Rut Depth Prediction Modeling Using LCPC Tester Of Hot Mix Asphalt

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Abstract

Rut Depth Prediction Modeling Using LCPC Tester of Hot Mix Asphalt

Rutting is considered as one of the major modes of deterioration to flexible pavements. The goal of this study is to contribute to the understating of this phenomenon, and to establish a simple tool predict the resistance to rutting of asphalt pavements based on the experimentation and modeling. Several asphalt mixes will be considered in this study (EG-10, EGA-10, EGS-10, and EG-20, EC-10, SMA). The majority of these mixes are commonly used in Quebec for road construction. Only the SMA (Stone Mastic Asphalt) is less common currently but it popularity is in continuous increase as high-performance mix.

The adopted laboratory test for this study is the LCPC French rutting tester. All mixes will be designed according to the LC Method for bituminous mix design. Influence of the following mix design parameters will be investigated in this research: **Binder content (P_b). Air voids (V %). PG is performance grade of the binder (unmodified and modified binders). Voids filled with asphalt (VFA). NMAS is nominal maximum aggregate size represented by D60/D10 of particles in the mix. Percentage of filler.**

In the modeling part of this thesis, a detailed analysis will be conducted on the experimental results to obtain a correlation between rutting performance and the different mix design parameters. The modeling would allow the development of computer software for the prediction of pavement resistance to rutting, for different bituminous mixes.

Y1=A*HH^Nb+LOG(HH+LL)+B/Va+F*LOG(VFA)+D/Pb^Na+E*NMAS+LOG(Cu)^Ng+LOG(Filler)+const

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NOMENCLEATURE

HMA	Hot Mix Asphalt
HH	Highest temp.
LL	Lowest temp.
Pb	Asphalt percentage
Va	Air Void
VFA	Voids filled with Asphalt
Cu	Coefficient of uniformity
NMAS	Nominal maximum aggregate size
Gmm	Maximum Specific gravity of a mix
Gmb	Bulk specific gravity of a mix
Gsb	Bulk specific gravity of aggregate
Gsa	Apparent specific gravity of aggregate
Gse	Effective specific gravity of aggregate
Pbe	Effective asphalt percentage

ABBREVIATIONS

ESG-14: Semi-Grained asphalt mix used mainly for full- depth and base courses
ESG-10: Semi-Grained asphalt mix used mainly as surface course
EGA-10: Grained asphalt mix with asbestos fibres used mainly as surface course
EG-10: Grained asphalt mix used mainly as surface course
EG-20: Grained asphalt mix for base courses (Called recently GB-20)
EC-10: Correction asphalt mix for pavement maintenance applications
SMA: Stone Mastic Asphalt mix with Gap-graded gradation and fibres and high asphalt content

Chapter 1

1. INTODUCTION

1.1 Background

Rutting of pavements is a very common type of deterioration to roads. It is the continuous pavement surface deflection in the longitudinal direction of the pavement and occurs mainly in the wheel paths due to heavy traffic on pavements. It is considered as one of the major pavement deterioration modes of flexible pavements. Rutting has different negative aspects on the roads security and on the economy. When the rut depth increases, and the condition becomes very hazardous, more particularly in rainy weather due to aquaplaning phenomenon. The adherence of tires will be lower and risk of accidents will be significantly increased. Also, driving on rutted pavements will increase the tires and fuel consumption of vehicles. In addition, a poor design will require frequent rehabilitations and will increase the cost.

Rutting may occur due to different reasons. In general, rutting may occur in the asphalt layer when some aspects of the mix design, or the structural pavement design, are not adequate for traffic or climatic conditions of the pavement. The use of soft binder or high binder content, inadequate gradation or unsuitable aggregates may lead to rutting. Also, rutting may be caused by insufficient compaction of asphalt layers or also when the thickness of the asphalt courses is less than the required thickness to resist the vertical stresses. In addition to these reasons, rutting may occur due to high deformations in non-treated granular layers or in the subgrade (inadequate materials, insufficient thickness, compaction or drainage problems).

Different studies have been conducted over the years to enhance the resistance to rutting of flexible pavements. Nevertheless, the phenomenon is still a major problem in roads. Rutting is mainly related to hot weather and heavy traffic. To enhance the resistance to rutting of asphalt pavements under these conditions, hard bituminous binders are usually used. However, the use of these binders may lead to a significant decrease in the resistance to low temperature cracking. This solution is not adapted to Canadian climatic conditions.

1.2 Expected Contribution.

Permanent deformation is one of the major pavement distress and related deterioration. It causes very serious condition to entire traffic users, where this may present hazardous conditions to life, economy, and unsafe traffic. Solving this problem completely may be a dream to all traffic and transportation engineers. Many research studies are in progress to eliminate this distress and deterioration problem.

The prediction of permanent deformation (rutting) will help in controlling the causes of the problem, and in eliminating the effect of these causes. To relate all causes and factors related to rut problem under a defined empirical relation will certainly have a positive contribution to identify the problem and predict the appropriate solution. Many researchers expected to have a positive achievement in this area, where this research work will add farther analysis and contribution to arrive at a reasonable solution to pavement distress (rutting). The French rutting tester (LCPC) will be adopted to produce rutting data, which will be useful in the analysis and modeling process. Collection of data from international recognize projects, such as West rack project will enhance the process of analysis promptly. From all data performed using LCPC rut tester, and comparison of data collected from other major projects, will form the positive tool to bring rut depth prediction model to final form.

1-3 Research Objectives and scope of work

The main objective of this study is to establish a simple tool to predict the resistance to rutting of asphalt pavements based on the experimentation and modeling.

The LCPC rutting tester is laboratory equipment designed to investigate the rutting resistance of bituminous materials under comparable conditions to the stress applied on pavements. In Quebec, the test is conducted in accordance with MTQ standard. This research will carry the following objectives:

- Collect experimental data of different asphalt mixes to measure resistance to rutting, using the LCPC Rutting Tester.

- Perform detail analysis of experimental results to evaluate the role of different mix design parameters on the rutting.

- Develop® an empirical formula for the prediction of rut depth in pavement surface.

- Develop® computer software, to optimize rut prediction.

Several asphalt mixes will be considered in this study (EG-10, EGA-10, EGS-10, and SMA). The majority of these mixes are commonly used in Quebec for road construction. Only the SMA (Stone Mastic Asphalt) is less common currently, but its popularity is in continuous increase as high-performance mix.

All mixes will be designed according to the LC Method for bituminous mix design. This method is inspired from the Superpave mix design and the French mix design methods. The mix design uses the Superpave Gyratory Compactor to evaluate the compaction ability and uses the LCPC rutting tester for rutting resistance.

The influence of following mix design parameters will be investigated in this work:

- Binder content (P_b).
- Air voids (V %).
- PG grade of the binder (unmodified and modified binders).
- Voids in mineral aggregates (VMA).

- Voids filled with asphalt (VFA).
- Percentage of effective binder (P_{be}).
- Percentage of filler.

Data from well known asphalt pavement projects will be referred to for the detail analysis and research optimization. WESTRACK project data, and data from major MTQ (Ministry of Transportation Qc) project will add a comprehensive information to the entire research analysis.

In the modeling part of the study, a detailed analysis will be conducted on the experimental results to obtain a correlation between rutting performance and the different mix design parameters. The goal of this part is to develop an empirical equation for the prediction of rut depth on asphalt pavement surface. The calibration and the validation of the model will be conducted through field measurements of several acknowledged projects in North America. The data will be obtained from different sources such as (LTPP, MTQ, Westrack, etc.).

The last part of this research project will be dedicated to the conception and the development of a simple computer tool for the prediction of rutting resistance of asphalt mixes. This tool will be mainly based on the experimental data obtained from the FLRT testing and from additional data of other tests from different sources (MTQ, Sintra, ETS) as mentioned in the modeling part.

1.4 Methodology

In this research study, a methodology has been adopted to develop a mathematical model to predict rut depth in pavement using LCPC tester. The adopted methodology involves six steps:

- Conducting literature review
- Collecting data obtain laboratory rutting tester LCPC.
- Determining the selected mix and related data for detail analysis.
- Analyzing of parameters that influence the mix design to rutting problem.

- Developing a mathematical model for predicting process.
- Developing a computer model as a tool for system process.

1.5 Thesis Organization

The thesis work is organized in 5 chapters:

Chapter one presents the introduction of the problem, contribution, objectives, and methodology. Chapter two presents the literature review, analysis from several projects involved in rut prediction and analysis, major projects, different tests adopted, and modeling of different research work.

Chapter three presents the introduction of LC design method adopted in Quebec, LCPC tester introduction, different HMA used in Quebec, data, and scope of work. Chapter four presents the complete analysis process, modeling with selected parameters, procedure adopted in modeling, a computer program using selected parameters, and analysis of all parameters involved in the design studies, develop a mathematical model involving selected parameters, and develop small computer program with use of all parameters involved in the design process. Chapter five presents the summary and conclusion.

Chapter-2

2- Literature Review

2-1 General.

Rutting is defined as the permanent deformation in asphalt pavements that forms the surface depression in the wheel path. It imposes unfavorable conditions in the traffic maneuver causing traffic safety problems and hazards to human life in addition to economic losses. Rutting of pavements is an early indicator of pavement failure. Therefore, rut depth measurements and prediction are usually included in most road monitoring programs. The resistance to rutting is included in some of the mix design methods such as LC mix design method of the Québec Ministry of Transportation. This research work will focus on the study and analysis of asphalt pavement behavior to rutting using LCPC tester for various design mixes.

2-2 Types of Rut in Pavement

Two types of rutting are defined and included in the various researches conducted so far for this purpose.

1. Rutting due to pavement deformation (creep rutting); This type of rutting occurs when the pavement surface exhibits wheel path deformation and depression, this will occur generally in one or more of following cases:
    - Mix design problem (aggregate, void ratio, VMA, and asphalt content, and asphalt gradation).
    - Compaction at construction site and related characteristics of the pavement structure condition.
    - Surrounding environnemental conditions (drainage system, confinement of subgrade, soil etc.).
    - Traffic loading, volume, and speed.

2. Rutting due to Subgrade Deformation: This type of rutting will occur when subgrade exhibits wheel path deformation and depression, due to subgrade deformation. In this case, the pavement will settle into subgrade causing surface

depression (deformation) in the wheel path. This type of ruts are considered as hazardous to vehicles as it tends to pull a vehicle towards the rut path as the wheels are steered across the rut, where this deformation usually caused by compaction and lateral movement of the subgrade soil due to all above mentioned factors. The subgrade rut is considered as a deep rut because the effect of excessive loading and result of other factors. The concept to involve the effect of subgrade, in spite the fact that subgrade condition may be excellent, but still will have a minor effect on the occurrence and performance of rutting. So this part will be on focus during the research work. To define the problem of rutting in asphalt pavement surface, certain factors affecting the rut occurrence are pointed out. Rutting can result from excessive loads or tire pressures causing stresses that approach or exceed the shear strength of the materials resulting in depressions under the load and often heave alongside the loaded area (Monismith, 1976) and (Paterson, 1987). Some of the important external factors affecting the rut occurrence at pavement surface such as (loading, climate, and materials).

Loading:

Loading is the direct impact of traffic into the pavement surface. Rutting accumulates faster as the load duration increases (Hubber and Heiman, 1987 or Phang, 1988). Other factors that influence the rutting performance of the pavement are tire type and tire inflation pressure (Phang, 1988, Khandhal et. Al. 1993).

Climatic Condition:

Climate affects the rutting to a large extent the performance and mechanical properties of pavement components**.** Seasonal weather variations introduce material properties variations and therefore periodic changes of pavement characteristics (OECD, 1988). Asphalt cements are considered as very susceptible to temperature. At higher temperatures they become softer and the bonds between particles become weaker. Consequently, the relative movement between particles becomes easier.

When water freezes, it expands around 9 percent of its original volume. Thus, severe heaving cannot be accounted for, as explained by (Yoder et. Witzak, 1975). The super cooled water and ice will have a strong affinity with the result of water being drawn to the ice crystals that are initially formed. If the soil is highly susceptible to capillary action, ice crystals will continue to grow until ice lenses begin to form, the lenses in turn grow until heaving results. During thawing periods, the pavement capacity may be greatly reduced as a result of unfrozen soft material (i.e., material with high water content) immediately under the pavement. This phenomenon is known as *Spring Breakup* (Yoder et. Witzak, 1975). It can accentuate by periods of high rainfall during fall and winter seasons particularly during the frost melting period. With respect to precipitation, it is commonly known that for a given amount of traffic, surface distress will occur more rapidly if the surface course is frequently wet (OECD, 1988). Where the effect of precipitation is more important in cracked pavements, it allows the ingress of water from the pavement surface to the underlying layers with the consequent detrimental effects on rutting performance.

Properties of Material in Asphalt Concrete Mix

The asphalt concrete mixes and granular materials used in road construction are composed of three phases. For asphalt layers, the three phases are: mineral aggregates, asphalt content, and air voids. For granular materials the asphalt phase is replaced by water.

Aggregate

Apart the gradation, the most important characteristics of the aggregates recognized as affecting the mix resistance to permanent deformation are surface texture, shape, porosity, and aggregate mineralogy. Kandhal et al. (1993), described that manufactured sand is generally angular and that its incorporation in the mix, increases rutting resistance. Buttoon et al. (1990) show results suggesting the aggregate gradation.

Asphalt cement

The most important characteristic of asphalt cement with regard to rutting performance is the stiffness at high temperature, at low shear strain the binder stiffness is high at the simple constant height test, which is more susceptible to rut (Sousa et. al., 1993). Huges and Maupin (1987), concluded that the mix design viscosity of the asphalt additive binder combination does not appear as important as the gradation, probably because the gradation are chosen to provide sufficient aggregate interlock to minimize the effect of binder viscosity.

Air Voids

The air void volume change in the pavement is a function of construction compaction. More compaction will lead to higher stability (i.e., more rut resistance pavements), within the acceptable and analyzed ratio. Huber et. Heiman. 1987, studied eleven pavement sections that carry similar traffic volumes but exhibit different performances. They concluded that asphalt content and voids filled with asphalt were the basic parameters affecting rutting. The major causes of rutting were excessive asphalt content and lower air voids in the asphalt mixture. Finally the aggregate gradation controls the voids in the mineral aggregate and combined with asphalt content and the compaction energy, where this phenomena can be classified by means of specific gravity of the aggregate in the mix.

2-3 Different modes of pavement failure to rutting.

As explained by Patterson (1987), there are two mechanisms of traffic-associated deformation that are important to the research efforts: <u>densification</u> and <u>plastic flow</u>. The densification involves volume changes in material resulting from tighter packing of the material particles and in some cases from the degradation of the particles to smaller sizes. It is controlled by means of good compaction during construction process. Plastic flow is the second mechanism of permanent deformations. It involves essentially no volume change and consists of shear displacements, which result in both depression and heave. It occurs when the induced shear stresses exceed the shear strength of the material. This mechanism controlled in pavement design by selection of materials according to a surrogate measure of shear strength (e.g., California Bearing Ratio, CBR, for soils, or Hveem stability for bituminous materials). As result, a higher strength material is required at upper layer of the pavement, where several research work contributed a valuable measured in this issue, it will be discussed in following the chapters.

2-4 Field and Laboratory rutting tests and prediction process

Rutting tests could be subdivided into empirical tests or (reduced-scale tests), and mechanical tests. In this analysis, it is important to introduce the possible tests and focus on the reliable rut tester (LCPC) with enough data collection. Some projects were performed to study the general analysis on rutting and conclude the causes, environmental situation of roads as described in the following research work.

2.4.1 Empirical Tests

2.4.1.1. Peak and Base to valley

This test is a simple scale test. The rut can be measured directly using a striate scale on both sides of the pavement surface, and a measuring scale to measure rut as in Figure (2-1).

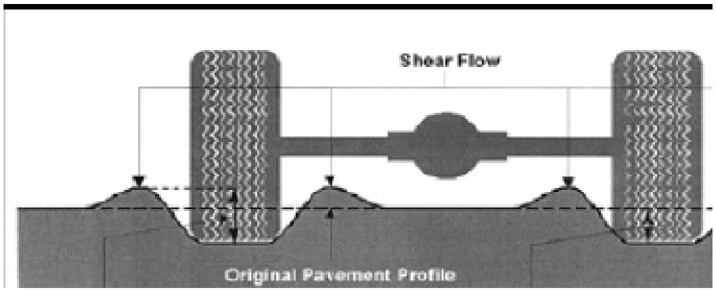


Figure (2-1) Total rut depth, WesTrack Performance FHWA-1998

2.4.1.2. LCPC Rutting Tester.

The French pavement rutting tester LCPC (Laboratoire Central des Ponts et Chausses). This tester measures the rutting susceptibility of asphalt pavement, as explained in details in 3.1.1. Several tests were conducted to study the behavior of asphalt pavement surface using the LCPC rut tester, J-F Corte et al., 1992.

2.4.1.3. Hamburg Rut Tester.

The Hamburg rut tester is another device tester to measure rut. The amount of deformation of the sample is measured continuously throughout the test. The total deformation and the deformation rate indicate the material's ability to resist rutting and raveling once it is placed in service.

Figure (2-2) Hamburg rut tester, (FHWA, 2006).

The following project studded and analyzed the pavement mix design with modified polymer binder using Hamburg rut tester. **CTAA, 2002, MTE Services Inc.**

2.4.1.4. APA Asphalt Pavement Tester (Analyzer)

The Asphalt Pavement Analyzer (APA) is a multifunctional Loaded Wheel Tester (LWT) used for evaluating permanent deformation (rutting), fatigue cracking and moisture susceptibility of both hot and cold asphalt mixes.

Figure (2-3) Asphalt Pavement Analyzer with PLC PC based control system. Pavement Technology Inc, 2006

Kandhal and R.B. Mallick, 2001, tested densed-graded HMA samples with superpave gyratory compactor, they used APA tester and Superpave shear tester (SST) for rut measurements. (Huang et al, 2004) another researcher conducted APA tester for rut evaluation. The author concluded to a lack of interlocking of aggregate structure, and insufficient bonding between aggregate and asphalt binder, or both.

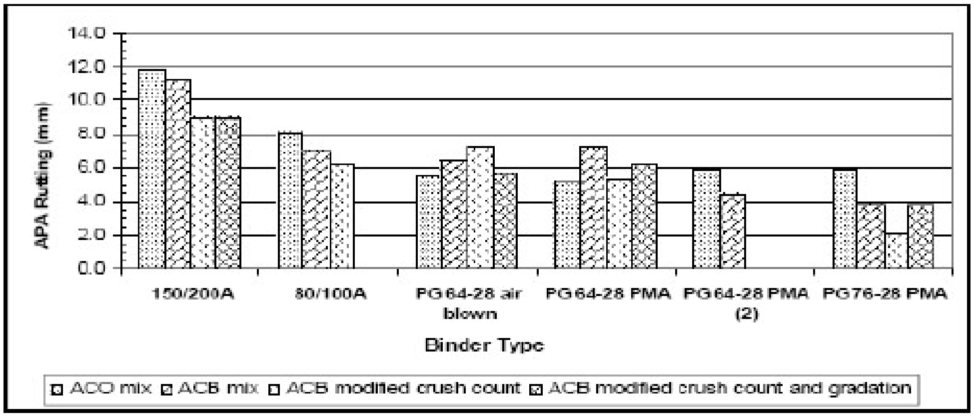


Figure (2-4) (APA) Rutting of Mixes. B. Huang et al, 2004.

Another research project using the APA is, CTAA, 2004. Where Leonard Dunn, Hugh B.Donovan, conducted at the city of Edmonton to study and analyze the susceptibility of asphalt mix to rutting.

2.4.1.5. Simple Performance Test

Figure (2-5) Simple performance rut tester, (FHWA), 2006

The photograph in Figure (2-9) shows a technician running the Simple Performance Test to evaluate an asphalt mixture for its response to permanent deformation (rutting) or fatigue cracking. Several and various researches implemented this test for analysis, and many important results must be counted.

In the following publication paper of simple performance tester used to evaluate the permanent deformation (rutting).

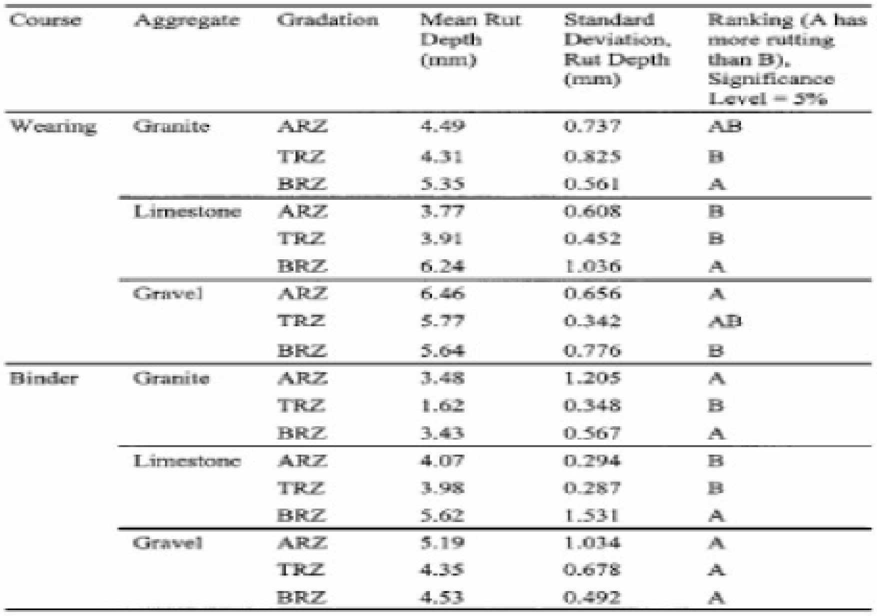
The laboratory testing program included mixtures and performance data from three major experimental sites: the Minnesota Road Project **(MnROAD)**, the Federal Highway (**FHWA**) Accelerated Loading Facility Study (**ALF**), and the FHWA Performance Related Specifications Study (WesTrack), The data collected from the above test projects utilized for obtaining a reasonable results, of dynamic and static tests.

2.4.2 Mechanical Tests

2.4.2.1. Super Pave Shear Tester

The SST is a closed-loop feedback, servo-hydraulic system. The repeated shear at constant height test estimates rut depth. Kandhal, Mallick**, 2001.**

Table (2-1) Rd Statistics for PG-64-22, TRR (1767), 2001



Course	Aggregate	Gradation	Mean Rut Depth (mm)	Standard Deviation, Rut Depth (mm)	Ranking (A has more rutting than B), Significance Level = 5%
Wearing	Granite	ARZ	4.49	0.737	AB
		TRZ	4.31	0.825	B
		BRZ	5.35	0.561	A
	Limestone	ARZ	3.77	0.608	B
		TRZ	3.91	0.452	B
		BRZ	6.24	1.036	A
	Gravel	ARZ	6.46	0.656	A
		TRZ	5.77	0.342	AB
		BRZ	5.64	0.776	B
Binder	Granite	ARZ	3.48	1.205	A
		TRZ	1.62	0.348	B
		BRZ	3.43	0.567	A
	Limestone	ARZ	4.07	0.294	B
		TRZ	3.98	0.287	B
		BRZ	5.62	1.531	A
	Gravel	ARZ	5.19	1.034	A
		TRZ	4.35	0.678	A
		BRZ	4.53	0.492	A

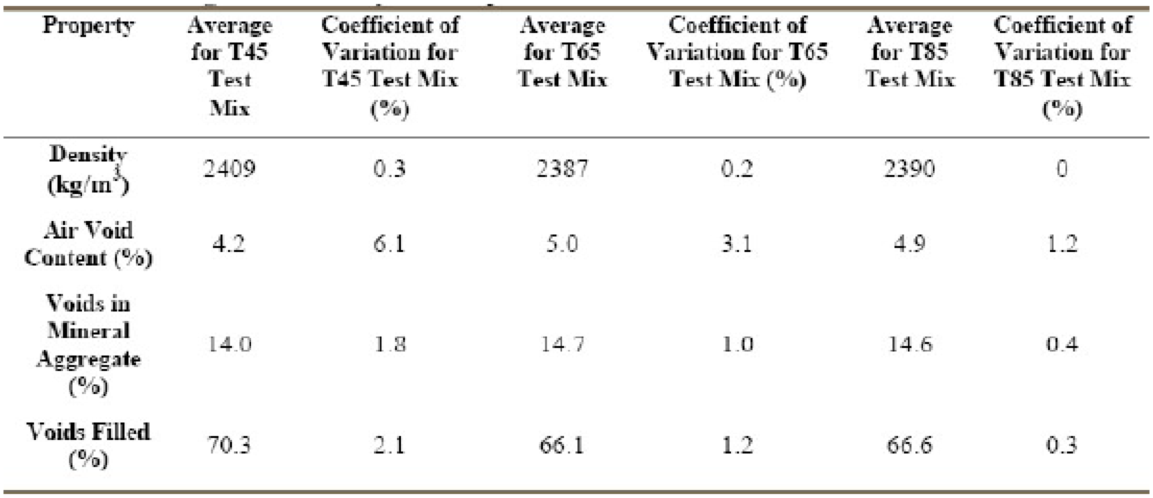
Table 2-1 is the comparison of Rd for several aggregate gradation size.

This research concludes that the properties of aggregate and its gradation will play an important factor in the study of pavement susceptibility to rutting.

2.4.2.2. Creep test and marshal flow

The creep tests have been widely used to evaluate and characterize rutting potential in hot mix asphalt (HMA), both confined and unconfined test are used. The confined-creep test was found to be more representative of in-place performance (Mat. in Civ., 1994). In Marshal testing, the volumetric data of aggregate, voids, and asphalt content will play a magnificent role for the analysis of mix design elements for test to evaluate pavement resistance to rutting. The following work publication had some result in this issue, Carlberg. Et, al,2003.

Table (2-2) Average Marshall Physical Properties for Test Mixes, TAC-2003



Property	Average for T45 Test Mix	Coefficient of Variation for T45 Test Mix (%)	Average for T65 Test Mix	Coefficient of Variation for T65 Test Mix (%)	Average for T85 Test Mix	Coefficient of Variation for T85 Test Mix (%)
Density (kg/m^3)	2409	0.3	2387	0.2	2390	0
Air Void Content (%)	4.2	6.1	5.0	3.1	4.9	1.2
Voids in Mineral Aggregate (%)	14.0	1.8	14.7	1.0	14.6	0.4
Voids Filled (%)	70.3	2.1	66.1	1.2	66.6	0.3

As shown in Table (2-4) the volumetric analysis of the Marshall test mix samples found that, the volumetric constituents determined by the Marshall procedure would be deemed to rut resistant, author indicates that the air content controlled by gyratory and marshal are more in control and accessibility.

Another project and research work attributed to rutting potential, Yang , et al,1991. Conducted a work investigated the feasibility of predicting fatigue cracking and rutting in full depth asphalt pavements by centrifuge modeling. The models were tested to 10,000 cycle repetition to measure the tensile strength.

2.4.2.3. Indirect tensile fatigue test

The indirect tensile test is conducted by applying a compressive load to a cylindrical specimen through two diametrically opposite, arc-shaped, rigid loading strips. As in NCHRP 9-19 research project, including an indirect tensile strength test, a resilient modulus test, a fatigue test, and a creep test. According to ASSHTO TP9-96, the indirect tensile strength is determined by applying a constant rate of ram movement to failure.

The creep compliance is represented by the following equation:

D (t) = D1*t^m1

Where D_1, m_1 = material regression coefficient.

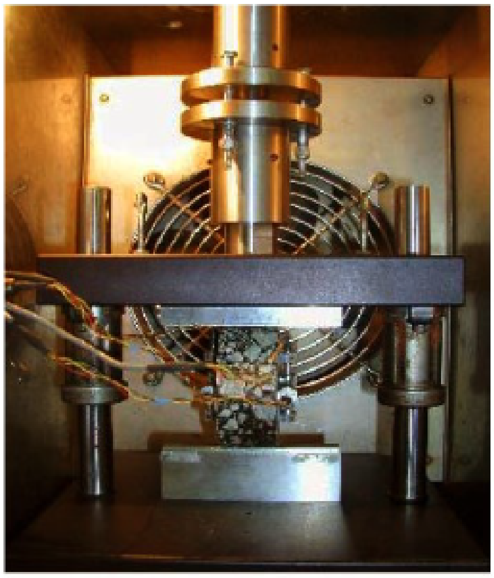


Figure (2-6) Indirect Tensile Test, NCHRP, 9-19, 2004.

The calculation of creep compliance will help on calculating the stiffness modulus of the mix, which is part of the empirical proposed theoretical model of this research.

Roque and Buttlar (1992) developed a measurement and analysis system to determine asphalt concrete properties, primarily thermal cracking, using the indirect tensile testing mode, which was incorporated in ASSHTO TP9-96. Creep compliance was calculated using the following equations:

$D(t) = X*D*b*C/P*GL$

Where $D(t)$ = creep compliance,

X = horizontal deformation,
D = diameter of specimen,
b = thickness of specimen,
P = load applied,
GL = gauge length, and
C = correction factor.

Poisson's ratio was computed as:

Poisson's ratio = $-0.1+1.48(X/Y)^2-0.778(b/D)^2*(X/Y)^2$

where X = horizontal deformation, and

Y = vertical deformation. **Wen, Haifang, 2001.**

The calculation of creep compliance is quite important to running research work, as it describes the calculation of stiffness modulus, which used for the calculation of Rd. Detail work and analysis is described in ch-3.

2.4.2.4 Full Scale evaluation and field result tests

Three major projects in the US used for the experimental plan to evaluate, collect data, study and analyze the pavement behavior and its resistance against rutting and fatigue are, MnRoad, FHWA ALF, and WesTrack. Data collected from the three test projects are considered valuable and comprehensive to many researcher at this time till some new test result may come and add new information.

Figure (2-7) MnRoad full scale project, www.mnroad.dot.state.mn.us, 2000.

All three projects are providing a rich data for the study of pavement analysis, rutting is one of the main prospective in these resources. The data collected was used to study different aspect and the analysis from individual angle. Several research studies were completed using data from either of the three projects or a comparison between the analyses for all data of the three projects. This specific analysis is of considerable contribution to the work study of rut depth but it is limited to a certain condition result and it bring the analysis to a advance contribution as of value of air void from 4-5 percent will result in close rutting with both field and laboratory test, which means it is more reasonable air voids percentage to control and predict rutting.

ALF Testing for Development of Improved Superpave Binder Specification

Figure (2-8) The FHWA ALF's and PTF, FHWA, 2000.

Asphalt Pavement Technology Labs, Accelerated Load Facility (ALF).

The Pavement Testing Facility (PTF) is used to rapidly collect data on pavement performance under conditions in which axle loading and climatic conditions are controlled. The FHWA conducted a field pavement study at turner, using the accelerated loading facility

WESTRACK project (FHWA, 1998)

Introduction

It is considered one of the most extensive and full scale projects to provide collective and comprehensive data for the analysis of pavement problems (Rut, crack etc). WESTRACK is a multimillion dollar accelerated pavement testing facility located approximately 100 km (60mi) southeast of Reno, Nevada. Sponsored by the Federal Highway Administration (FHWA) and the National

Cooperative Highway Research Program. The track is a 3 km (1.8 mi) oval track, a schematic of which is shown in Figure (2-14). Thirty-four test sections have been evaluated including the 26 original sections and 8 replacement sections.

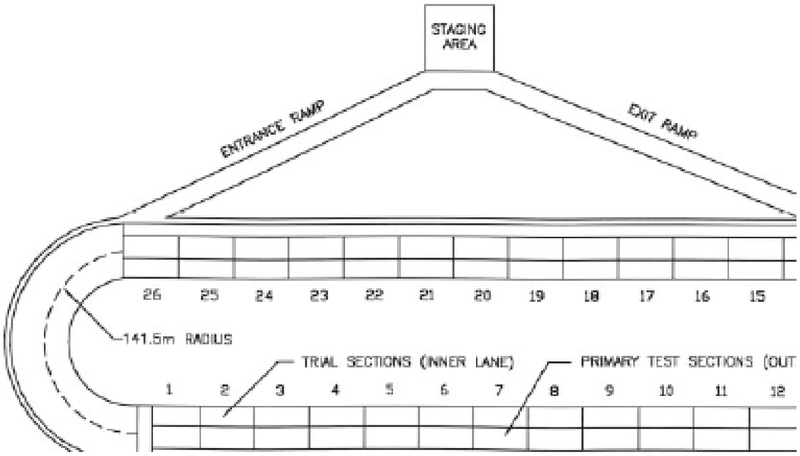


Figure (2-9) Layout of WESTRACK, WesTRack Team (not to scale), 1998.

Vehicle Loading

As in Figure 2-14, the configuration of loading system to enable calculate the ESAL at each loading cycle.

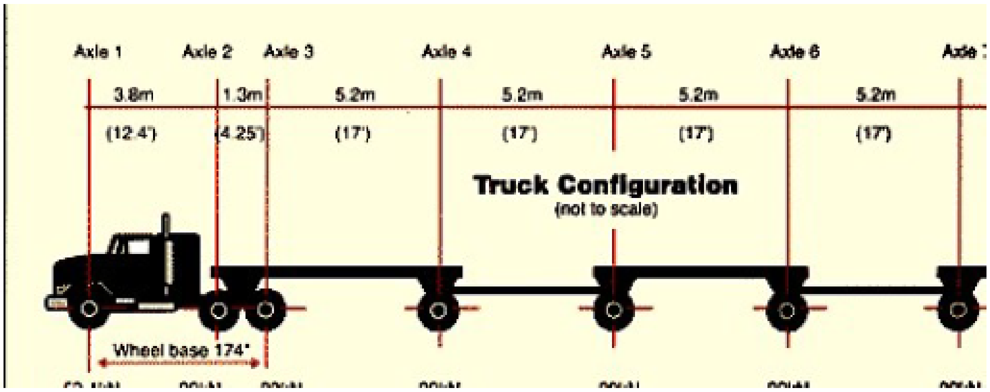


Figure (2-10) Loading truck and axle distribution at W.T. (WesTrack Team, 1998).

Asphalt Binder.

A single performance-graded asphalt binder was chosen, PG 64-22.

Aggregate Type, Surface Texture, Shape and Gradation.

A single primary aggregate source was selected for study. Three gradations were utilized. A gradation on the fine side of the Superpave 19 mm nominal maximum

Asphalt Binder Content.

Optimum asphalt binder content was determined by the SHRJP volumetric mix design procedure for the "fine" and "coarse" gradations.

In-Place Air Voids.

Three levels of in-place air voids were selected for study in the project (4%, 8%, and 12%) For fine, fine plus, and course mixes.

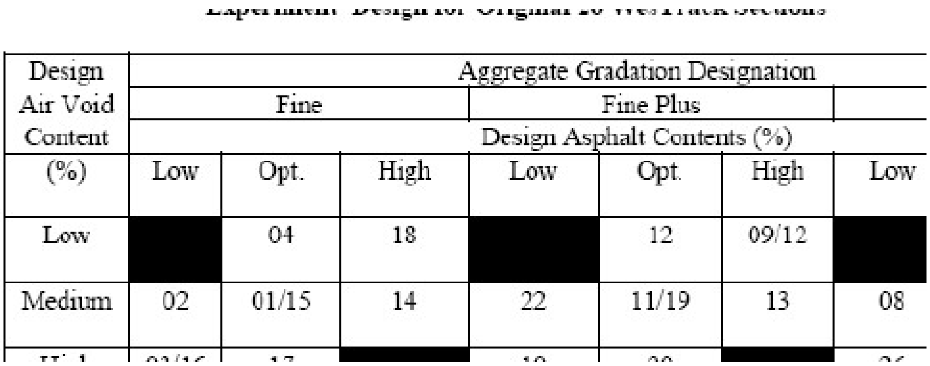
Thickness of Hot-Mix Asphalt.

A single thickness of hot-mix asphalt was selected. The structural section for the track was designed to provide fatigue failure for typical hot-mix asphalt at about 3.3 million ESALs. The structural section consists of 150 mm (6 in) of scarified and mixed subgrade soil, 300 mm (12 in) of engineered fill which was obtained from the natural subgrade materials, 300 mm (12 in) of dense-graded crushed aggregate base course and 150 mm (6 in) of hot-mix asphalt, constructed in two 75 mm (3 in) lifts.

Experimental Design

The experimental design is shown in Table 2-5. Three aggregate gradations, three asphalt binder contents and three in-place air void contents were selected.

Table (2-3) Experiment design for Original 26 sections (WESTRACK, 1998).



Design Air Void Content	Aggregate Gradation Designation						
	Fine			Fine Plus			
	Design Asphalt Contents (%)						
(%)	Low	Opt.	High	Low	Opt.	High	Low
Low	■	04	18	■	12	09/12	■
Medium	02	01/15	14	22	11/19	13	08

Data adopted from Westrack.

After the detailed mix design used in the Westrack project, the most useful data required for the research purpose is the accumulated ESAL obtained from the field and the related rut depth measured for each specific sections. Fine mix analysis will be studded in detail for the achievement of this research.

Influence of Mix Design performance on Rutting

The influence of mix design structural parts as (Aggregate and gradation, Asphalt content, Air Voids, VMA, VFA, and related performance and or polymer modification, all will have direct effect on the behavior of the pavement surface immediately after construction and while it is subjected to heavy traffic loading. Each element will have its specific effect and partial contribution on the final feature and mechanical behavior of the asphalt pavement surface.

In chapter 4 of the Asphalt Institute Manual they describe the relation between different factors who can describe the characteristics of pavement mix design, so this mathematical relation is relevant to analyze the required calculation and procedure under consideration at the design stage for mix design process. The analytical procedures apply either to paving mixtures compacted in the laboratory or to undisturbed sample cut from a pavement in the field, where the efficacy of compaction, either during construction or after years of service can be determined by comparing the specific gravity of an undisturbed sample cut from the pavement with the laboratory compacted specific gravity of the same paving mixture. The Asphalt Institute recommended that VMA values should be calculated in terms of aggregate bulk specific gravity.

Bulk Specific Gravity of Aggregate.

(a) Bulk specific gravity, Gsb

$$Gsb = (P1+P2+\ldots..+Pn) / ((P1/G1+P2/G2+\ldots..+Pn/Gn))$$

Where

P1, P2, Pn = Percentage by weight of aggregate, 1, 2, n

G1, G2, Gn = bulk specific gravity of aggregate, 1, 2, n

Maximum Specific Gravity of Mixture with different asphalt content, G_{mm}

$G_{mm} =(P_{mm})/ ((P_s/G_{se} + P_b/G_b)$

Where

P_{mm} = total loose mixture = 100 percent by total weight of mixture

P_s = aggregate, percent by weight of total mixture

P_b = asphalt, percent by total weight of mixture

G_{se} = effective specific gravity of aggregate

G_b = specific gravity of asphalt

Asphalt Absorption P_{ba}

$P_{ba} = 100\ [(G_{se} – G_{sb})/ (G_{se} .G_{sb})]*G_b$

G_{sb} = bulk specific gravity of aggregate

G_{se} = effective specific gravity of aggregate

G_b = specific gravity of asphalt

Effective Asphalt Content of Paving Mixture P_{be}

$P_{be} = P_b – (P_{ba}/100)* P_s$

P_b = asphalt, percent by total weight of mixture

P_{ba} = Asphalt Absorption

P_s = aggregate, percent by total weight of mixture

VMA in Compacted Paving Mixture

$VMA = 100 – (G_{mb.} P_s)/ G_{sb}$

Where

G_{mb} = bulk specific gravity of compacted mixture (ASTM D 2726)

G_{sb} = bulk specific gravity of aggregate

P_s = aggregate, percent by total weight of mixture

Air Void in Compacted Mixture V_a

$V_a = 100*[(G_{mm} - G_{mb})/ G_{mm}]$

G_{mm} = maximum specific gravity of paving mixture as determined directly for paving mixture by ASTM method D 2041

G_{mb} = bulk specific gravity of compacted mixture (ASTM D 2726).

All above mathematical formulas is well established as standard for design process, referring to Asphalt Institute manual. The correlation among the elements of pavement mix design as stated could lead to an advance mathematical relation gathering the related elements involved in the factors characteristics of each mix design and this will be described in modeling.

2.5. Parameters that influence Rut in Pavement

2.5.1. Influence of air voids (Va) and voids in mineral aggregate (VMA).

Air voids has a direct and very effective influence on the behavior of pavement surface before and after construction of roads, values for air voids are expressed in percentage by volume of the paving mixture, the importance of conducting analysis for air voids in the paving mixture it exceed the construction level to after construction, so the deterioration of asphalt pavement through several distress problem such as (rutting), cracking, raveling, potholes, surface deformation and roughness, rutting or what is called as permanent deformation is the target for analysis during this research work.

The air void volume change in the pavement is a function of construction compaction; more compaction will lead to higher stability (i.e., more rut resistance pavements),Huber and Heiman, 1987. Where Brown,1987, concluded that the major causes of rutting were excessive asphalt content and lower air voids in the asphalt mixture.

This research work will carry analysis for different asphalt pavement samples, having variable air void values. The LCPC will be applied for such test, details will be discussed in the modeling.

Anna et al, 2001. In his publication has pointed out certain results for the air voids, air voids filled with asphalt, and voids in mineral aggregate as such:

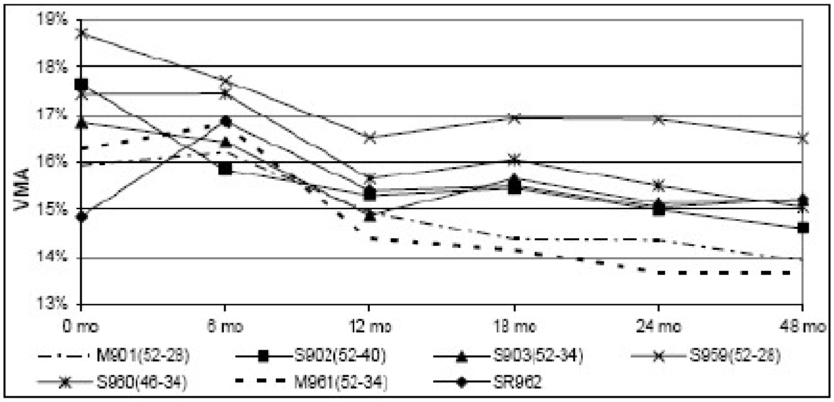


Figure (2-11) Progression of (VMA). CTAA, 2001.

The decrease in VMA over time by a percent 2 to 3, and this means decrease in air voids, where this will affect the behavior of pavement resistant to rutting, so the design VMA value is very important in order to achieve a higher susceptibility of pavement surface to rutting, eventually the air voids is part of the VMA and should have the most adequate specific design to resist against rutting.

NCHRP REPORT 478, (Relationship of Superpave Gyratory Compaction Properties to HMA Rutting Behavior), This work research include data from various pavement projects to evaluate the behavior of pavement surface under the influence of gyratory compaction process, this means the influence of air voids in the pavement mix design specifically superpave mix.

2.5.2. Influence of the Asphalt Content

The asphalt content is the second important factor that affects rutting, the analysis is quite important to relate its effective influence to pavement surface.

$$P_{be} = P_b – P_{ba}/100 *P_s$$

Where P_{be} = effective asphalt content, percent by total mass of mixture

P_b = asphalt content, percent by total mass of mixture

P_{ba} = absorbed asphalt, percent by mass of aggregate

P_s = aggregate content, percent by total mass of mixture

The average increase in asphalt content affects the pavement surface to rutting with noticeable result. Many research works analyzed the asphalt contents and its relation to pavement behavior to rutting.

2.5.3. Influence of the performance grade (PG)

2.5.4. Influence of the penetration

Penetration of an asphalt or what is called the stiffness; this is an early indication for the resistance feature of the asphalt and the entire mix, in (**CTAA, 1998),** stiffness is also indicated as a significant influencing factor with respect to rutting potential. Dawley, 1998,conducted work indicate that binder stiffness is a significant influencing factor with respect to instability rutting performance, particularly during the initial service period. As was found with the SMA mix, using harder or stiffer asphalt binder results in a decrease of rutting susceptibility. The stiffer the asphalt binder is the greater the decrease in rutting susceptibility.

2.5.5. Influence of polymer modification

The polymer modification is a positive indication to improve the properties of the asphalt binder and the entire behavior of pavement resistibility to rutting. In the following publication, M. Murphy et, CTAA-33-2000, indicated that, bitumen's modified with recycled polymers improves the pavement susceptibility to rutting.

2.5.6. Influence of the VMA (Voids in Mineral Aggregates)

VMA or voids in mineral aggregates, is one of the most important factor in the design mix criteria studies, due to related influence of the volumetric calculation and design percentage, it is measured as volumetric percentage of entire mix by volume. The design mix of the VMA is of a higher relevant importance for the entire asphalt mix design, due to the presence of volume percentage design of the air voids and the percentage of asphalt content (effective asphalt content), the higher VMA values may result in pavement more susceptible to rutting, and lower values too, the design criteria prove to have relatively measured range values, which it prove more resistance to rutting.

The decrease in VMA over time by a percent 2 to 3 will affect the behavior of pavement resistant to rutting, so the design VMA value is very important in order to achieve a higher susceptibility of pavement surface to rutting.

The calculation process, VMA in Compacted Paving Mixture

$VMA = 100 - (G_{mb.} P_s) / G_{sb}$

Where

G_{mb} = bulk specific gravity of compacted mixture (ASTM D 2726)

G_{sb} = bulk specific gravity of aggregate

P_s = aggregate, percent by total weight of mixture

This calculation is important result and it could combined with other volumetric calculation to farther mix design elements properties to improve adequate mathematical relation, and how such relation can affect the modeling of rut with relation to rut parameters.

2.5.7. Influence of the FVA (Voids Filled with Asphalt)

VFA or voids filled with asphalt, is an important parameter affecting pavement surface with respect to rutting, the higher values is the better to rutting resistance without exceeding certain percentage as indicated in many research work. The VFA will show an increase in percentage over time with the increase of rut, again this is an important factor to promote a reasonable aggregate porosity and control the air voids.

2.6 Rutting in management system

Pavement management system is: "The system which involves the identification of optimum strategies at various management levels and maintains pavements at an adequate level of serviceability. Rutting is considered as one of the major distress problem to pavement surface. Pavement management is considered as important tool to design, predict, implement, and bring the pavement to construction and utility, later to rehabilitation, all this process must have an adequate system to be managed. (Fred Finn, 1997) adopted an article on pavement management system at (National Workshop on Pavement Management in New Orleans, La. 1997). He presented that Dr. Karl Pister, described the potential benefits of systems engineering. Pister presented an approach for estimating "optimality" in the decision-making process as part of a management system. He even provided general mathematical solutions to achieve such optimality for a pavement management system. Pister did not invent systems engineering, he simply pointed out that pavement design and pavement management were very complicated problems and that one way to handle complicated problems is through the use of systems engineering.

The U.S. Army Corps of Engineers developed a somewhat more rational way of calculating an index, but in the final analysis, it is based largely on engineering judgment. The participants in the 1980 national workshops in Phoenix and Charlotte attempted to evaluate the possibilities for the development and implementation of PMS. Some of the significant products from these workshops were summarized in the Proceedings published by FHWA in June 1981.

In addition to engineering experience, PMS operations require a knowledge of statistics, modeling, economics, theories of optimization (operations research), computer science (sophisticated programming), and database management. The Transportation Research Board established a Pavement Management Section with committees on Pavement Management Systems and Pavement Rehabilitation. Literally hundreds of papers have been presented and published in Records of the Board. The American Association of State Highway and Transportation Officials (AASHTO) issued "Guidelines for Pavement Management Systems.

According to a 1996 survey by FHWA, which included information from the 52 agencies, the dominant forms of distress being measured and included in respective PMS databases are rutting, faulting, and cracking. Surface friction information is measured and stored by 39 agencies. Five states measure deflection at the network level, and nine have deflection measurements under development. Clearly, the implementation of PMS databases is generating a large amount of empirical and useful information on the condition of pavements. This information is needed for prioritization, optimization, and the development of prediction models.

Based on this type of information, FHWA has contracted to develop standardized protocols for at least these four types of measurements: rut depth, faulting, and various types of cracking. Protocols can describe procedures to follow and methods for quality assurance.

2.7. Rutting Prediction models

Many models and research achievements in prediction of rutting, which added important contributions to the work and analysis of rutting prediction models, some of the models considered the influence of one factor, some they considered more than one but all focus on the prediction of rutting with the influence of various factor. Adrain, 2000, Developed progression model to predict the rut depth measurement, by combining data from multiple sources (WESTRACK and ASHTOO) for a PH.D defense work, in his attempt, data was collected and analyzed to conclude a prediction model. His analysis concluded that, the development of an empirical rutting progression model with an experimental data set from WesTrack is described. The salient features of the model specification are as follows: (a) three properties of the mix are sufficient to model the performance of the asphalt concrete pavement at WesTrack accurately; (b) the model captures the effects of the high air temperatures at WESTRACK; and (c) the model predicts rut depths by adding predicted values of the increment to rut depth for each time period, which is particularly advantageous in a pavement management context.

MODEL SPECIFICATION

The following equation was specified for the model:

Rd = y_0 + mit* ΔNit*e^ γ 7*Nit, **Adrian et al, 2001**

Rd = rut depth predicted

y_0 = Initial rut after construction

mit = a function for characteristics of pavement

ΔNit = a variable representing load repetition

γ 7 = hardening parameter

Nit = a variable representing accumulative load repetition

This equation indicates that the rut depth increments are proportional to the loading in the corresponding periods, .*Nit*’s, where these increments decrease with increasing cumulative loading, *Nit* (for negative γ 7). The third multiplicative term, *mit*, is assumed to vary with pavement characteristics and environmental conditions. Because in WesTrack almost 100 percent of the rutting is due to permanent deformation of the asphalt concrete layer, *mit* is assumed to be a function of the mix characteristics only. The predictions of the model will be limited to rutting originating in the asphalt concrete layer.

And .Nit are given by

Nit = a variable representing the cumulative number of load repetitions applied to pavement section.

Nit = ∑ Δ Vis {[FL/SAL] ^βs + Ri [AL1/SAL] ^βs + [AL2/ β1 SAL] ^ β6]}

Δ Vis = number of vehicles passes on road section

FL = load on front axle of the truck (53.4 kN)

AL1 = load on single-load axle

AL2 = load on tandem-load axle (2*89 = 178 kN)

Δ = parameter determining the equivalencies between axle load

The assumed value of δ is 0.39

Rd = δi + ai (1- e ^biNit) rut depth as per ASHOO model

ai and bi = functions for the characteristics of pavement

The rut depth model Rd = y_0 + mit ΔNe^ γ 7*Nit, **Adrian et al, 2001.** Another modeling system to predict the pavement rutting considering elastic modulus variations, Li et al, 1999: In this work the author proposed model for predicting the elastic modulus of Ac. Thus, the existing mix design approaches can be improved by using the modulus prediction model. Elastic modulus is one of the most important mechanical properties of asphalt concrete (AC) mixes because it is related to the strength of AC.

2.8. Different techniques to enhance the resistance to rutting of flexible pavement.

Rutting is considered as the most bothering failure of the asphalt pavement. Since many decades several attempts been implemented to achieve most suitable process to enhance the resistance to rutting in flexible pavement.

1. -Improving Aggregate or stone (design mix, aggregate size, shape, soundness, and type)
2. -Improving asphalt by modified emulsified polymer asphalt
3. -Modifying the pavement foundation, this will illustrate the principle of soil mechanics, and improving of resilient modulus of foundation soil. Which means the implementation of elastic theory?
4. -Improving the soil condition (Pavement Foundation). As Brown, 2000.

Another publication article, Thomas, 2003. Using the stone mastic asphalt mix, to enhance the pavement mixture to resist rutting.

2.9. Experimental Studies

2.9.1. Introduction

Part of this research work will be the experimental laboratory test of different pavement samples, will be taken from a known pavement mixes. various mix design samples will be taken and test with LCPC (French Tester), where rut readings of several cycle loads will be observed, such result will prove rutting occurrence due to several cycle loads in the laboratory using (LCPC Tester) and such reading of rutting due to respected cycle loading will be compared with a similar rut reading from field and road readings, in comparison the result will indicate the empirical and mathematical relation among different mix design elements. An observed reading from various field projects will be used in this research work for the detail analysis to predict rut and reach to a reasonable mathematical model to predict and control rutting.

2.9.2. Description of the LCPC rutting tester (N. L. Canada), 2003

LCPC rutting tester is the French (Laboratoire Central des Ponts et Chaussees) Pavement Rutting Tester (NLC). This tester is used in France to evaluate mixtures subjected to heavy traffic; mixtures that incorporate materials that tend to lead to rutting, such as some natural sands; and mixtures that have no performance history. It is also used for quality control purposes during construction process; a detail description of LCPC tester is available in section (**3.1**). French Rutting Tester-Is a self contained chamber with a temperature regulation device, a table platform that can lift the sample to the tire with a predetermined amount of force, and a motor to move the tires across the slabs at a rate of one cycle per second.

2.9.3 Test Procedure

Check and/or fill the tires to 87 psi (0.6 Mpa). The tire pressure will need to be decreased due to the higher air temperature in the tire that comes from the increased temperature in the chamber. The test is taken at room temperature and reported, the first reading at 1000 cycles, then run cycles to 10,000 and take readings of rutting for each specific sample. The report shall include the following parameters:

- Maximum compression or rutting, mm
- Number of Passes
- Test Temperature
- Sample Air voids

Test Time: 8 hrs (30,000 cycles @ 67 cycles/min)

Table (2-4) Description of Available Criteria for LCPC, (N. L. Canada), 2003.

Criteria	Test Condition				
	Wheel	Load	Specimen Size (mm)	Cycles	Temperature
10 mm	Pneumatic (600 kPa) 400 mm diameter, 90 mm wide	1124 lb (5000 N)	500 × 180 × 100	30,000	Dry, 60°C

Following the reported data to be collected from the French test, a measured rutting result will be used for the detail analysis as described earlier:

Sample test, where all characteristics and properties of each sample mix is observed and reported. Rut report, for each sample will be observed and reported for the detail comparison and analysis. Equating the result observed from all samples, and adopting the final relation of all mix sample properties in a mathematical correlation form to predict the rut depth measurement. The mathematical or empirical formula is not the only objective, but the relation among the various mixture elements to predict and produce minimum and acceptable rut is the major target.

2.10. Modeling.

Is a process of generating an empirical and or mathematical relation involving the influence of all recorded elements in the pavement mixture, many research work have achieved certain result in this direction, but each research approach deled with different concepts and arrived at a positive contribution to modeling of rut measurement and reported the resultant data.

In this research work analysis, the model will not only focus on reporting the influence, but will work to develop the mathematical correlation and influence of each element, to compare the entire behaviour of the asphalt mix under the effect of traffic axel loading. The predicting of rut depth model is a process of mathematical relation resulted from data obtained, and from the rut depth measured in the laboratory and field (Road).

2.11. Conclusion

The final conclusion of literature review.

- The rut depth is influence by aggregate size and shape, or physical properties which can be determined by specific gravity of aggregate particles and mixture.
- The rut depth is influence by designed VMA, void ratio, and observed VFA.
- The rut depth is influence by the effective percentage of asphalt content.
- The total asphalt content could be designed to bring maximum susceptible mixture to rutting or permanent deformation.
- The rut depth will increase gradually with the increase of traffic loading, the relation is non linear as the curve can show, till it reach the maximum deformation.

- The construction environments of the pavement surface are a valuable influence to the entire behavior of the pavement with relation to rut occurrence.
- The influence of the pavement underneath (Soil), will affect the behavior of pavement, and a correlation between pavement mixture and pavement foundation should have the acceptable mathematical relation to improve the modeling process.
- The final modeling or mathematical relation will be formed from the correlation of all parameters that will have direct effect on mix design such as (Va, Pb, VFA, PG, NMAS, Cu& Filler).

Chapter-3

LCPC Rutting Tester.

Three main steps will be performed in this chapter:

1. Lab. Experiments adopted on various asphalt mixes for data collection from laboratory work.
2. Data collection from various major projects conducted for the same purpose Rut measurement and control.
3. Objectives and scope of work

3.1. The experimental data of various HMA will be collected from respected local asphalt pavement campaign, which will be conducted in laboratory of roads pavements. The adopted test for the experimental study is the LCPC rutting tester (Orniéreur LCPC).

3.2. LCPC Rutting Tester

The LCPC rutting tester or the French Laboratory Rutting Tester (FLRT), shown in Figure 3-1, is laboratory equipment designed to investigate the rutting resistance of bituminous materials under conditions comparable to the stress applied to pavements, in accordance with MTQ standard LC26-410.

Rectangular specimens (slabs) of bituminous mixes are subjected to repeated passes of a wheel fitted with a tire, mounted on a carriage that moves back and forth at a sinusoidal rhythm, inducing permanent deformations. The tested specimens is prepared in the laboratory using the LCPC slabs compactor “BBPAC” (Figure 3-2) or obtained from the field by sawing existing pavements.

Two specimens can be placed in the pavement rutting tester at a time, on two separate supports, for testing with the same or different parameters, and for the same temperature. The rolling loads are maximally channelled on each slab as the wheel always passes on the same trajectory. The tires apply always vertical loads on the surface of each slab during the test. It is also possible to create a skidding component if desired by varying the angle of tire in the horizontal plan. The temperature of the test is regulated using five temperatures probes distributed in the thermal chamber. Since the early 1990s, the French Laboratory Rutting Tester (FLRT) has been used in Quebec to evaluate asphalt mixes for rutting resistance. The FLRT is currently an integral part of the LC mix design method of the Quebec Ministry of Transportation (MTQ).

In the FLRT, the repetitive load is applied by a pneumatic tire (400 mm diameter and 80 mm wide) passing on the surface of the slab at a frequency of 1 Hz. Two slabs can be tested simultaneously in one run of the FLRT. The pressure of the tires is set at 600 ± 30 kPa. The applied load is 5000 ± 50 N and the typical testing temperature is 60° C. The rut depth and the number of cycles are measured at 100, 300, 1000, 3000 and 10000 cycles and 30000 cycles. The total number of cycles in the test is limited to 10000 for fine graded mixes and to 30000 for coarse graded mixes. The rut depth for each slab is calculated as the average of 15 measurements conducted on the surface of the slab at the end of the test. The percentage of rutting is given as the average of the results obtained for the two tested slabs divided by the initial thickness of the slab. It should not exceed 20 % for fine graded mixes and 10% for coarse graded mixes. The MTQ standards 26-400 and 26-401 are provided integrally in the appendixes of this document.

Figure (3-1) two photographs of the LCPC rutting tester from different positions (Laboratories of Sintra inc.-Saint-Hyacinthe, Quebec)

Figure (3-2) LCPC slabs compactor (Laboratories of Sintra inc.-Saint-Hyacinthe, Quebec)

3.3 LC Mix Design Method

The LC mix design method is inspired from the Superpave and the French mix design methods. The mix design uses the Superpave Gyratory Compactor to evaluate the compaction ability and uses the LCPC rutting tester for rutting resistance.

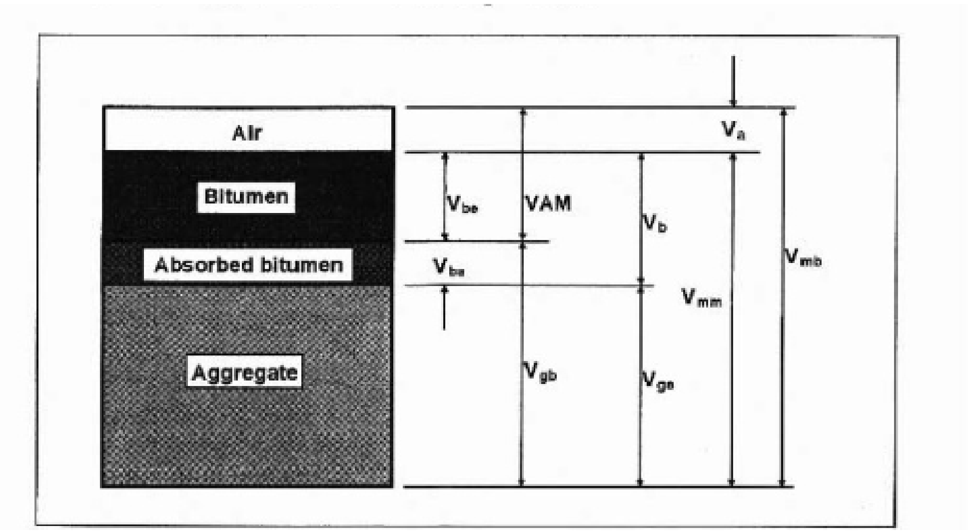


Figure (3- 3): Mix Design Volumetric presentation for LC method.

VMA = Voids in Mineral Aggregate;

Vmb = Builk Volume of compacted mixture;

Vmm = Voidless volume of compacted mixture;

Vbe = Volume of effective asphalt binder (corresponds to VFA=voids filledf with asphalt, in terms of volume);

Va = air voids volume;

Vb = Volume of asphalt;

Vbe = Volume of effective asphalt binder;

Vsb = Volume of mineral aggregate, by builk specific gravity;

Vse = Volume of mineral aggregate, by effective specific gravity;

Volumetric calculation Procedure

The followings are calculations steps and procedure for the volumetric analysis using LC method:

- Determine the bulk specific gravity for the aggregate (Gsb), for course aggregate greater than 5mm. And fine aggregate less than 5mm, using test methods NQ 2560-067, and NQ 2560-065 respectively.

- Determine asphalt specific gravity (Gb) according to test method ASTM D 70.
- Determine the combined specific gravity of all aggregates sizes used in the mix.
- Determine the maximum specific gravity (Gmm) of the mix according to test method LC 26-045.
- Determine the effective specific gravity of the aggregate (Gse) for the same mixture.
- Determine the percentage of asphalt absorbed by the aggregate (Pba).
- Determine the initial asphalt percentage in the mix (Pbi).
- Determine the maximum theoretical density (Gmm) of the mix for the initial asphalt percentage (Pbi).
- Determine the air voids (Va) in the compacted mixture, using the gyratory compactor.
- Determine the percentage of the (VMA), and VFA.

Following this procedure, the different volumetric of the designed mix are determined. The sample of the mix can be prepared, for required mix type, later compacted and prepared to be tested at the FLRT rutting test.

Determination of the optimal binder content:

The LC design method includes two design levels (1, 2). Level 1 consists on the determination of different parameters of the mix design based on the type of the mix, the traffic and other related parameters. Level 2 allows for verification of resistance to rutting to the designed mix in Level 1 using the FLRT. The principle characteristics of the LC method are the setting of the volume of the effective asphalt binder (Pbe) for each mix type, later to optimize the aggregate grade used to respond to air voids specifications (Va), at a given compacting level.

The workability of the pavement mixture as measured in the Superpave Gyratory Compactor (SGC). The characteristics of the gyratory compactor used in LC method:

- 600 KP, pressure on the surface of the specimen.
- 150 mm interior diameter mould.
- 30 gyrations per minute-speed.
- 1.25-degree. The angle of inclination of the mould during the compaction.

Moisture Sensitivity

The final step of the LC method is the mix sensitivity to moisture. The moisture sensitivity is established by the comparison between Marshal Stability level of the specimens which were soaked and those which were not. The comparison value should be greater than 70%.

3.4. Tested materials

Table (3-1) shows the different types of mixes used in province of Quebec for paving projects administrated by the MTQ. For each mix, it specifies the different types of usage and the level of recommendation (To be avoided, Adapted, and Recommended).

Table (3-1) Type of pavement Mixes, MT. Quebec, 2000.

Criteria of HMA Selection

Type of Mix	EB-20	ESG-14	ESG-10	EGA-10	EG-10
Usage					
Base	3	2			
Unique Layer	1	3			
Surface		2	3	3	3
Intermediate					
Correction			1		
Performance					
Surface Texture	3	3	3	4	5
Resistance to rut	5 Excellent	4 very good	4 very good	4 very good	3 good

3.5. Sample of Mixes to be used in the test experiment

3.5.1 EG-10 Pavement Mix Type

The EG-10 is a high-performance grained asphalt mix developed by the Quebec Ministry of Transportation MTQ since 1990. In this mix, the gradation curve is situated lower than the maximum density curve. It was designed to be applicable at thin surface course on both old and new pavement.

The EG-10 is designed for surface layers for highways in rural areas with high speed traffic. It offers a better skid resistance in rain and freezing rain conditions due to its rough surface. Given the particle size distribution, it is highly resistant to segregation and can be laid easily. EG-10 mix requires the use of high quality fully crushed aggregates. However, only polymer modified binder of grade PG64-34 must be used to manufacture this mix type.

3.5.2 EGA-10 Pavement Mix Type

EGA-10 is a grained asphalt mix that belongs to same family of EG-10 but it contains asbestos fibres. Its high mastic content and the fact that it is highly gap-graded make for a more closed, denser surface than standard grained asphalt mixes. It was designed to be applied as a thin surface layers (40 to 70 mm) on existing pavements. EGA-10 is highly fatigue resistant and retards reflective cracking. The high mastic content reduces the permeability of the mix and protects the pavement structure while maintaining its load-bearing capacity.

It is commonly known that asbestos is hazardous to human life and can cause cancer if been swallowed directly. The introduction of asbestos must be done very carefully. High and preventative care must be taken during the mixing process. The EGA-10 mix is highly recommended as rut resistant mix.

3.5.3 ESG-10 Pavement Mix Type

The EGS-10 is Semi-Grained Asphalt Mix for which the gradation curve is situated below the maximum density curve. The performance of the ESG-10 mix depends on the properties of its components. The thickness of asphalt layers with this type of mix varies from 40-70 mm depending on aggregate angularity. It is suited for use on national, regional and municipal roads. The aggregate gradation of ESG-10 makes it more impermeable than EG-10. However, if the used aggregates are angular, they can then confer better resistance to rutting with PG64-LL grade performance, refer to Figure (3-6) in the appendix.

3.5.4 Stone Mastic Asphalt (SMA)

The Stone Mastic Asphalt is a gap-graded gradation mix, which combines good aggregates and high binder content. The aggregates used in the fabrication of the SMA must be high-quality fully crushed aggregates. The granular skeleton of the SMA consists of up to 80% of coarse aggregate and up to 13% of filler all by weight percentage. The gap-graded aggregate mixture provides a stable stone-to-stone skeleton. Aggregate interlock and particle friction are maximized. This gives the structure its stability leads to a better resistance to permanent deformations and then to rutting (Baaj et al., 2003). The resistance to fatigue and the durability of the SMA is also increased thanks to the high binder content and the high percentage of filler (Perraton et al., 2003). These two components create the mastic in the mix. The popularity of the SMA increases significantly in North America due to its high performance.

Stabilizing additives, such as organic or mineral fibers are also used in the composition of the SMA. They help stabilizing the asphalt mortar and prevent binder drain-down from the aggregate. Very common additives are cellulose fibers. They contribute to the volume of the asphalt mortar without making the mastic brittle or negatively, influencing the properties of the bitumen. The fibers used in the province of Quebec are asbestos fibers (Baaj et al., 2003).

Table (3-2) Gradation and mix parameters of SMA, (Perraton et al., 2006).

Dosage		Sieve Size	Passing (%)
Bitumen (% by weight)	6.43	14 mm	100
Fibres content (% by weight)	1.3	10 mm	87
Maximum relative density (D_{mm})	2.402	5 mm	29
Superpave Gyratory Compactor Results		2.5 mm	20
		1.25 mm	19
Voids at 10 gyrations (%)	14.8	630 µm	18
Voids at 60 gyrations (%)	6.9	315 µm	17
Voids at 80 gyrations (%)	5.8	160 µm	17
Voids at 200 gyrations (%)	3.0	80 µm	12.9

3.6. Data Collection from Major Projects

Several and various comprehensive data from major projects serving asphalt pavement rut problem will be collected for the purpose of model development and comparison of data result for detail analysis, and to confirm with the result of the predicted rut model. The aggregate gradation of data collection from westrack (Fine, Fine Plus, and Course), which is having a similar mix type design for the comparison purpose with the result of this research.

In Table (3-10), which contain the data of 26 sections, of all mix types course& fine aggregate with the result of rut data from 4000 ESAL to 4700000 ESAL, and the record of rut at considerable intervals, making the benefit of such data more positive and encouraging?

During the research work, the rut depth calculated with respect to number of cycles will enable to produce the required rut depth formula and compare it with the data present from WestRack project, data in appendix Table (3-9).

3.7. Scope of work and objectives

The following is the anticipated scope of work schedule for the research project:

- Preparation of pavement mixes using LC method.
- Prepare the mix sample and compact it using gyratory compactor.
- The FLRT will be used to measure rut of various mixes.
- Data collected from LCPC tester is the main collective data for the analysis of various mixes.
- Obtain a selective data from laboratory performed data observation of major projects, conducted for the same Purpose.
- Detailed analysis of experimental data to withdraw some pertinent conclusions on the influence of mix design parameters on the rutting.
- Establish a simple rut prediction model based on experimental data and field data.
- Establish a simple computer tool (Predication software).

Chapter-4

Laboratory Experiential Data and Research Work

4-1 Introduction

In this chapter, the data obtained for different asphalt mixes will be analyzed and a rut prediction formula will be proposed. In the analysis, we will focus mainly on the mixes with 10mm Nominal Maximal Aggregates Size. However, the model may be generalized for other mixes but enough data should be available. A generalization tentative is shown at the end of this chapter with the available data.

The first step of the analysis work is to analyze the available data of the different ESG-10 mixes and propose a prediction formula at 1000 and 3000 cycles of loading. The model is then generalized to cover other 10mm mixes (ESG-10, EG-10 and EC-10). For each analyzed mix, the following parameters are determined, calculated or measured:

1- PG grade of the asphalt binder using in the mix. The PG grade is characterized by two numbers, the high temperature (HH) and the low temperature (LL). For example, the PG 58-34 means that the high temperature of the PG grade is 58°C and the low temperature of the PG grade is -34°C. The high temperature (HH) affects significantly the resistance to rutting as a higher HH means a higher resistance to deformation and leads usually to a better performance at high temperature. The low temperature of the PG grade (LL) affects the resistance to low temperature cracking. It is then not considered here for rutting analysis.

2- The percentage of the binder (Pb) by weight the total weight of the mix. Usually, for well deigned mixes, the higher the Pb the lower the resistance to rutting.

3- The air voids percentage (Va) in the compacted mix to N_{des} affects also the resistance to rutting. The mixes with higher air voids percentage tend usually to a phenomenon of post-compaction and may lead to an increase in the rutting.

4- The gradation of the aggregates in the mix affects the resistance to rutting. Coarse graded mixes, such as EG and ESG, and gap graded mixes, such as the SMA and EGA, offer usually better resistance to rutting comparing to fine graded mixes thanks to their grained Skelton. Moreover, the percentage of the filler in the mix affects the quality of the mastic and may affect the resistance to rutting. In this analysis, the gradation of the mix is described using three values:

    a) The Nominal Maximum Aggregates Size (NMAS): The size of the first sieve with more than 90% passing.
    b) The Percentage of filler in the aggregates: The percentage of the aggregates passing the sieve No. 200.
    c) The coefficient of uniformity (Cu): It is ratio D60/D10, where D60 is the particle diameter corresponding to 60% passing and the D10 is the size corresponding to 10% passing in the gradation curve.

5- The Voids Filled with Asphalts (VFA): This value is one of the mix design values. It depends on the level of compaction and on other volumetrics. It reflects how the binder and the aggregates interfere together in the final mix. To obtain this value, a full LC mix design procedure should be conducted.

6- The rut depth measured using the LCPC rutting test at different numbers of cycles (1000, 3000, 10000 and 30000). For the 10mm mixes, the important numbers of cycles are 1000 and 3000 cycles as LCPC indicate.

4-2 Model analysis procedure:

Two levels will be considered in data analysis. In level 1, the proposed model will be based on data for one mix type (ESG-10). Level 2, will include other mixes with 10mm Nominal Maximum Aggregates Size. A tentative to generalize the model with other mixes with 14 mm and 20 mm Nominal Maximum Aggregates Size is also proposed.

The mix design parameters considered in both cases are: The high temperature of the PG grade, the percentage of binder in the mix Pb, the Nominal Maximum Aggregate Size (NMAS), the percentage of filler (Filler), the coefficient of uniformity (Cu), the air void at N_{des} and the Voids Filled with Asphalt (VFA).

The optimization of the model is based on the ***Least-Squares Method*** and the model parameters are determined using the *Solver* module in *Microsoft Excel®*. In each of the two levels, the following steps were followed:

1- Data collection: for each mix, the different mix design parameters are gathered in addition to the rut depth percentages at different numbers of cycles.
2- The form of the prediction formula is proposed and initial values for the parameters of the formula are attributed.
3- Using the proposed formula, the values of rut depth percentages are calculated for a given number of cycles (Example @ 1000 cycles) for each mix.
4- The errors between the measured and the predicted values of the rut depth percentages are calculated for each mix. Each error is squared and the sum of error is calculated for all mixes.
5- Using the *Solver* application in *Microsoft Excel®*, the sum of errors is minimized and the parameters of the prediction formula are then determined.
6- The results of the prediction formula are compared those obtained by measurements.

4-3 Level 1: Modeling using ESG-10 mixes only

In this part, the modeling will cover only the available mixes of the ESG-10 type. The available data for this type include 15 different mixes. For modeling purposes, we considered only the rut depth percentage values at 1 000 cycles and 3 000 cycles as those at 10 000 are not enough to propose a model. The LC mix design method requires that the rut depth percentage should be less than 20% at 3 000 cycles.

The steps explained in paragraph 4-2 are followed:

1- Data collection: The different mix design parameters used in the model are shown in Table 4-1 below.

Table (4-1) Mix design parameters used for the prediction of rut for ESG-10 mixes

Mix type	PG grade	HH (°C)	Pb (%)	Va @ N_{des} (%)	VFA (%)	Filler (%)	NMAS (mm)	Cu (mm/mm)
ESG-10	PG 58-34	58	5.55	6.3	66.5	7	10	26.4
ESG-10	PG 58-34	58	6.7	4.9	73.9	5.2	10	20.7
ESG-10	PG 58-34	58	6.6	4.9	73.6	5.2	10	20.7
ESG-10	PG 64-34	64	5.5	5.9	75.6	6.9	10	33.2
ESG-10	PG 58-34	58	6.25	4.8	73.8	5.7	10	29.0
ESG-10	PG 58-34	58	6.6	4.6	75.2	6	10	25.2
ESG-10	PG 64-34	64	5.55	5.0	69.3	6.7	10	34.4
ESG-10	PG 64-34	64	5.07	6.0	65.6	6.8	10	25.0
ESG-10	PG 58-28	58	5.26	6.2	64.7	5.3	10	16.9
ESG-10	PG 64-34	64	5.93	4.9	71.4	5.5	10	23.1
ESG-10	PG 70-28	70	5.38	5.9	66.1	5.6	10	21.1
ESG-10	PG 64-34	64	5.19	5.5	67.9	6.3	10	20.1
ESG-10	PG 64-28	64	5.45	5.5	68.1	7.1	10	35.4
ESG-10	PG 58-34	58	5.25	5.6	67.3	3.2	10	17.8
ESG-10	PG 58-34	58	5.3	6.5	63.6	4.6	10	15.5

2- The form of the prediction formula is proposed as follow:

$$Y = A \times (HH)^{N_a} + B \times P_b^{N_b} + C \times (V_a)^{N_c} + D \times (VFA)^{N_d}$$
$$+ E \times (Filler)^{N_e} + F \times (NMAS)^{N_f} + G \times (Cu)^{N_g} + Const.$$

Where, Y = Predicted rut depth percentage

A, B, C, D, E, F, G, N_a, N_b, N_c, N_d, N_e, N_f, N_g and Const. The constants of rut predication formula at a given number of cycles is, the number of cycles indication.

HH, P_b, V_a, VFA, $Filler$, $NMAS$ and Cu are the mix design parameters

Initial values for the parameters of the formula are attributed

- Predicted formula development process.

3- Using the proposed formula, the values of rut depth percentages are calculated for a given number of cycles (1 000 cycles and 3 000 cycles separately) for each mix.

4- The errors between the measured and the predicted values of the rut depth percentages are calculated for each mix. Each error is squared and the sum of error is calculated for all mixes. The calculations are shown in Table 4-2.

Table (4-2) Least squares method calculations at 1 000 and 3 000 cycles for ESG-10 mixes

Measured rut		*Predicted rut*		*Errors^2*		*Sum of Errors^2*	
Rut @ 1000	Rut @ 3000	Rut @ 1000	Rut @ 3000	1000 cycles	3000 cycles	14.37	56.76
4.5	6.1	5.1	7.0	0.329	0.768		
6.2	8.1	5.3	6.4	0.822	2.949		
6.2	8.1	5.3	6.4	0.777	2.874		
3.5	6.8	3.7	6.3	0.043	0.241		
	7.8		6.6	0.000	1.538		
5.1	5.4	5.9	6.5	0.631	1.173		
	2.7		6.3	0.000	12.711		
5.5	8.1	4.4	6.8	1.250	1.808		
5.2	8.2	4.9	7.1	0.088	1.142		
3.3	5.1	4.6	6.0	1.735	0.750		
4	6.7	3.3	5.7	0.553	0.933		
6.5	10.2	4.5	6.6	4.115	13.059		
3.1	3.5	4.6	6.4	2.245	8.149		
4.1	5.5	4.4	5.4	0.078	0.003		
3.3	4	4.6	6.9	1.704	8.666		

5- Using the Solver application in Microsoft® Excel®, the sum of errors is minimized and the parameters of the prediction formula are then determined. The obtained results for 1000 and 3000 cycles are shown in Table 4-3.

Table (4-3) Rut prediction formula constants at 1000 and 3000 cycles for ESG-10 mixes only

@ 1000 cycles

A1	B1	C1	D1	E1	F1	G1	
367.92	70.47	133.13	254.63	-65.04	971.04	-354.45	
Na1	Nb1	Nc1	Nd1	Ne1	Nf1	Ng1	Const1
-0.8344	-3.4831	-2.4310	-0.9000	-0.0241	-1.6217	-17.0473	23.9859

@ 3000 cycles

A2	B2	C2	D2	E2	F2	G2	
115.79	12299.39	37942.80	7054.64	-734.00	15797.84	-354.45	
Na2	Nb2	Nc2	Nd2	Ne2	Nf2	Ng2	Const2
-0.5176	-5.6827	-15.9804	-8.1682	-5.1528	-3.4224	-17.0473	-13.8440

6- The results of the prediction formula are compared those obtained by measurements.

The obtained formula with the values of the parameters issued from the Solver application at 10 000 cycles is as follow:

The Figures 4-1 and 4-2 show the correlation between measured rut and predicted rut at 1 000 cycles and 3 000 cycles respectively.

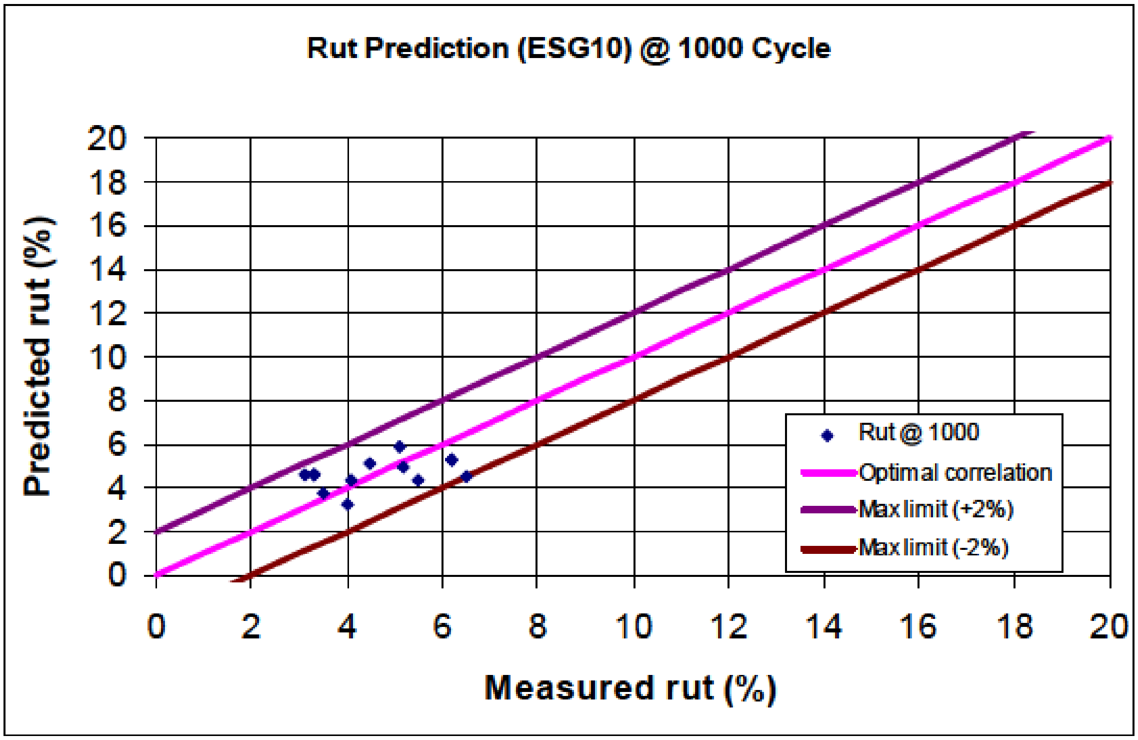


Figure (4-1) Correlation between measured and predicted rut at 1000 cycles for ESG-10 mixes only

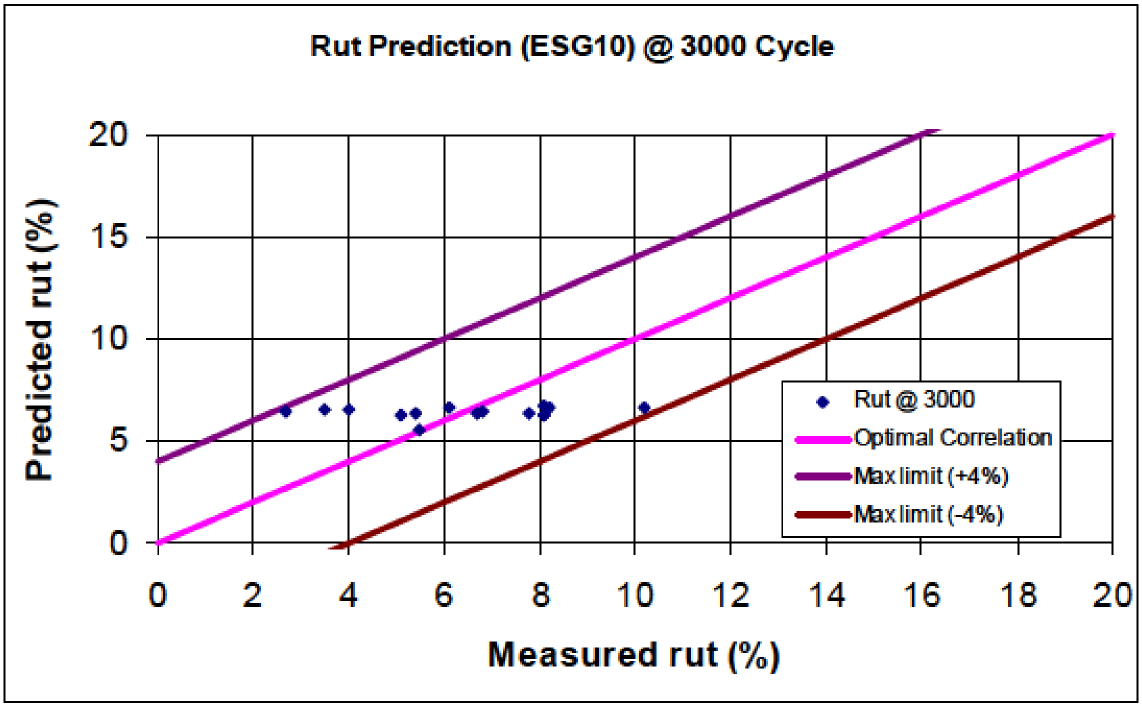


Figure (4-2) Correlation between measured and predicted rut at 3000 cycles for ESG-10 mixes only

In Figures 4-1 and 4-2, three lines are shown. The central line, called "Optimal correlation" shows the theoretical correlation between the predicted rut and the measured rut. This correlation represents the following equation:

$$\textit{Predicted Rut} = \textit{Measured Rut}$$

This theoretical correlation is impossible to reach experimentally. The main raison behind this is that the LCPC rutting test is not a deterministic test but an empirical test. In other words, the repeatability and the reliability of this kind of test are not high. This test gives usually an indication on the resistance to rutting and not a reliable and repeatable value. Unfortunately, our literature review didn't yield any relevant document to support this information.

The examination of Figures 4-1 and 4-2 shows that the predicted values of rut depth percentage are in general close to the optimal correlation line. Figure 4-1 shows that all points are within the range of ±2% indicated by the two other lines. The points in Figure 4-2 are within the range of ±4% of the theoretical line.

Based on these results, the prediction model at 1000 cycles would allow then to predict the rut value within ±2% certainty level and at 3000 within ±4% certainty level.

The certainty envelopes at 1000 and 3000 cycles are then presented as follow:

$$\textit{At 1 000 cycles: Predicted Rut} = \textit{Measured Rut} \pm 2\%$$

$$\textit{At 3 000 cycles: Predicted Rut} = \textit{Measured Rut} \pm 4\%$$

These certainty levels are very acceptable for this test. However, the data used for the calibration of the model are very limited. It is important then to increase the volume of the database and to validate the model with other tests.

4-4 Level 2: Modeling using 10mm Nominal Sizes mixes

In this part, the modeling will cover all mixes with 10mm Nominal Maximum Aggregates Size. The total number of mixes is 28. The considered types are: ESG-10, EG-10, EC-10 and EGA-10. Also here, only the rut depth percentage values at 1 000 cycles and 3 000 cycles are considered.

Similarly to the work explained in paragraph 4-3 for ESG-10 mixes, the steps explained in paragraph 4-2 are followed:

1- Data collection: The different mix design parameters used in the model are shown in Table 4-4 below.

Table (4-4) Mix design parameters used for the prediction of rut for all mixes with 10mm Nominal Maximum Aggregates Size.

Mix type	PG grade	HH (°C)	Pb (%)	Va @ N_{des} (%)	VFA (%)	Filler (%)	NMAS (mm)	Cu (mm/mm)
EC-10	PG 64-34	64	5.93	4.6	72.6	7.8	10	27.9
EC-10	PG 64-34	64	5.55	5.8	67.5	7.4	10	21.4
EC-10	PG 64-34	64	5.93	4.6	73.0	6.5	10	25.4
EG-10	PG 64-34	64	5.4	5.7	66.9	6.9	10	31.8
EGA-10	PG 64-34	64	5.55	5	69.3	6.7	10	34.4
EGA-10	PG 58-34	58	6.25	4.8	73.8	5.7	10	29.0
EGA-10	PG 64-34	64	5.5	4.9	70.6	6.9	10	33.2
EGA-10	PG 58-34	58	6.6	4.9	73.6	5.2	10	20.7
EGA-10	PG 58-34	58	6.7	4.9	73.9	6.3	10	20.7
EGA-10	PG 58-34	58	6.6	6.1	69.2	6.3	10	30.8
EGA-10	PG 58-34	58	6.1	8.5	61.8	7.4	10	25.1
EGA-10	PG 58-28	58	6.28	6.2	68.8	6.7	10	30.4
EGA-10	PG 58-34	58	6.6	4.6	75.2	6	10	25.2
ESG-10	PG 58-34	58	5.55	6.3	66.5	7	10	26.4
ESG-10	PG 58-34	58	6.7	4.9	73.9	5.2	10	20.7
ESG-10	PG 58-34	58	6.6	4.9	73.6	5.2	10	20.7
ESG-10	PG 64-34	64	5.5	5.9	75.6	6.9	10	33.2
ESG-10	PG 58-34	58	6.25	4.8	73.8	5.7	10	29.0
ESG-10	PG 58-34	58	6.6	4.6	75.2	6	10	25.2
ESG-10	PG 64-34	64	5.55	5	69.3	6.7	10	34.4
ESG-10	PG 64-34	64	5.07	6	65.6	6.8	10	25.0
ESG-10	PG 58-28	58	5.26	6.2	64.7	5.3	10	16.9
ESG-10	PG 64-34	64	5.93	4.9	71.4	5.5	10	23.1
ESG-10	PG 70-28	70	5.38	5.9	66.1	5.6	10	21.1
ESG-10	PG 64-34	64	5.19	5.5	67.9	6.3	10	20.1
ESG-10	PG 64-28	64	5.45	5.5	68.1	7.1	10	35.4
ESG-10	PG 58-34	58	5.25	5.6	67.3	3.2	10	17.8

2- The same form of the prediction formula is proposed

$$Y = A\times(HH)^{N_a} + B\times P_b^{N_b} + C\times(V_a)^{N_c} + D\times(VFA)^{N_d}$$
$$+ E\times(Filler)^{N_e} + F\times(NMAS)^{N_f} + G\times(Cu)^{N_g} + Const.$$

Where, Y = Predicted rut depth percentage

A, B, C, D, E, F, G, N_a, N_b, N_c, N_d, N_e, N_f, N_g and Const. are the constants of rut predication formula at a given number of cycles.

HH, P_b, V_a, *VFA, Filler, NMAS* and *Cu* are the mix design parameters

Initial values for the parameters of the formula are attributed.

3- Using the proposed formula, the values of rut depth percentages are calculated for a given number of cycles (1 000 cycles and 3 000 cycles separately) for each mix.

4- The errors between the measured and the predicted values of the rut depth percentages are calculated for each mix. Each error is squared and the sum of error is calculated for all mixes. The calculations are shown in Table 4-5.

Table (4-5) Least-Squares method calculations at 1 000 and 3 000 cycles for all mixes with 10mm Nominal Maximum Aggregates Size

Measured rut		***Predicted rut***		***Errors^2***		***Sum of Errors^2***	
Rut @ 1000	Rut @ 3000	Rut @ 1000	Rut @ 3000	1000	3000	30.68	128.10
5.1	8.4	5.6	8.1	0.291	0.114		
4.1	7.6	4.6	7.2	0.208	0.152		
5.7	11.7	5.3	8.0	0.128	13.794		
5.8	11.8	4.6	7.3	1.440	19.892		
5.5	7.8	5.1	7.6	0.172	0.023		
7.8	9.8	5.7	7.6	4.286	5.057		
3.5	6.8	5.2	7.7	2.798	0.808		
6.2	8.1	5.4	7.3	0.581	0.671		
6.2	8.1	5.7	7.4	0.249	0.490		
2.8	4.4	4.9	6.9	4.306	6.305		
5.6	9.9	4.8	7.5	0.571	5.669		
5.8	7.8	5.0	7.0	0.721	0.690		
5.4	6.8	6.0	7.9	0.377	1.146		
4.5	6.1	5.2	7.3	0.480	1.407		
6.2	8.1	5.4	7.3	0.620	0.719		
6.2	8.1	5.4	7.3	0.581	0.671		
3.5	6.8	3.8	6.5	0.106	0.071		
N.A.	7.8	N.A.	7.6	0.000	0.062		
5.1	5.4	6.0	7.9	0.835	6.103		
N.A.	2.7	N.A.	7.6	0.000	24.476		
5.5	8.1	4.5	7.5	0.997	0.398		
5.2	8.2	5.0	7.4	0.031	0.607		
3.3	5.1	4.7	7.4	2.064	5.405		
4	6.7	3.4	7.1	0.389	0.165		
6.5	10.2	4.6	7.4	3.645	7.846		
3.1	3.5	4.7	7.3	2.616	14.675		
4.1	5.5	4.5	5.0	0.158	0.207		
3.3	4	4.7	7.2	2.030	10.475		

5- Using the Solver application in Microsoft® Excel®, the sum of errors is minimized and the parameters of the prediction formula are then determined. The obtained results for 1000 and 3000 cycles are shown in Table 4-3.

Table (4-6) Rut prediction formula constants at 1000 and 3000 cycles for all mixes with 10mm Nominal Maximum Aggregates Size

@ 1000 cycles

A1	B1	C1	D1	E1	F1	G1	
367.92	70.47	133.13	254.63	-65.04	971.04	-354.45	
Na1	Nb1	Nc1	Nd1	Ne1	Nf1	Ng1	Const1
-0.8344	-3.4831	-2.4310	-0.9000	-0.0241	-1.6217	-17.0473	24.1052

@ 3000 cycles

A2	B2	C2	D2	E2	F2	G2	
104.74	12299.32	37942.81	7054.77	-733.41	15797.84	-354.45	
Na2	Nb2	Nc2	Nd2	Ne2	Nf2	Ng2	Const2
-1.0311	-6.3753	-6.5571	-1.8125	-4.8578	-3.4005	-17.0473	-4.4679

6- The results of the prediction formula are compared those obtained by measurements. The Figures 4-3 and 4-4 show the correlation between measured rut and predicted rut at 1 000 cycles and 3 000 cycles respectively for all mix with 10 mm NMAS.

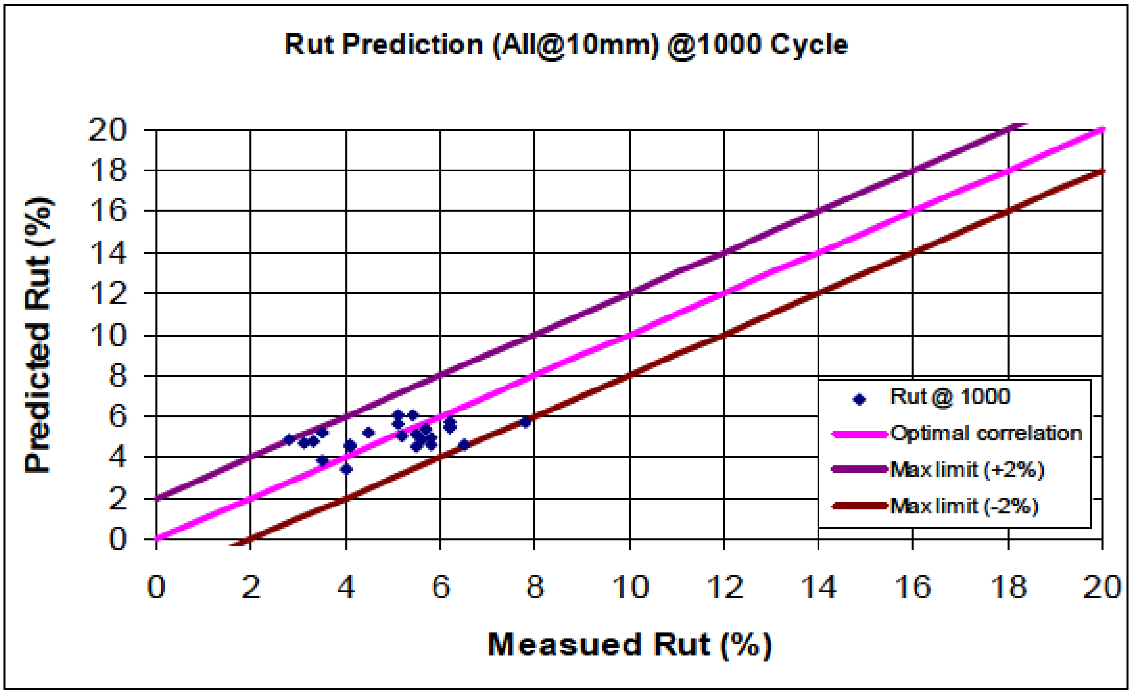


Figure (4-3) Correlation between measured and predicted rut at 1000 cycles for all mixes with 10mm Nominal Maximum Aggregates Size

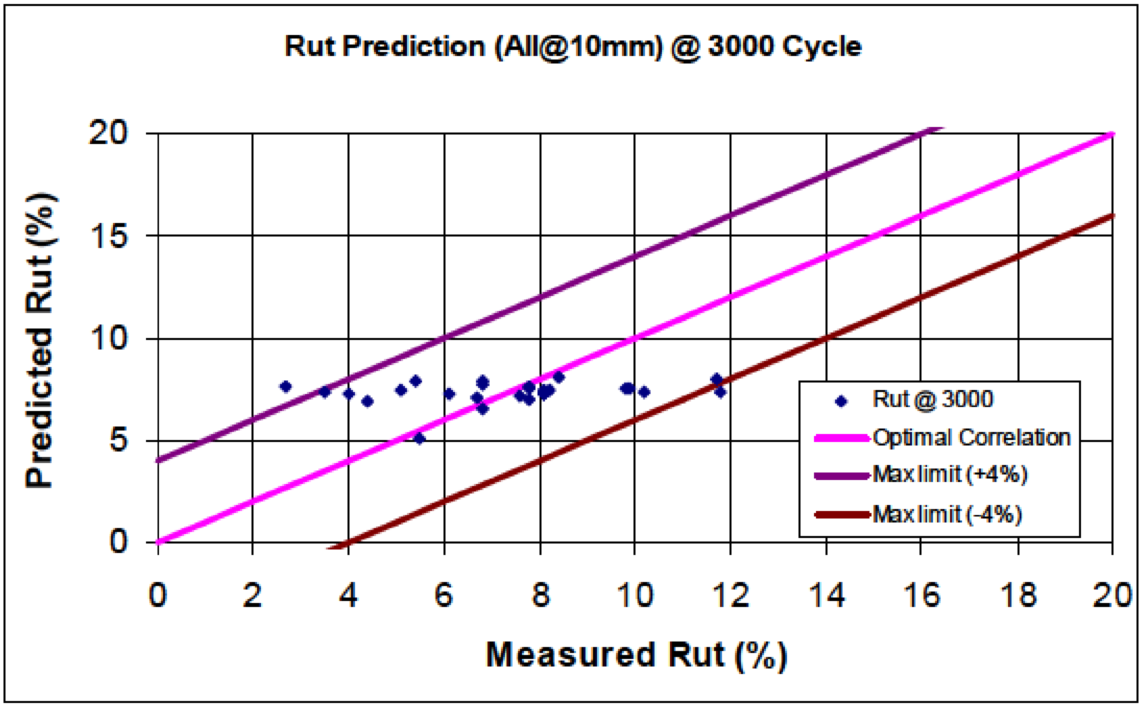


Figure (4-4) Correlation between measured and predicted rut at 3000 cycles for all mixes with 10mm Nominal Maximum Aggregates Size

The conclusions withdrawn from Figures 4-3 and 4-4 are similar to those of Figures 4-1 and 4-2 with ESG-10 mixes. The values of predicted rut range within the envelop of ±2% certainty level between the maximum limit and minimum limits lines. At 3000 cycles, only 2 points are out of the envelop of ±4% certainty level.

The certainty envelops at 1000 and 3000 cycles are then presented as follow:

At 1 000 cycles: Predicted Rut = Measured Rut ±2%

At 3 000 cycles: Predicted Rut = Measured Rut ±4%

Similarly to the results obtained with the ESG-10 mixes, the results fit well within the same certainty levels of when using all the mixes with 10mm Nominal Maximum Aggregates Size. As mentioned earlier, these certainty levels are very acceptable for this test. However, the data used for the calibration of the model are very limited again as only few tests data are available for the EC-10 and EG-10. A validation with a wider range of tests results seems necessary.

4-3 Model application for mixes with different

Only three GB-20 and three ESG-14 mixes are available in the database. However, the proposed has been applied on all mixes including these six mixes. The results of the Least-Squares Method are presented in Tables 4-7 to 4-9.

Table (4-7) Mix design parameters used for the prediction of rut for all mixes

Mix type	PG grade	HH (°C)	Pb (%)	Va @ N_{des} (%)	VFA (%)	Filler (%)	NMAS (mm)	Cu (mm/mm)
EC-10	PG 64-34	64	5.93	4.6	72.6	7.8	10	27.9
EC-10	PG 64-34	64	5.55	5.8	67.5	7.4	10	21.4
EC-10	PG 64-34	64	5.93	4.6	73.0	6.5	10	25.4
EG-10	PG 64-34	64	5.4	5.7	66.9	6.9	10	31.8
EGA-10	PG 64-34	64	5.55	5	69.3	6.7	10	34.4
EGA-10	PG 58-34	58	6.25	4.8	73.8	5.7	10	29.0
EGA-10	PG 64-34	64	5.5	4.9	70.6	6.9	10	33.2
EGA-10	PG 58-34	58	6.6	4.9	73.6	5.2	10	20.7
EGA-10	PG 58-34	58	6.7	4.9	73.9	6.3	10	20.7
EGA-10	PG 58-34	58	6.6	6.1	69.2	6.3	10	30.8
EGA-10	PG 58-34	58	6.1	8.5	61.8	7.4	10	25.1
EGA-10	PG 58-28	58	6.28	6.2	68.8	6.7	10	30.4
EGA-10	PG 58-34	58	6.6	4.6	75.2	6	10	25.2
ESG-10	PG 58-34	58	5.55	6.3	66.5	7	10	26.4
ESG-10	PG 58-34	58	6.7	4.9	73.9	5.2	10	20.7
ESG-10	PG 58-34	58	6.6	4.9	73.6	5.2	10	20.7
ESG-10	PG 64-34	64	5.5	5.9	75.6	6.9	10	33.2
ESG-10	PG 58-34	58	6.25	4.8	73.8	5.7	10	29.0
ESG-10	PG 58-34	58	6.6	4.6	75.2	6	10	25.2
ESG-10	PG 64-34	64	5.55	5	69.3	6.7	10	34.4
ESG-10	PG 64-34	64	5.07	6	65.6	6.8	10	25.0
ESG-10	PG 58-28	58	5.26	6.2	64.7	5.3	10	16.9
ESG-10	PG 64-34	64	5.93	4.9	71.4	5.5	10	23.1
ESG-10	PG 70-28	70	5.38	5.9	66.1	5.6	10	21.1
ESG-10	PG 64-34	64	5.19	5.5	67.9	6.3	10	20.1
ESG-10	PG 64-28	64	5.45	5.5	68.1	7.1	10	35.4
ESG-10	PG 58-34	58	5.25	5.6	67.3	3.2	10	17.8
ESG-10	PG 58-34	58	5.3	6.5	63.6	4.6	10	15.5
ESG-14	PG 64-34	64	5.2	6.7	62.9	7.4	14	27.4
ESG-14	PG 64-28	64	5.04	4.5	70.8	4.3	14	15.9
ESG-14	PG 64-28	64	4.41	4.5	69.7	4.3	14	15.9
GB-20	PG 64-34	64	4.59	4.4	68.9	5.8	20	36.6
GB-20	PG 64-34	64	4.5	6.3	60.3	7.4	20	25.5
GB-20	PG 64-28	64	4.41	6.6	59.0	4.4	20	28.7

Table (4-8) Least-Squares method calculations at 1 000 and 3 000 cycles for all mixes

Measured rut		*Estimated rut*		*Errors^2*		*Sum of Errors^2*	
Rut @ 1000	Rut @ 3000	Rut @ 1000	Rut @ 3000	1000	3000	38.81	137.68
5.1	8.4	5.2	7.6	0.012	0.590		
4.1	7.6	4.6	7.4	0.289	0.056		
5.7	11.7	5.0	7.5	0.516	17.230		
5.8	11.8	4.7	7.5	1.193	18.584		
5.5	7.8	5.0	7.5	0.260	0.070		
7.8	9.8	5.5	7.3	5.199	6.104		
3.5	6.8	5.0	7.5	2.175	0.521		
6.2	8.1	5.3	7.1	0.738	0.976		
6.2	8.1	5.5	7.2	0.473	0.750		
2.8	4.4	5.0	7.1	5.051	7.488		
5.6	9.9	5.0	8.0	0.383	3.794		
5.8	7.8	5.1	7.2	0.503	0.339		
5.4	6.8	5.6	7.5	0.060	0.456		
4.5	6.1	5.3	7.6	0.685	2.235		
6.2	8.1	5.3	7.1	0.790	1.043		
6.2	8.1	5.3	7.1	0.738	0.976		
3.5	6.8	3.7	6.6	0.034	0.029		
	7.8		7.3	0.000	0.222		
5.1	5.4	5.6	7.5	0.298	4.306		
	2.7		7.5	0.000	23.373		
5.5	8.1	4.6	7.7	0.752	0.154		
5.2	8.2	5.3	7.7	0.013	0.203		
3.3	5.1	4.7	7.2	1.849	4.478		
4	6.7	3.6	7.2	0.130	0.280		
6.5	10.2	4.6	7.5	3.426	7.268		
3.1	3.5	4.7	7.4	2.722	15.356		
4.1	5.5	4.9	5.2	0.623	0.112		
3.3	4	5.1	7.6	3.315	12.919		
1.8	2.6	2.7	3.7	0.824	1.138		
2.9	3.6	3.0	3.4	0.003	0.024		
2.9	3.6	3.1	4.2	0.028	0.347		
1.1	1.7	2.7	3.3	2.551	2.603		
3.1	4.7	2.4	3.3	0.482	2.034		
3.5	4.3	1.9	3.0	2.691	1.622		

Table (4-9) Rut prediction formula constants at 1000 and 3000 cycles for all mixes

@ 1000 cycles

A1	*B1*	*C1*	*D1*	*E1*	*F1*	*G1*	
362.88	*70.41*	*21.94*	*248.03*	*-50.98*	*970.72*	*-354.45*	
Na1	*Nb1*	*Nc1*	*Nd1*	*Ne1*	*Nf1*	*Ng1*	*Const1*
-0.8371	*-8.9277*	*-0.9048*	*-0.7683*	*-0.0213*	*-2.4517*	*-17.0473*	*24.6735*

@ 3000 cycles

A2	*B2*	*C2*	*D2*	*E2*	*F2*	*G2*	*Const2*
104.80	*12299.32*	*37942.81*	*7054.77*	*-733.57*	*15797.84*	*-354.45*	*-5.6449874*
Na2	*Nb2*	*Nc2*	*Nd2*	*Ne2*	*Nf2*	*Ng2*	
-0.8973	*-6.2606*	*-6.8930*	*-1.7817*	*-4.8264*	*-3.4069*	*-17.0473*	

The correlations between measured and predicted rut values at 1000 and 3000 cycles are shown in Figures 4-5 and 4-6.

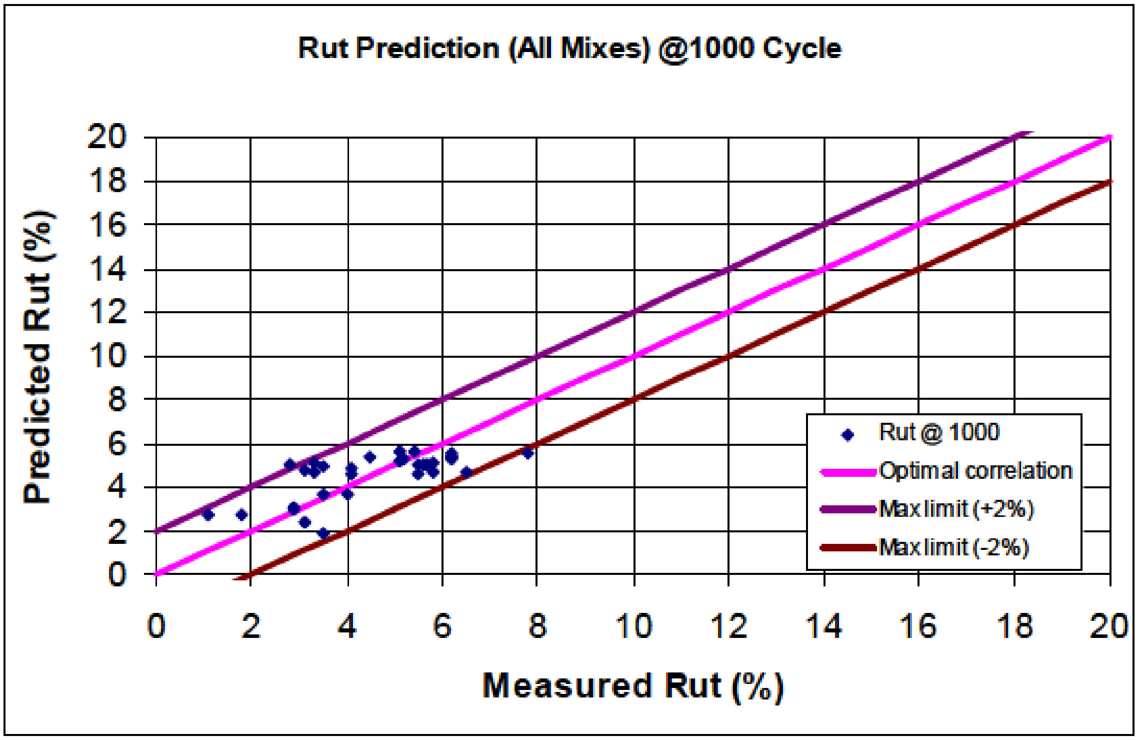


Figure (4-5) Correlation between measured and predicted rut at 1000 cycles for all mixes

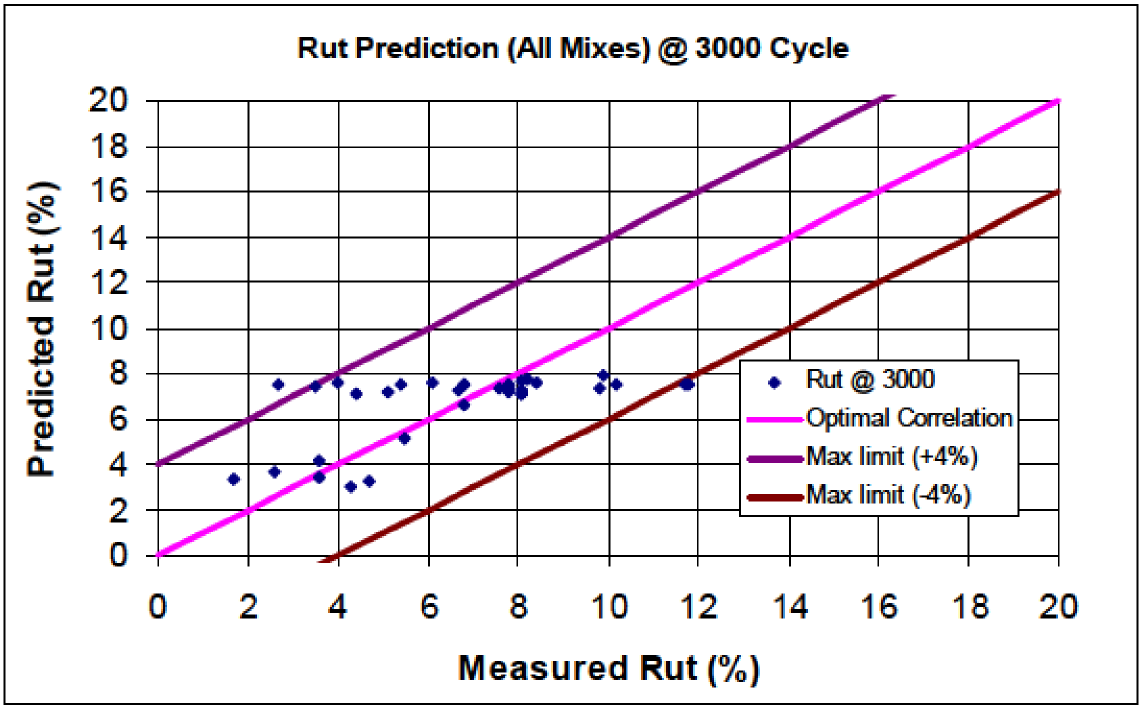
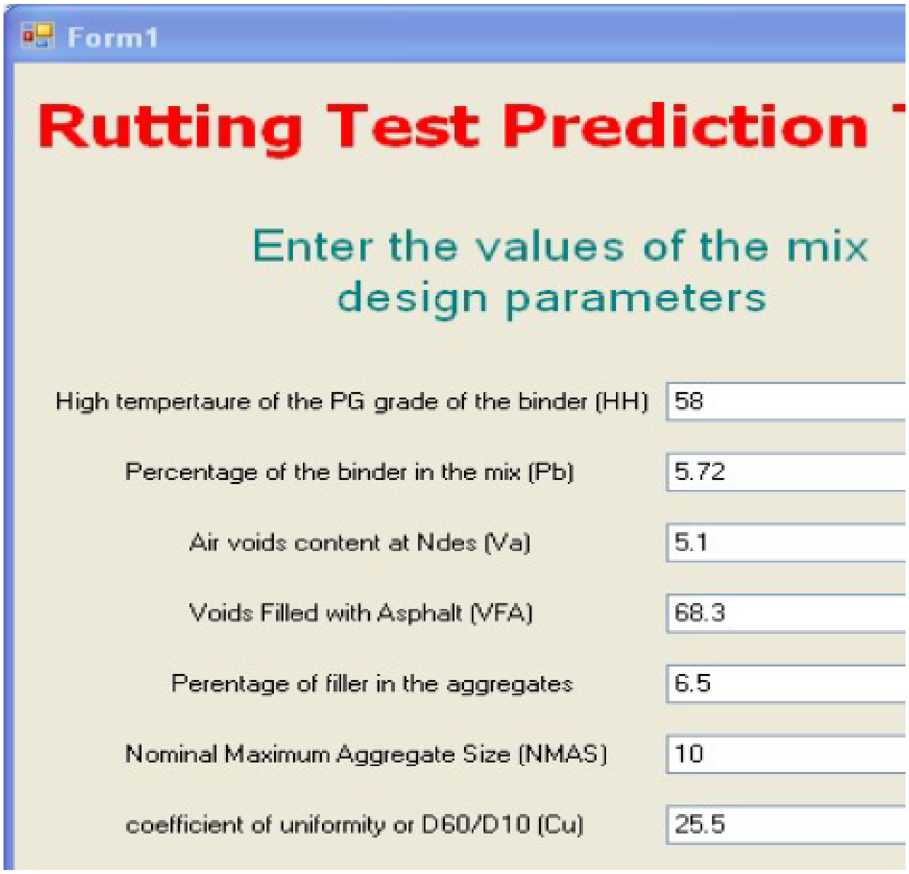


Figure (4-6) Correlation between measured and predicted rut at 3000 cycles for all mixes

Similarly to the other cases, the values of predicted rut range within the ±2% certainty level at 1000 cycles and only 2 points are slightly out of the envelop of ±4% certainty level at 3000 cycles. This result is promising but needs actually to be validated with more results.

4-5 Computer rut prediction Model

The computer tool proposed in the work a Visual Basic program allowing the user to enter the values of the mix design parameters used by the model as input and sends the values of the rut as output. The Figures 4-7 and 4-8 show an example of the input and output.

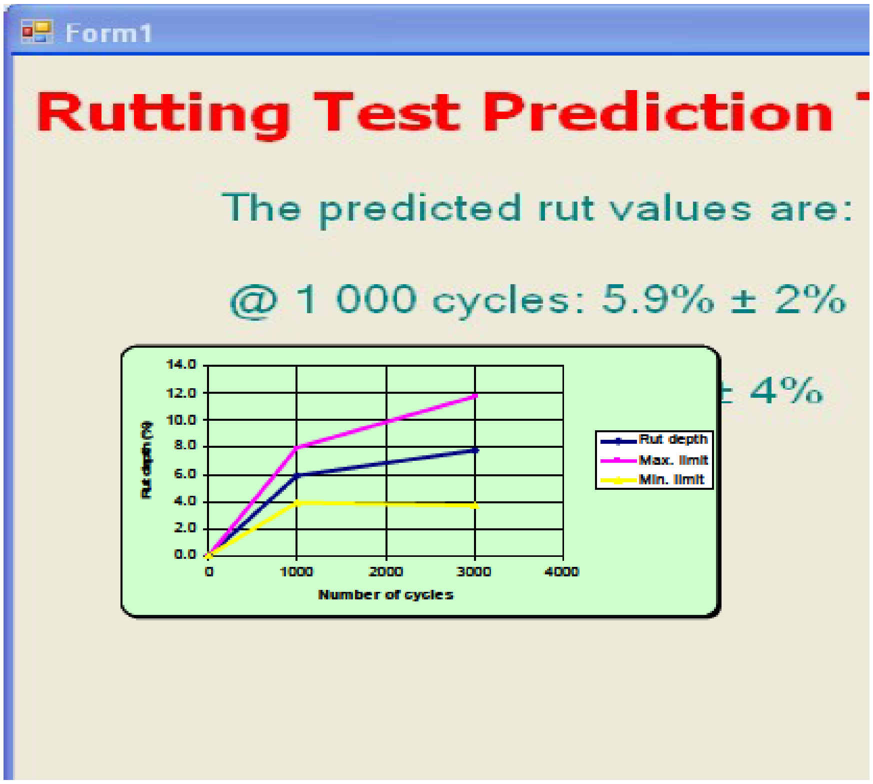


Rutting Test Prediction

Enter the values of the mix design parameters

High tempertaure of the PG grade of the binder (HH)	58
Percentage of the binder in the mix (Pb)	5.72
Air voids content at Ndes (Va)	5.1
Voids Filled with Asphalt (VFA)	68.3
Perentage of filler in the aggregates	6.5
Nominal Maximum Aggregate Size (NMAS)	10
coefficient of uniformity or D60/D10 (Cu)	25.5

Figure (4-6) Input of mix design parameters for the rut prediction with the computer tool



Rutting Test Prediction

The predicted rut values are:

@ 1 000 cycles: 5.9% ± 2%

± 4%

Figure (4-7) Output of the predicted rut values

The rut prediction in the computer tool uses the values of the formula parameters obtained in paragraph 4-3 for all mixes. The following two formulas are used at 1 000 cycles and 3 000 cycles respectively.

$$
\begin{aligned}
Rut\%_{@1000} &= 362.88 \times (HH)^{-0.8371} + 70.41 \times P_b^{-8.9277} + 21.94 \times (V_a)^{-.9048} + 248.03 \times (VFA)^{-0.9048} \\
&- 50.98 \times (Filler)^{-.0213} + 970.72 \times (NMAS)^{-2.4517} - 354.45 \times (Cu)^{-17.0473} + 24.9735
\end{aligned}
$$

$$
\begin{aligned}
Rut\%_{@3000} &= 104.80 \times (HH)^{-0.8973} + 12299.32 \times P_b^{-6.2606} + 37942.81 \times (V_a)^{-6.8930} + 248.03 \times (VFA)^{-0.7683} \\
&- 733.57 \times (Filler)^{-4.8264} + 15797.84 \times (NMAS)^{-3.4069} - 354.45 \times (Cu)^{-17.0473} - 5.6449874
\end{aligned}
$$

The output of program is presented graphically to show the expected range of rut with the number of cycles. The minimum and maximum limits are shown on the graphic.

Chapter-5

Conclusion and Future Work

5.1. Contribution.

The process adopted to predict the rut depth using data collected from various laboratory resources. The concept first carried to predict rut depth for one mix type, including the parameters that could be designed in any engineering design laboratory office, the next step is to adopt the same design process to predict rut depth using the influence of various mixes used at Quebec province here in Canada.

The methodology and procedure adopted to achieve the required result and it is summarized as follows:

- Calculation of all required parameters used in the analysis such as (Pb, Va, VFA, NMAS, Cu, Filler).
- Other parameters are left to conclude for future work.
- Determine the HH and LL value for the specific mix.
- Tabulate the all parameters in a table format to enable transference of data to required model prediction.
- Analysis each parameter influences to rutting to evaluate the degree of such influence. However, this enabled to predict the empirical correlation between rut and each parameter.
- Form the predicted empirical equation as the sum of effect of all selected parameters to rut appearance.
- Predict rut depth to all mixes used in the study analysis using the **NEW PREDICTED RUT EMPERICAL FORMULA.**
- Anew procedure adopted to check the validation of this model.
- Compare the predicted rut depth with measured data using the square least method.
- Correct the square difference of all calculated and measured rut depth.

- Develop small computer model adopting the same empirical model developed to calculate the rut depth.

The importance of predicting rut occurrence before mix design is completed, and predicting the behavior of pavement surface to rutting is considered one step towards, finalizing mix design suitability to resist occurrence of rut. The prediction model is usefulness of such prediction model will enable, the HMA mix designer to choose most appropriate mix design parameters percentage, and the workability of all parameters percentage in the HMA mix to produce the most acceptable rut resistance mix design.

The workability of such prediction modeling within the scale of this research, it prove an acceptable prediction result of rutting, to enable engineers prepare mix design with min rut resistance. Finally this computer model is tested using all mixes and the result is promising for future research.

5-2 Future work

The result of this research work will contribute to the comprehensive work detected at various locations to arrive at most reasonable rut prediction. Finally such prediction will help on most appropriate resizable pavement surface to rutting.

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