.364046	0.015804	23.03559	0
AGGT	-0.50981	0.029093	-0.06349	0.003623	-17.5233	1.83E-41
EMLTYP	0.117694	0.030481	0.056827	0.014717	3.861201	0.000155

Summary of Stepwise Regression; DV: LN_WATER

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
GRAD	1	0.501006	0.251007	0.251007	64.34413	1.07E-13	1
LN-CONST	2	0.762062	0.580738	0.329732	150.2135	8.57E-26	2
AGGT	3	0.912423	0.832515	0.251777	285.6229	1.21E-39	3
EMLTYP	4	0.919109	0.844761	0.012246	14.90888	0.000155	4

Table B5: Analysis of Variance; DV: LN-WATER CONTENT

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	6.125258	4	1.531315	190.3526	0
Residual	1.190604	148	0.008045		
Total	7.315862				

Table B6: Correlation Matrix

	AGGT	GRAD	EMLTYP	LN-CONST	LN-WATER
AGGT	1	0.006634	-0.00644	0.159437	-0.39364
GRAD	0.006634	1	0.326915	0.254923	-0.5033
EMLTYP	-0.00644	0.326915	1	-0.02226	-0.13122
LN-CONST	0.159437	0.254923	-0.02226	1	0.428454
LN-WATER	-0.39364	-0.5033	-0.13122	0.428454	1

Table B7: Regression Summary for Dependent Variable: “EML%” For Slurry Seal Mixes Linear Model

R= .91348408 R^2= .83445316 Adjusted R^2= .82644283
F(3,62)=104.88 p<.00000 Std.Error of estimate: 2.0835

	BETA	St. Err. of BETA	B	St. Err. of B	t(62)	p-level
Intercpt			32.40673	1.174097	27.60142	1.56E-36
GRADT	-0.73714	0.051705	-4.97369	0.348866	-14.2567	3.09E-21
AGGT	-0.47946	0.051705	-1.55639	0.167841	-9.27302	2.54E-13
TREAT	-0.29318	0.051673	-1.95	0.343683	-5.67383	3.93E-07

Summary of Stepwise Regression; DV: EMLFINL

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
GRADT	1	0.720344	0.518896	0.518896	69.02741	1.16E-11	1
AGGT	2	0.865157	0.748496	0.2296	57.51316	2.09E-10	2
TREAT	3	0.913484	0.834453	0.085957	32.19237	3.93E-07	3

Table B8: Analysis of Variance; DV: EML%

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	1328.898	3	442.9659	104.1721	3.56E-24
Residual	263.6395	62	4.25225		
Total	1592.537				

Table B9: Correlation Matrix

	AGGT	GRADT	TREAT	EML%
AGGT	1	7.48E-18	1.42E-16	-0.47097
GRADT	7.48E-18	1	4.29E-17	-0.72791
TREAT	1.42E-16	4.29E-17	1	-0.28935
EML%	-0.47097	-0.72791	-0.28935	1

Table B10: Regression Summary for Dependent Variable: "EML%" For Micro Surfacing Mixes Linear Model

R= .79737069 R^2= .63580002 Adjusted R^2= .60458288
F(3,35)=20.420 p<.00000 Std.Error of estimate: .60536

	BETA	St. Err. of BETA	B	St. Err. of B	t(35)	p-level
Intercpt			10.55707	0.619423	17.04338	1.59E-18
TREAT	-0.56871	0.10213	-0.69642	0.125065	-5.5685	2.86E-06
AGGT	-0.50228	0.102097	-0.29092	0.059133	-4.91967	2.04E-05
GRADT	-0.31527	0.102113	-0.62579	0.202687	-3.08744	0.003936

Summary of Stepwise Regression; DV: EMLFIN

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
TREAT	1	0.541316	0.293023	0.293023	15.33547	0.000398	1
AGGT	2	0.732537	0.53661	0.243587	18.92388	0.000112	2
GRADT	3	0.797371	0.6358	0.09919	9.532289	0.003936	3

Table B11: Analysis of Variance; DV: EML%

	Sums of Squares	Df	Mean Squares	F	p-level
Regress.	21.90122	3	7.300407	20.36702	8.22E-08
Residual	12.54549	35	0.358443		
Total	34.44671				

Table B12: Correlation Matrix

	AGGT	GRADT	TREAT	EML%
AGGT	1	-1.3E-15	1.79E-16	-0.48801
GRADT	-1.3E-15	1	-7E-17	-0.30026
TREAT	1.79E-16	-7E-17	1	-0.55505
EML%	-0.48801	-0.30026	-0.55505	1

Table B13: Regression Summary for Dependent Variable: "EML%" For Slurry Seal Mixes Transformed Model

R= .92368765 R^2= .85319888 Adjusted R^2= .84421106

F(3,50)=99.281 p<.00000 Std.Error of estimate: 2.1681

	BETA	St. Err. of BETA	B	St. Err. of B	t(50)	p-level
Intercpt			27.27669	1.035993	26.32904	1.41E-30
LN-GRAD	-0.73625	0.054752	-8.91789	0.663183	-13.4471	4.57E-18
LN-AGGT	-0.49295	0.054752	-4.48169	0.497779	-9.00336	5.83E-12
TREAT	-0.29318	0.054735	-1.95	0.364049	-5.35642	2.25E-06

Summary of Stepwise Regression; DV: EMLFINL

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
LN-GRAD	1	0.724147	0.524389	0.524389	56.23051	1.12E-09	1
LN-AGGT	2	0.875923	0.767242	0.242853	52.16841	3E-09	2
TREAT	3	0.923688	0.853199	0.085957	28.69121	2.25E-06	3

Table B14: Analysis of Variance; DV: EML%

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	1358.751	3	452.917	94.92831	2.02E-20
Residual	233.7862	49	4.771148		
Total	1592.537				

Table B15: Correlation Matrix

	AGGT	GRADT	TREAT	EML%	LN-AGGT	LN-GRAD	LN-TREAT
AGGT	1	1.12E-16	5.9E-17	-0.47097	0.967607	-9.6E-17	5.04E-17
GRADT	1.12E-16	1	9.57E-17	-0.72791	-8.9E-17	0.988764	1.97E-16
TREAT	5.9E-17	9.57E-17	1	-0.28935	6E-17	9.45E-17	0.988764
EML%	-0.47097	-0.72791	-0.28935	1	-0.48823	-0.73087	-0.28091
LN-AGGT	0.967607	-8.9E-17	6E-17	-0.48823	1	-1.7E-16	3.19E-17
LN-GRAD	-9.6E-17	0.988764	9.45E-17	-0.73087	-1.7E-16	1	1.74E-16
LN-TREAT	5.04E-17	1.97E-16	0.988764	-0.28091	3.19E-17	1.74E-16	1

Table B16: Regression Summary for Dependent Variable: "LN-EML%" For Micro Surfacing Mixes Transformed Model

R= .87173562 R^2= .75992299 Adjusted R^2= .73668973

F(3,32)=34.042 $p<.00000$ Std.Error of estimate: .06966

	BETA	St. Err. of BETA	B	St. Err. of B	t(32)	p-level
Intercpt			2.308329	0.060382	38.22885	1.2E-27
LN-TREAT	-0.61962	0.088085	-0.18419	0.026184	-7.03435	6.73E-08
LN-AGGT	-0.56427	0.088065	-0.12485	0.019486	-6.40738	3.87E-07
LN-GRAD	-0.31356	0.088078	-0.20787	0.058391	-3.56	0.00122

Summary of Stepwise Regression; DV: LN-V5

	Step +in/-out	Multiple R	Multiple R-square	R-square change	F - to entr/rem	p-level	Variabls included
LN-TREAT	1	0.593852	0.35266	0.35266	17.97786	0.000187	1
LN-AGGT	2	0.813494	0.661773	0.309113	29.24552	6.67E-06	2
LN-GRAD	3	0.871736	0.759923	0.09815	12.67362	0.00122	3

Table B17: Analysis of Variance; DV: LN-EMLFIN

	Sums of Squares	df	Mean Squares	F	p-level
Regress.	0.480045	3	0.160015	32.70841	9.95E-10
Residual	0.151657	31	0.004892		
Total	0.631702				

Table B18: Correlation Matrix

	AGGT	GRADT	TREAT	EML%	LN-AGGT	LN-GRAD	LN-TREAT
AGGT	1	9.01E-17	2.85E-17	-0.48801	0.967607	-5.8E-17	5.95E-17
GRADT	9.01E-17	1	7.77E-18	-0.30026	6.34E-17	1	2.06E-17
TREAT	2.85E-17	7.77E-18	1	-0.55505	4.82E-17	1.32E-17	0.988764
EML%	-0.48801	-0.30026	-0.55505	1	-0.54793	-0.30026	-0.57744
LN-AGGT	0.967607	6.34E-17	4.82E-17	-0.54793	1	-6.5E-17	4.13E-17
LN-GRAD	-5.8E-17	1	1.32E-17	-0.30026	-6.5E-17	1	-3.6E-18
LN-TREAT	5.95E-17	2.06E-17	0.988764	-0.57744	4.13E-17	-3.6E-18	1

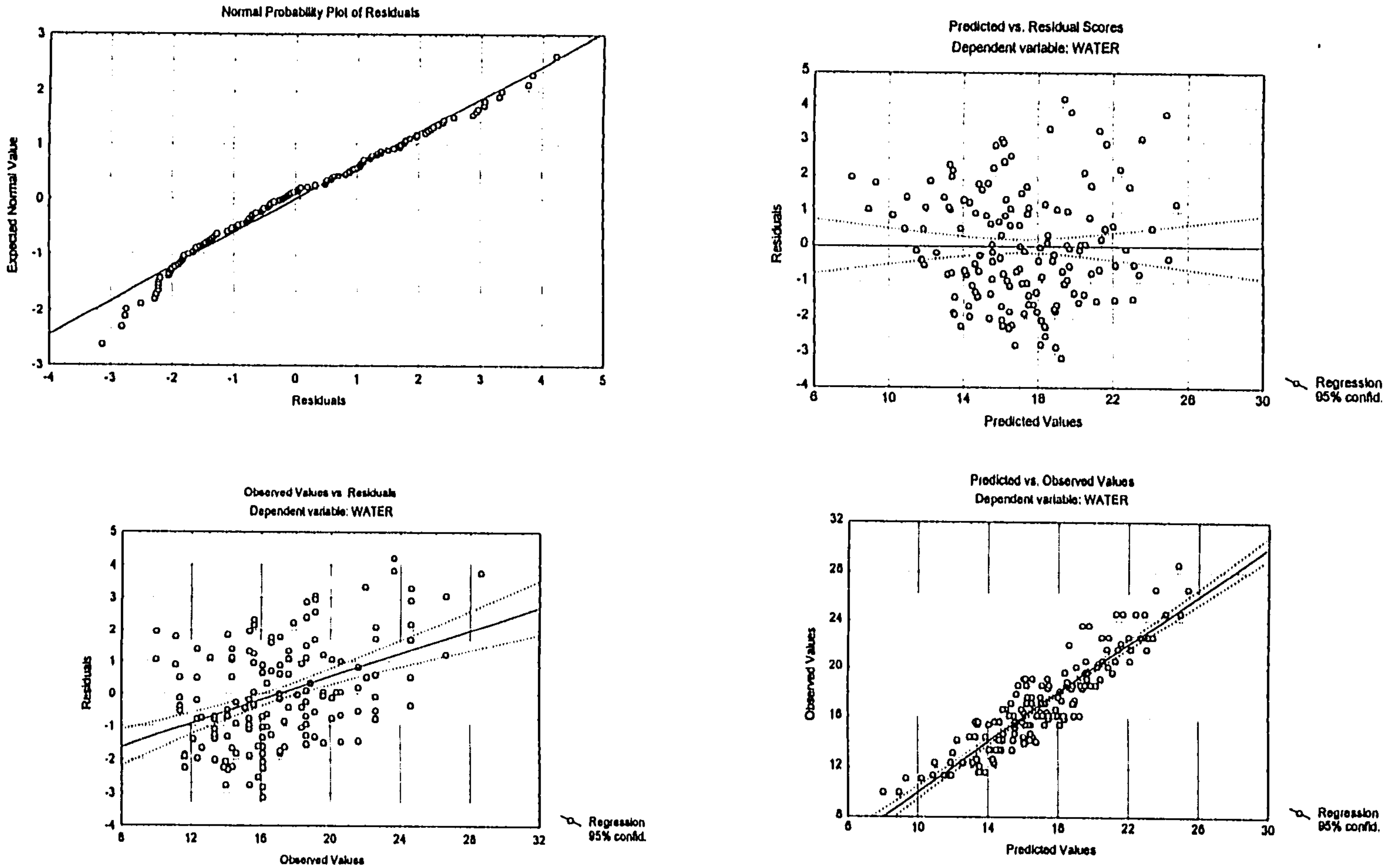


Figure B1: Probability Plots of Linear Models for Total Water Content of All Mixes

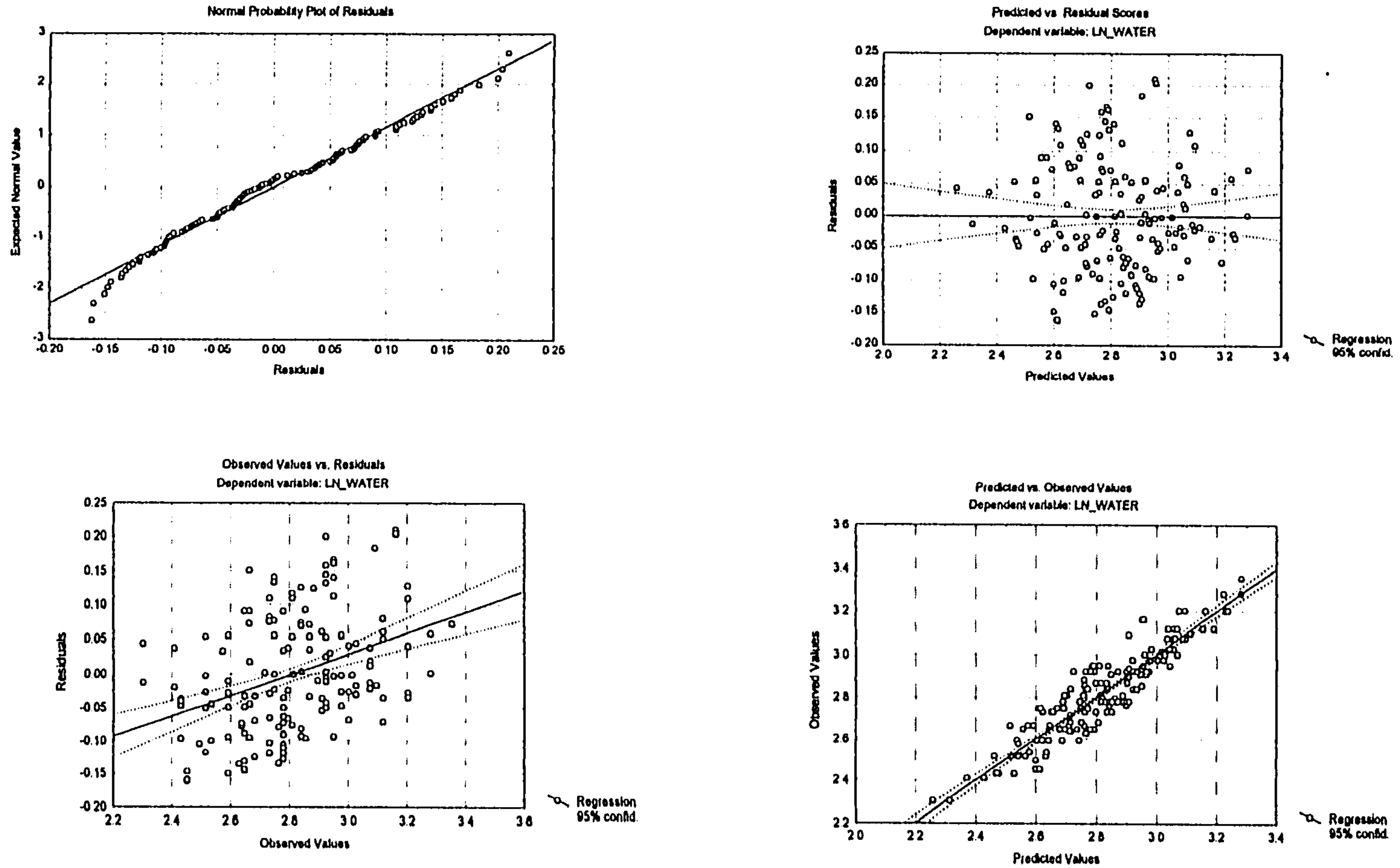


Figure B2: Probability Plots of Transformed Models for Total Water Content of All Mixes

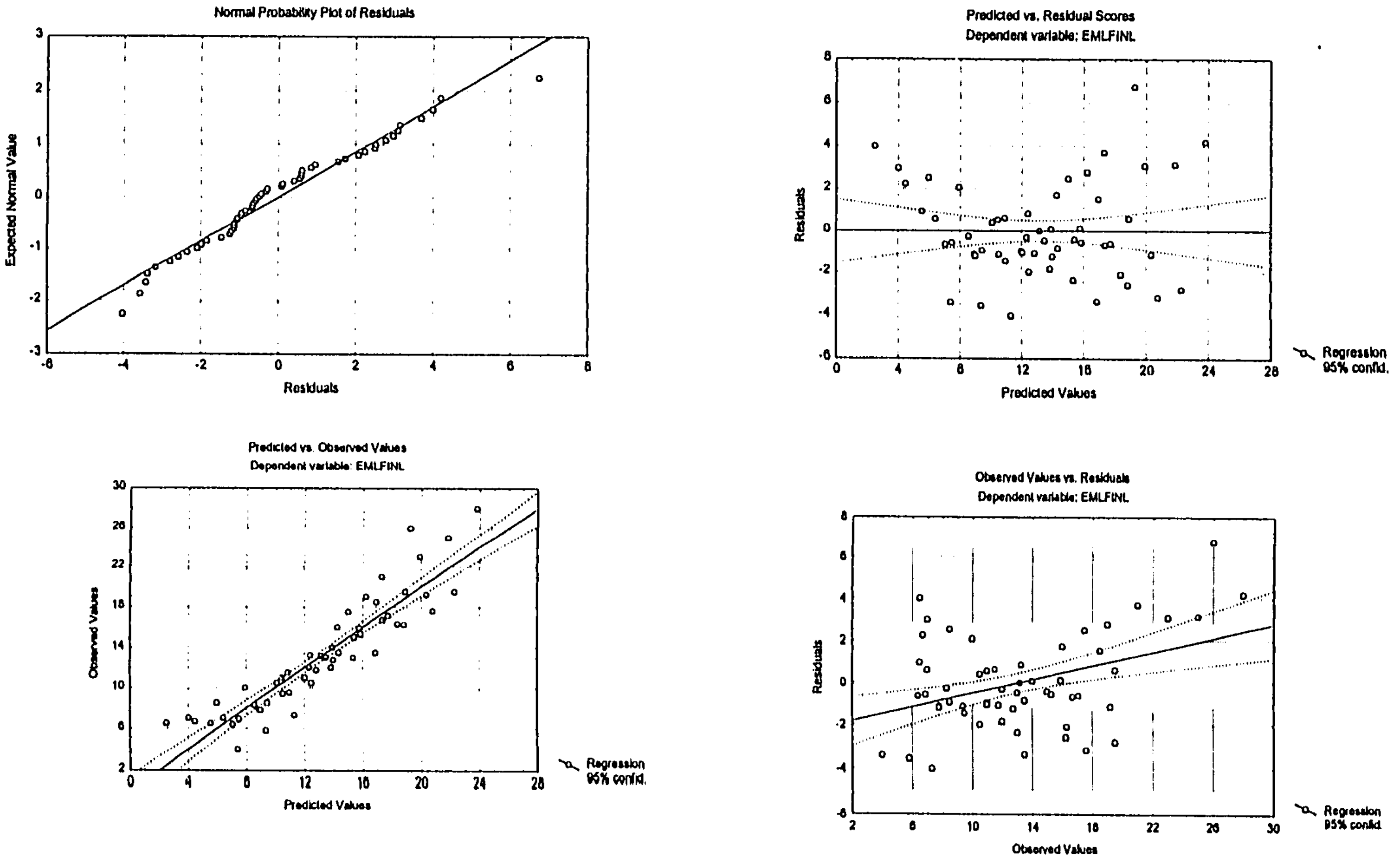


Figure B3: Probability Plots of Linear Models for Emulsified Asphalt Content of Slurry Seal Mixes

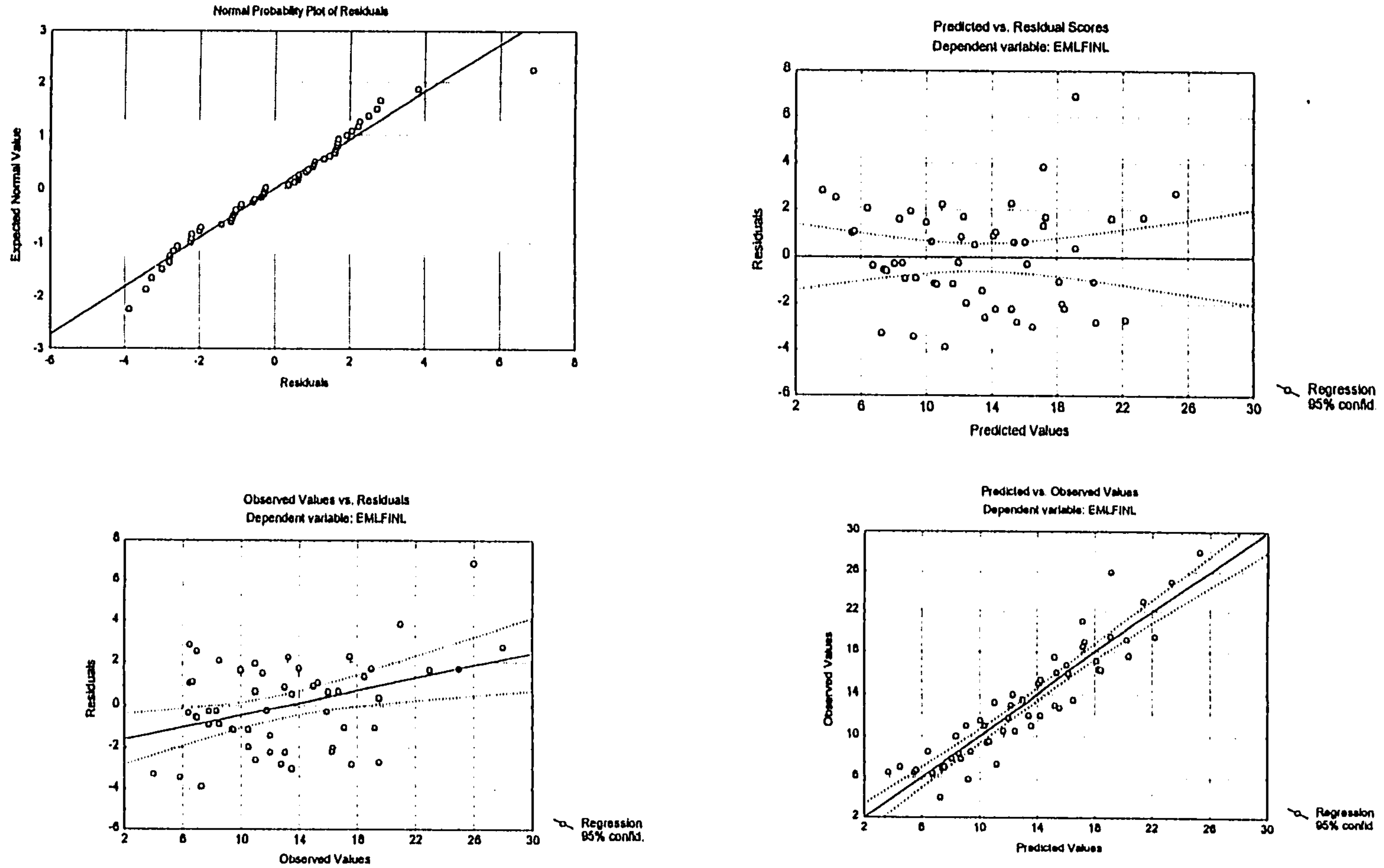


Figure B4: Probability Plots of Transformed Models for Emulsified Asphalt Content of Slurry Seal Mixes

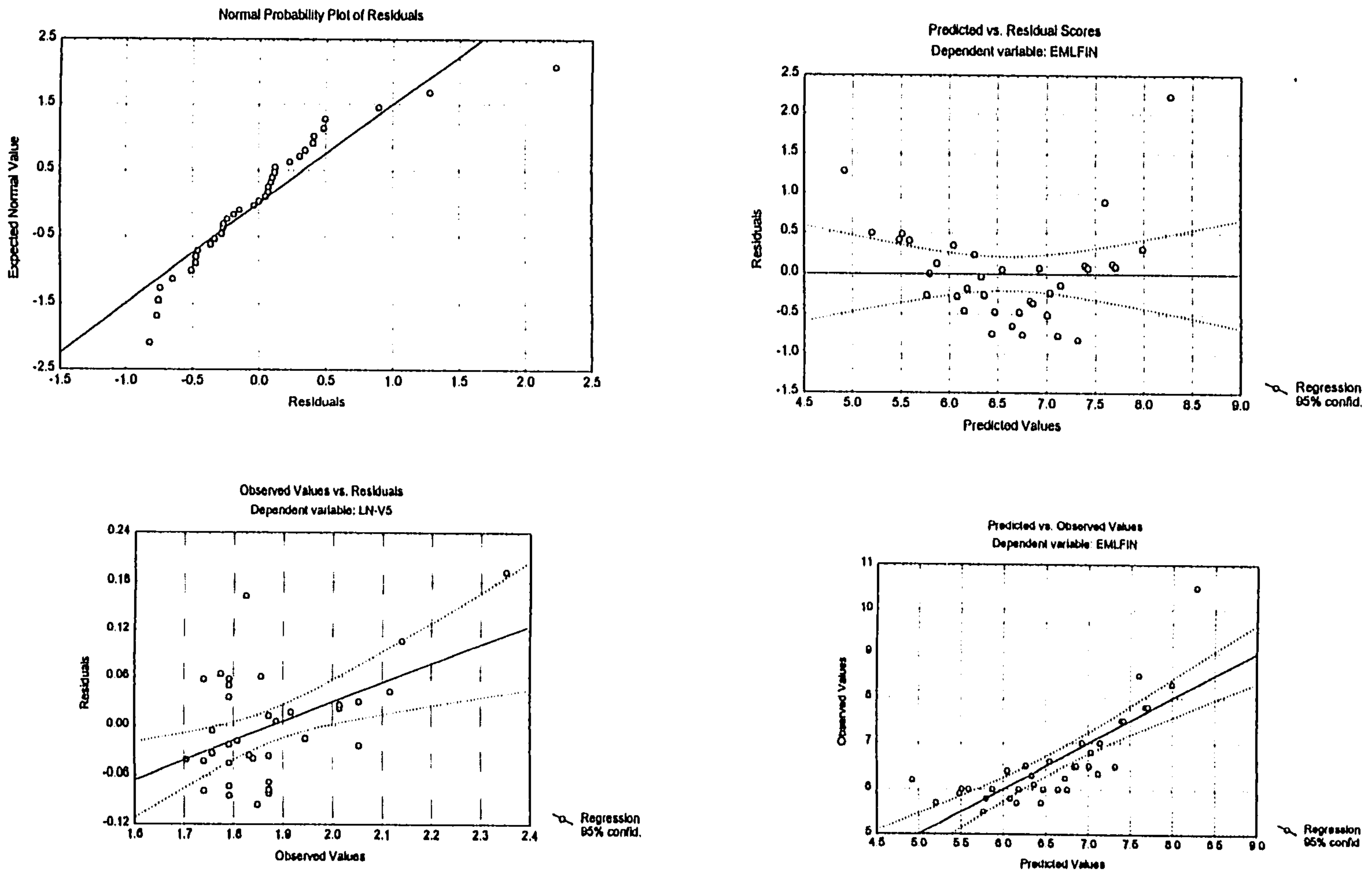


Figure B5: Probability Plots of Linear Models for Emulsified Asphalt Content of Micro Surfacing Mixes

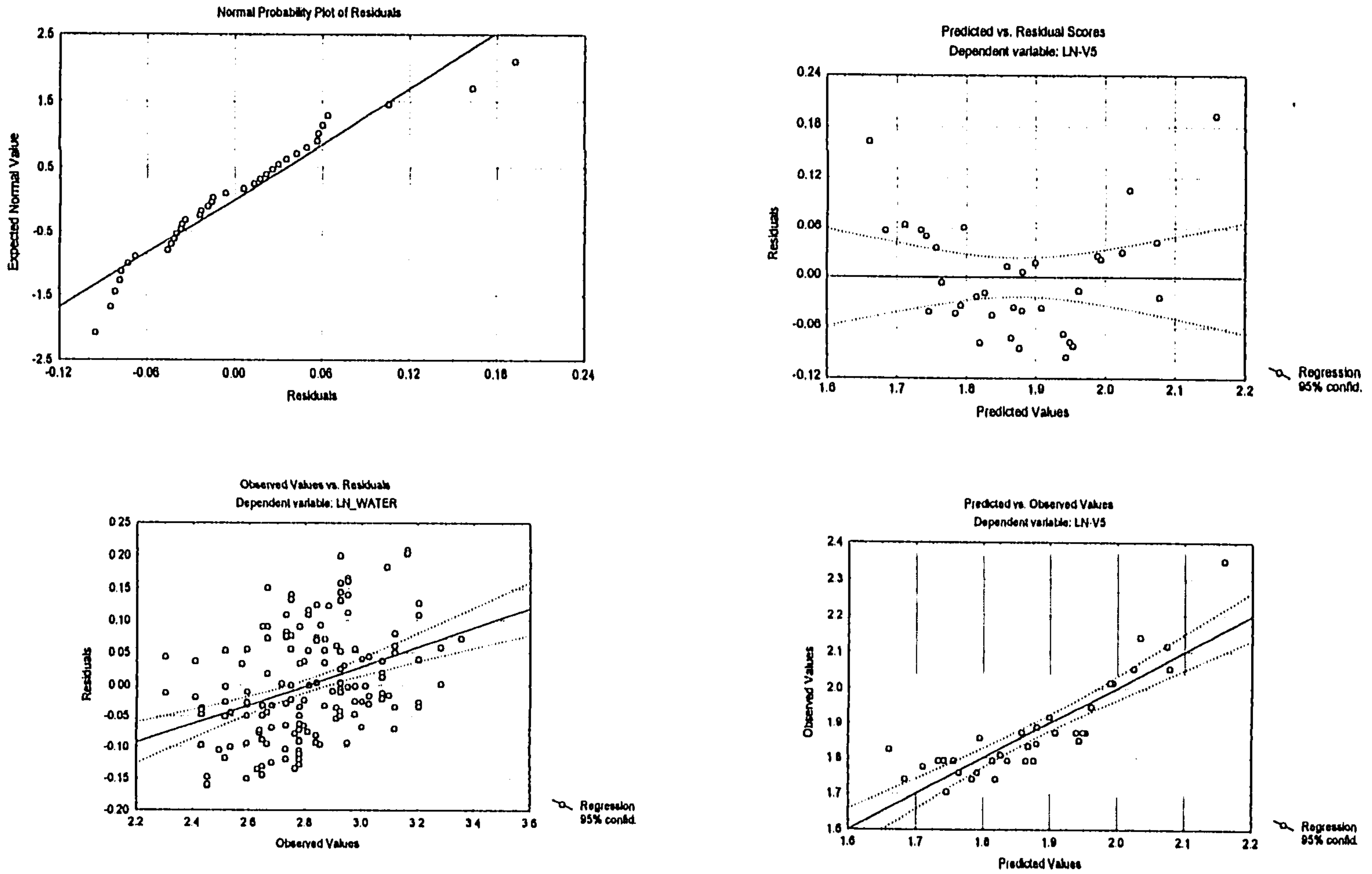


Figure B6: Probability Plots of Transformed Models for Emulsified Asphalt Content of Micro Surfacing Mixes

APPENDIX C

Calculation Sheets for Present Worth Economic Analysis of Slurry Seal and Micro Surfacing Mixes

Table C1: Calculation Sheet of Present Worth Method for Type I Slurry Seal Mixes

Year	LS	P8LS	P30LS	60%LS	30%LS	SS	P.W Factor	LS	P8LS	P30LS	60%LS	30%LS	SS
0	3.25	3.26	3.30	3.29	3.33	3.36	1	3.250	3.255	3.301	3.293	3.326	3.360
1	0.00	0.00	0.00	0.00	0.00	0.00	0.9615	0.000	0.000	0.000	0.000	0.000	0.000
2	0.00	0.00	0.00	0.00	0.00	0.00	0.9246	0.000	0.000	0.000	0.000	0.000	0.000
3	3.25	0.00	0.00	0.00	0.00	0.00	0.889	2.889	0.000	0.000	0.000	0.000	0.000
4	0.00	3.26	3.30	3.29	0.00	0.00	0.8548	0.000	2.783	2.822	2.815	0.000	0.000
5	0.00	0.00	0.00	0.00	3.33	0.00	0.8219	0.000	0.000	0.000	0.000	2.734	0.000
6	3.25	0.00	0.00	0.00	0.00	3.36	0.7903	2.568	0.000	0.000	0.000	0.000	2.655
7	0.00	0.00	0.00	0.00	0.00	0.00	0.7599	0.000	0.000	0.000	0.000	0.000	0.000
8	0.00	3.26	3.30	3.29	0.00	0.00	0.7307	0.000	2.379	2.412	2.406	0.000	0.000
9	3.25	0.00	0.00	0.00	0.00	0.00	0.7026	2.283	0.000	0.000	0.000	0.000	0.000
10	0.00	0.00	0.00	0.00	3.33	0.00	0.6756	0.000	0.000	0.000	0.000	2.247	0.000
11	0.00	0.00	0.00	0.00	0.00	0.00	0.6496	0.000	0.000	0.000	0.000	0.000	0.000
12	3.25	3.26	3.30	3.29	0.00	3.36	0.6246	2.030	2.033	2.062	2.057	0.000	2.099
13	0.00	0.00	0.00	0.00	0.00	0.00	0.6006	0.000	0.000	0.000	0.000	0.000	0.000
14	0.00	0.00	0.00	0.00	0.00	0.00	0.5775	0.000	0.000	0.000	0.000	0.000	0.000
15	3.25	0.00	0.00	0.00	3.33	0.00	0.5553	1.805	0.000	0.000	0.000	1.847	0.000
16	0.00	3.26	3.30	3.29	0.00	0.00	0.5339	0.000	1.738	1.763	1.758	0.000	0.000
17	0.00	0.00	0.00	0.00	0.00	0.00	0.5134	0.000	0.000	0.000	0.000	0.000	0.000
18	3.25	0.00	0.00	0.00	0.00	3.36	0.4936	1.604	0.000	0.000	0.000	0.000	1.658
19	0.00	0.00	0.00	0.00	0.00	0.00	0.4746	0.000	0.000	0.000	0.000	0.000	0.000
20	0.00	3.26	3.30	3.29	3.33	0.00	0.4564	0.000	1.486	1.507	1.503	1.518	0.000
Total	22.75	19.53197	19.80803	19.75875	16.63113	13.44	P.W Cost =	16.430	13.674	13.867	13.832	11.672	9.773
								LS	P8LS	P30LS	60%LS	30%LS	SS
						Uniform Annual Cost =		1.209	1.006	1.020	1.018	0.859	0.719

Table C2: Calculation Sheet of Present Worth Method for Type II Slurry Seal Mixes

Year	LS	P8LS	P30LS	60%LS	30%LS	SS	P.W Factor	LS	P8LS	P30LS	60%LS	30%LS	SS
0	3.50	3.52	3.57	3.54	3.58	3.61	1	3.500	3.524	3.565	3.543	3.576	3.610
1	0.00	0.00	0.00	0.00	0.00	0.00	0.9615	0.000	0.000	0.000	0.000	0.000	0.000
2	0.00	0.00	0.00	0.00	0.00	0.00	0.9246	0.000	0.000	0.000	0.000	0.000	0.000
3	0.00	0.00	0.00	0.00	0.00	0.00	0.889	0.000	0.000	0.000	0.000	0.000	0.000
4	3.50	0.00	0.00	0.00	0.00	0.00	0.8548	2.992	0.000	0.000	0.000	0.000	0.000
5	0.00	3.52	0.00	3.54	0.00	0.00	0.8219	0.000	2.897	0.000	2.912	0.000	0.000
6	0.00	0.00	3.57	0.00	0.00	0.00	0.7903	0.000	0.000	2.818	0.000	0.000	0.000
7	0.00	0.00	0.00	0.00	3.58	3.61	0.7599	0.000	0.000	0.000	0.000	2.718	2.743
8	3.50	0.00	0.00	0.00	0.00	0.00	0.7307	2.557	0.000	0.000	0.000	0.000	0.000
9	0.00	0.00	0.00	0.00	0.00	0.00	0.7026	0.000	0.000	0.000	0.000	0.000	0.000
10	0.00	3.52	0.00	3.54	0.00	0.00	0.6756	0.000	2.381	0.000	2.394	0.000	0.000
11	0.00	0.00	0.00	0.00	0.00	0.00	0.6496	0.000	0.000	0.000	0.000	0.000	0.000
12	3.50	0.00	3.57	0.00	0.00	0.00	0.6246	2.186	0.000	2.227	0.000	0.000	0.000
13	0.00	0.00	0.00	0.00	0.00	0.00	0.6006	0.000	0.000	0.000	0.000	0.000	0.000
14	0.00	0.00	0.00	0.00	3.58	3.61	0.5775	0.000	0.000	0.000	0.000	2.065	2.085
15	0.00	3.52	0.00	3.54	0.00	0.00	0.5553	0.000	1.957	0.000	1.968	0.000	0.000
16	3.50	0.00	0.00	0.00	0.00	0.00	0.5339	1.869	0.000	0.000	0.000	0.000	0.000
17	0.00	0.00	0.00	0.00	0.00	0.00	0.5134	0.000	0.000	0.000	0.000	0.000	0.000
18	0.00	0.00	3.57	0.00	0.00	0.00	0.4936	0.000	0.000	1.760	0.000	0.000	0.000
19	0.00	0.00	0.00	0.00	0.00	0.00	0.4746	0.000	0.000	0.000	0.000	0.000	0.000
20	3.50	3.52	0.00	3.54	0.00	0.00	0.4564	1.597	1.608	0.000	1.617	0.000	0.000
Total	21	17.62081	14.26072	17.71593	10.72884	10.83	P.W Cost =	14.701	12.367	10.369	12.434	8.359	8.438
								LS	P8LS	P30LS	60%LS	30%LS	SS
							Uniform Annual Cost =	1.082	0.910	0.763	0.915	0.615	0.621

Table C3: Calculation Sheet of Present Worth Method for Type III Slurry Seal Mixes

Year	LS	P8LS	P30LS	60%LS	30%LS	SS	P.W Factor	LS	P8LS	P30LS	60%LS	30%LS	SS
0	4.00	4.05	4.08	4.04	4.08	4.11	1	4.000	4.046	4.080	4.043	4.076	4.110
1	0.00	0.00	0.00	0.00	0.00	0.00	0.9615	0.000	0.000	0.000	0.000	0.000	0.000
2	0.00	0.00	0.00	0.00	0.00	0.00	0.9246	0.000	0.000	0.000	0.000	0.000	0.000
3	0.00	0.00	0.00	0.00	0.00	0.00	0.889	0.000	0.000	0.000	0.000	0.000	0.000
4	0.00	0.00	0.00	0.00	0.00	0.00	0.8548	0.000	0.000	0.000	0.000	0.000	0.000
5	4.00	0.00	0.00	0.00	0.00	0.00	0.8219	3.288	0.000	0.000	0.000	0.000	0.000
6	0.00	4.05	0.00	0.00	0.00	0.00	0.7903	0.000	3.198	0.000	0.000	0.000	0.000
7	0.00	0.00	4.08	4.04	4.08	4.11	0.7599	0.000	0.000	3.101	3.072	3.100	3.123
8	0.00	0.00	0.00	0.00	0.00	0.00	0.7307	0.000	0.000	0.000	0.000	0.000	0.000
9	0.00	0.00	0.00	0.00	0.00	0.00	0.7026	0.000	0.000	0.000	0.000	0.000	0.000
10	4.00	0.00	0.00	0.00	0.00	0.00	0.6756	2.702	0.000	0.000	0.000	0.000	0.000
11	0.00	0.00	0.00	0.00	0.00	0.00	0.6496	0.000	0.000	0.000	0.000	0.000	0.000
12	0.00	4.05	0.00	0.00	0.00	0.00	0.6246	0.000	2.527	0.000	0.000	0.000	0.000
13	0.00	0.00	0.00	0.00	0.00	0.00	0.6006	0.000	0.000	0.000	0.000	0.000	0.000
14	0.00	0.00	4.08	4.04	4.08	4.11	0.5775	0.000	0.000	2.356	2.335	2.356	2.374
15	4.00	0.00	0.00	0.00	0.00	0.00	0.5553	2.221	0.000	0.000	0.000	0.000	0.000
16	0.00	0.00	0.00	0.00	0.00	0.00	0.5339	0.000	0.000	0.000	0.000	0.000	0.000
17	0.00	0.00	0.00	0.00	0.00	0.00	0.5134	0.000	0.000	0.000	0.000	0.000	0.000
18	0.00	4.05	0.00	0.00	0.00	0.00	0.4936	0.000	1.997	0.000	0.000	0.000	0.000
19	0.00	0.00	0.00	0.00	0.00	0.00	0.4746	0.000	0.000	0.000	0.000	0.000	0.000
20	4.00	0.00	0.00	0.00	0.00	0.00	0.4564	1.826	0.000	0.000	0.000	0.000	0.000
Total	20	16.18409	12.2408	12.12986	12.23637	12.33	P.W Cost =	14.037	11.768	9.537	9.451	9.533	9.607
								LS	P8LS	P30LS	60%LS	30%LS	SS
							Uniform Annual Cost =	1.033	0.866	0.702	0.695	0.701	0.707

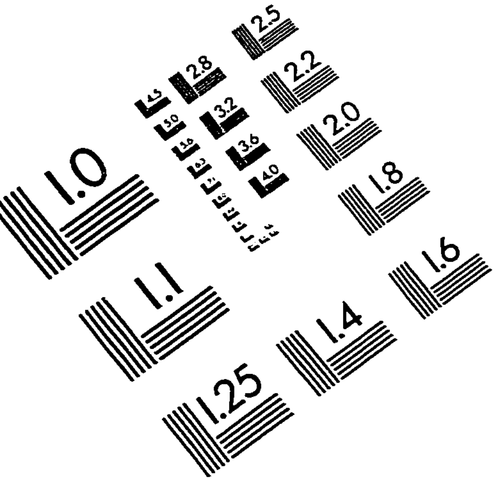
Table C4: Calculation Sheet of Present Worth Method for Type II Micro Surfacing Mixes

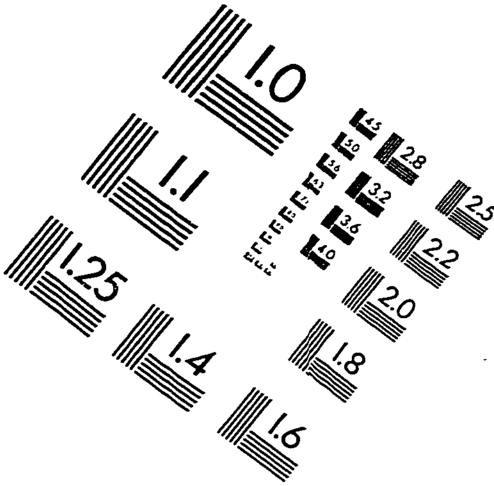
Year	LS	P8LS	P30LS	60%LS	30%LS	SS	P.W Factor	LS	P8LS	P30LS	60%LS	30%LS	SS
0	4.50	4.52	4.57	4.54	4.58	4.61	1	4.500	4.524	4.565	4.543	4.576	4.610
1	0.00	0.00	0.00	0.00	0.00	0.00	0.9615	0.000	0.000	0.000	0.000	0.000	0.000
2	0.00	0.00	0.00	0.00	0.00	0.00	0.9246	0.000	0.000	0.000	0.000	0.000	0.000
3	0.00	0.00	0.00	0.00	0.00	0.00	0.889	0.000	0.000	0.000	0.000	0.000	0.000
4	0.00	0.00	0.00	0.00	0.00	0.00	0.8548	0.000	0.000	0.000	0.000	0.000	0.000
5	4.50	0.00	0.00	0.00	0.00	0.00	0.8219	3.699	0.000	0.000	0.000	0.000	0.000
6	0.00	4.52	4.57	0.00	0.00	0.00	0.7903	0.000	3.572	3.612	0.000	0.000	0.000
7	0.00	0.00	0.00	4.54	0.00	0.00	0.7599	0.000	0.000	0.000	3.450	0.000	0.000
8	0.00	0.00	0.00	0.00	4.58	0.00	0.7307	0.000	0.000	0.000	0.000	3.347	0.000
9	0.00	0.00	0.00	0.00	0.00	4.61	0.7026	0.000	0.000	0.000	0.000	0.000	3.239
10	4.50	0.00	0.00	0.00	0.00	0.00	0.6756	3.040	0.000	0.000	0.000	0.000	0.000
11	0.00	0.00	0.00	0.00	0.00	0.00	0.6496	0.000	0.000	0.000	0.000	0.000	0.000
12	0.00	4.52	4.57	0.00	0.00	0.00	0.6246	0.000	2.823	2.854	0.000	0.000	0.000
13	0.00	0.00	0.00	0.00	0.00	0.00	0.6006	0.000	0.000	0.000	0.000	0.000	0.000
14	0.00	0.00	0.00	4.54	0.00	0.00	0.5775	0.000	0.000	0.000	2.622	0.000	0.000
15	4.50	0.00	0.00	0.00	0.00	0.00	0.5553	2.499	0.000	0.000	0.000	0.000	0.000
16	0.00	0.00	0.00	0.00	4.58	0.00	0.5339	0.000	0.000	0.000	0.000	2.445	0.000
17	0.00	0.00	0.00	0.00	0.00	0.00	0.5134	0.000	0.000	0.000	0.000	0.000	0.000
18	0.00	4.52	4.57	0.00	0.00	4.61	0.4936	0.000	2.231	2.256	0.000	0.000	2.275
19	0.00	0.00	0.00	0.00	0.00	0.00	0.4746	0.000	0.000	0.000	0.000	0.000	0.000
20	4.50	0.00	0.00	0.00	0.00	0.00	0.4564	2.054	0.000	0.000	0.000	0.000	0.000
Total	22.5	18.08429	18.27536	13.62336	13.73644	13.83	P.W Cost =	15.791	13.151	13.287	10.615	10.368	10.124
								LS	P8LS	P30LS	60%LS	30%LS	SS
							Uniform Annual Cost =	1.162	0.968	0.978	0.781	0.763	0.745

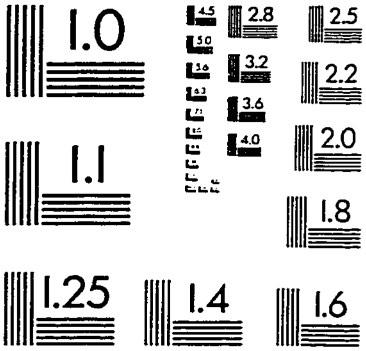
Table C5: Calculation Sheet of Present Worth Method for Type III Micro Surfacing

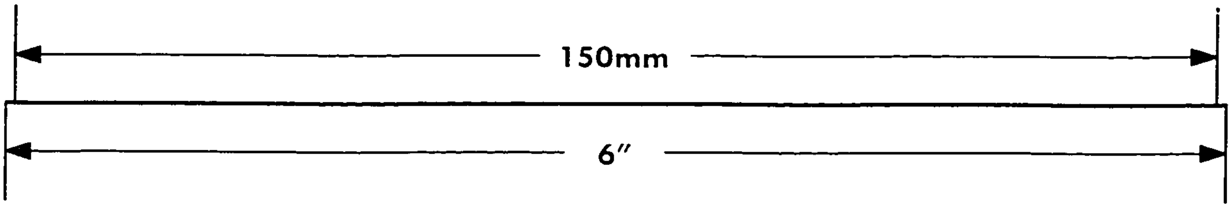
Year	LS	P8LS	P30LS	60%LS	30%LS	SS	P.W Factor	LS	P8LS	P30LS	60%LS	30%LS	SS
0	5.00	5.05	5.08	5.04	5.08	5.11	1	5.000	5.046	5.080	5.043	5.076	5.110
1	0.00	0.00	0.00	0.00	0.00	0.00	0.9615	0.000	0.000	0.000	0.000	0.000	0.000
2	0.00	0.00	0.00	0.00	0.00	0.00	0.9246	0.000	0.000	0.000	0.000	0.000	0.000
3	0.00	0.00	0.00	0.00	0.00	0.00	0.889	0.000	0.000	0.000	0.000	0.000	0.000
4	0.00	0.00	0.00	0.00	0.00	0.00	0.8548	0.000	0.000	0.000	0.000	0.000	0.000
5	0.00	0.00	0.00	0.00	0.00	0.00	0.8219	0.000	0.000	0.000	0.000	0.000	0.000
6	5.00	0.00	0.00	0.00	0.00	0.00	0.7903	3.952	0.000	0.000	0.000	0.000	0.000
7	0.00	5.05	5.08	0.00	0.00	0.00	0.7599	0.000	3.837	3.860	0.000	0.000	0.000
8	0.00	0.00	0.00	5.04	0.00	0.00	0.7307	0.000	0.000	0.000	3.683	0.000	0.000
9	0.00	0.00	0.00	0.00	5.08	0.00	0.7026	0.000	0.000	0.000	0.000	3.569	0.000
10	0.00	0.00	0.00	0.00	0.00	5.11	0.6756	0.000	0.000	0.000	0.000	0.000	3.452
11	0.00	0.00	0.00	0.00	0.00	0.00	0.6496	0.000	0.000	0.000	0.000	0.000	0.000
12	5.00	0.00	0.00	0.00	0.00	0.00	0.6246	3.123	0.000	0.000	0.000	0.000	0.000
13	0.00	0.00	0.00	0.00	0.00	0.00	0.6006	0.000	0.000	0.000	0.000	0.000	0.000
14	0.00	5.05	5.08	0.00	0.00	0.00	0.5775	0.000	2.916	2.934	0.000	0.000	0.000
15	0.00	0.00	0.00	0.00	0.00	0.00	0.5553	0.000	0.000	0.000	0.000	0.000	0.000
16	0.00	0.00	0.00	5.04	0.00	0.00	0.5339	0.000	0.000	0.000	2.691	0.000	0.000
17	0.00	0.00	0.00	0.00	0.00	0.00	0.5134	0.000	0.000	0.000	0.000	0.000	0.000
18	5.00	0.00	0.00	0.00	5.08	0.00	0.4936	2.468	0.000	0.000	0.000	2.507	0.000
19	0.00	0.00	0.00	0.00	0.00	0.00	0.4746	0.000	0.000	0.000	0.000	0.000	0.000
20	0.00	0.00	0.00	0.00	0.00	5.11	0.4564	0.000	0.000	0.000	0.000	0.000	2.332
Total	20	15.14617	15.24038	15.12343	15.2365	15.33	P.W. Cost =	14.543	11.800	11.874	11.417	11.153	10.895
								LS	P8LS	P30LS	60%LS	30%LS	SS
							Uniform Annual Cost =	1.070	0.868	0.874	0.840	0.821	0.802

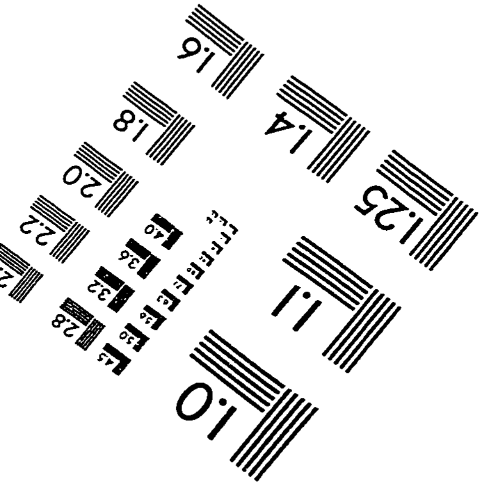
IMAGE EVALUATION
TEST TARGET (QA-3)

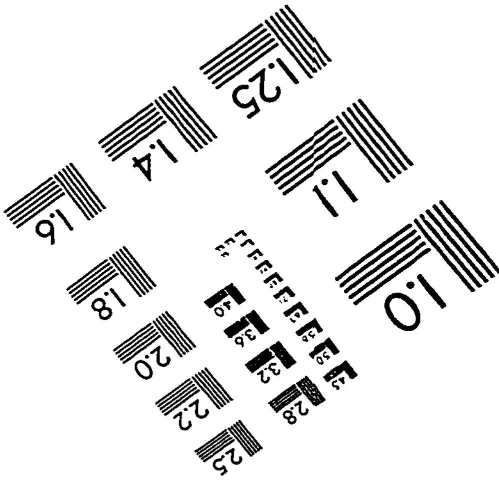












APPLIED IMAGE . Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989