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CHARACTERIZING THIN ASPHALT OVERLAY PERFORMANCE FOR HIGHWAY PAVEMENTS

A Thesis Submitted to the Department of Civil Engineering, University of Kerbala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering (Infrastructure Engineering)

By

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بسم الله الرحمن الرحيم

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سورة طه الآية ﴿١١٤﴾

ABSTRACT

Over the last decades, the Europe and U.S. transportation Departments and agencies of highway changed their polices from paving new highways to increase the potential of the existed infrastructures. This is recommended by maintenance and rehabilitation using many techniques of pavement preservation such as slurry seal, chip seal, microsurfacing, fog seal, crack treatment and thin asphalt overlay. These pavement preservation techniques are known as a practices of cost-effective and are designed to enhance safety, provide long service life and keep the public budgets. Thin overlay is generally the highest level of preventive maintenance treatment, which can be performed on asphalt-surfaced pavements. Thin asphalt overlays are typically 38.1 mm or less (1.5 inch or less) in thickness. This technique offer an economical resurfacing, preservation, and renewal paving solution for roads requiring safety and smoothness improvements. Thin asphalt overlays has been performed by many transportation agencies with varying success.

However, characterizing the performance of asphalt mixtures that used as thin asphalt is still under the question by different researchers and highway agencies worldwide. Thus, this research work focused on characterizing thin asphalt overlay suitable for local infrastructure highways network that provides acceptable resistance to rutting, raveling, cracking, and wet weather skid resistance by optimizing mixture constitutions.

In this study, the experimental program included: design the thin asphalt overlay mixtures using one gradation type (9.5 NMAS), three filler types (Conventional Mineral Filler (CMF), Ordinary Portland Cement (OPC), and Quick Lime (QL)), and five percentages of asphalt content to identify the optimum asphalt content. Then, SBS modified polymer binder was introduced for performance enhancement. This polymer was utilized in percentages of 2%, 4% and 6% of the bitumen content. Different volumetric (e.g., bulk density, air void, void in mineral aggregate and void filled with binder), mechanical (e.g., Marshall stability and flow, indirect tensile strength, creep compliance, wheel track, and skid resistance), and durability (cantabro test, and tensile strength ratio) testing methods were performed to identify the variations in thin asphalt mixtures characteristics due to such incorporations.

The results disclosed that the filler type have a great impact on the thin asphalt overlay (TAO) mixtures performance in terms of mechanical, durability and volumetric

properties; for example, mixture containing quick lime as a filler showed an increase in stability, indirect tensile strength, creep stiffness, and dynamic stability of (12, 39, 75, 71%) respectively when compared with the mixture comprising conventional mineral filler. On other hand, the addition of SBS modified polymer to the binder with three percentages led to significant improved in mechanical and durability properties such as creep stiffness, skid resistance and rutting resistance, abrasion loss and water damage resistance. The percentage of 2% SBS showed an increase in stability and indirect tensile strength of (118, 7.8, 15%), (93, 35, 38%) respectively compared with other percentage of SBS (0, 4, 6%) respectively when using filler type (CMF). It is worthy to mention that modeling some of these characteristics were achieve and verified for prediction purpose. However, the extensive experimental and analytical program disclosed two vital conclusions which are the ability of producing high performance thin asphalt mixtures using local materials with some additives, and the sensitivity of these mixture performance to their constitutions.

SUPERVISOR CERTIFICATE

I certify that this thesis entitled **“**CHARACTERIZING THIN ASPHALT OVERLAY PERFORMANCE FOR HIGHWAY PAVEMENTS**”,** which is prepared by "Mousa Zeki Yahiya", is under my supervision at University of Kerbala in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Infrastructure Engineering).

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LINGUISTIC CERTIFICATE

I certify that this thesis entitled **“**CHARACTERIZING THIN ASPHALT OVERLAY PERFORMANCE FOR HIGHWAY PAVEMENTS**”** which is prepared by Mousa Zeki Yahiya under my linguistic supervision. It was amended to meet the English style.

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We certify that we have read the thesis entitled "CHARACTERIZING THIN ASPHALT OVERLAY PERFORMANCE FOR HIGHWAY PAVEMENTS" and as an examining committee, we examined the student "Mousa Zeki Yahiya" in its content and in what is connected with it, and that in our opinion it is adequate as a thesis for degree of Master of Science in Civil Engineering (Infrastructure Engineering).

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This thesis is dedicated to:

My parents, my family, brothers, sisters and friends for their love and continuous support

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ABBREVIATIONS

AADT	*Annual Average Daily Traffic*
AASHTO	*American Association of State Highway and Transportation Officials*
ACP	*Asphalt Concrete Pavement*
ANOVA	*Analysis of Variance*
APA	*Asphalt Pavement Analyzer*
ASTM	*American Society for Testing and Materials*
BBTM	*Very Thin Asphalt Concrete (Beton Bitumeineux Tres Mince) used in CEN, abbreviation from the French.*
BD	*Bulk Density*
BFS	*Blast Furnace Slag*
BPN	*British Pendulum Number*
BS	*British Standards*
CC	*Creep Compliance Test*
CMF	*Conventional Mineral Filler*
CTM	*Circular Track Meter*
DFT	*Dynamic Friction Tester*
DS	*Dynamic Stability*
e	*Residual*
ESAL	*Equivalent Single Axle Loads*
EVA	*Ethylene Vinyl Acetate*
FAA	*Fine Aggregate Angularity*
FHWA	*Federal Highway Administration*
FS	*Furnace Slag*
GSRB	*General Specifications for Roads and Bridges*

HMA	*Hot Mixture Asphalt*
IDT	*Indirect Tensile Strength*
IRI	*International Roughness Index*
K	*Number of Regressor Variables*
LTPP	*Long Term Pavement Performance*
LVDT	*Linear Variable Differential Transducer*
MAE	*Mean Absolute Error*
MAPE	*Mean Absolute Percentage Error*
MPD	*Mean Profile Depth*
MF	*Marshall Flow*
MS	*Marshall Stability*
MS_E	*Mean Square of Residual*
MS_R	*Mean Square of Regression*
N	*Number of samples*
N_{design}	*Number of Gyrations*
NAPA	*National Asphalt Pavement Association*
NCAT	*National Center for Asphalt Technology*
NCHRP	*National Cooperative of Highway Research Program*
NMAS	*Nominal Maximum Aggregate Size*
OBC	*Optimum Binder Content*
ODT	*Oregon Department of Transportation*
OGFC	*Open-Graded Friction Course*
OPC	*Ordinary Portland Cement*
p	*Number of Parameters*

PB	*Polybutadiene*
PG	*Performance Grade*
PMA	*Polymer Modified Asphalt*
PMB	*Polymer modified binder*
PS	*Polystyrene*
QL	*Quick Lime*
R^2	*Coefficient of Determination*
RAP	*Reclaimed Asphalt Pavement*
RD	*Rut Depth*
RMSE	*Root Mean Square Error*
SBS	*Styrene-Butadiene-Styrene*
SBR	*Styrene Butadiene Rubber*
SMA	*Stone Matrix Asphalt*
SN	*Skid Resistance Number*
SPMA	*SBS Polymer Modified Asphalt Samples*
SPS	*Specific Pavement Study*
SPSS	*Statistical Product and Service Solutions*
SRV	*Skid Resistance Value*
SS_E	*Residual Sum of Squares*
SS_R	*Regression Sum of Squares*
SS_T	*Total of Sum Squares*
TAO	*Thin Asphalt Overlay*
TBO_S	*Thin Bonded Overlays*
TSR	*Tensile Strength Ratio*

UOK	*University of Kerbala*
UTBWC	*Ultra-Thin Bonded Wearing Course*
VFA	*Voids Filled with Asphalt*
VMA	*Voids in Mineral Aggregate*
WTT	*Wheel Track Test*
y^-	*Mean of Observed Values*
y_i	*Observation Value*
$y\^_i$	*Predicted Value*

Chapter One

INTRODUCTION

1.1 Background

In the course of the most recent 30 years, the transportation authorities in developed countries have transformed somehow from the construction of new roads to reestablishment and protection of the existing pavements. In other words, currently there is a distinguish focus on maximizing the benefit from the existing infrastructures to entire their potential. However, it was progressively discovered after a complete construction phase of pavements that they do not require additional improvements to assist movement loads as much as useful enhancements to give safety and smoothness. It is particularly valid for very much built thick layer of asphalt where failures are observed to be bound to the upper layers. With a specific end goal to keep an asphalt pavement in service, it is just important to take off the top layers and substitute them in a mill-and-fill operation. This sort of pavement is indicated as a long life or “Perpetual Pavement”. While improvements were made in the design that enable permanent Pavements to be enhanced and developed, different changes made in materials determination, blend outline, and development of surface layers to enhance their implementation (Newcomb, 2009).

In the 1980s these changes began with the presentation of polymers to help in rutting resistance. Stone Mastic Asphalt (SMA) was used in the US since 1990 (Newcomb, 2009). The outcome was pavement surface that can last more than 20 years without resurfacing. Likewise, in the 1990s, the Superpave method to design asphalt mixtures was presented and refined. This system consolidated the best highlights of past practices concerning materials choice and volumetric estimations. The outcome was a blend configuration custom fitted to particular capacities in the asphalt, for example, protection from cracking, slipping and rutting. Also, in the 1990s agencies found different issues became visible with development and implementation of surface blends. For example, when large aggregate used in mixtures, mixes were specified in relatively thin lifts. This means that the permeability is high and lead to reduce durability, and deterioration of longitudinal joints. In certain cases, premature separation of the pavement surface layers and non-uniform mat occurs due to temperature differentials occurring in the surface. Many techniques were developed to combat these issues, with the goal to design and construct long life surfaces. On the other hand, in mid-2000s, new methods were presented that permitted reducing temperature of asphalt mixtures and taking into consideration expanding utilization of recycling. Warm mix asphalt had enhanced the officially incredible natural record of the asphalt industry. Through asphalt mixture production, bringing down temperatures has decreased fuel consumption and emissions. Using of reclaim asphalt pavement (RAP) significantly expanded due to material handling processes and enhanced plant design. These new advancements were without a doubt have to preserve using Thin Asphalt Overlay (TAO). In 1999 AASHTO made study showed that TAO mixtures were the most preventive treatments techniques. This fame prompted various investigations on the materials, plan, and development of thin overlays so as to improve asphalt conservation procedures (Cooley and Brown, 2003), (Chou, Datta and Pulugurta, 2008a), (Brown, 2004), (Brown and Heitzman, 2013), (Corley-Lay and Mastin, 2007).

1.2 Thin Asphalt Overlay Technology

Thin asphalt overlay (TAO) is a bituminous surface layer that enhances the current properties of asphalt structure as far as strength layer and eliminating the deformability (NICHOLLS *et al.*, 2007). The thickness of TAO is normally under 1.5 inches (38.1 mm). It utilized as a restoration and conservation treatment layer with numerous advantages; it offer an economical resurfacing, preservation, and renewal paving solution for roads requiring safety and smoothness improvements (Im *et al.*, 2015). TAOs do not just give another asphalt surface to a small amount of the expense of repaired roadway, yet they are likewise the main preventive support method that the structural value and broadens the pavement's service life.

Brown and Heitzman (2013) stated that the TAOs are more costly in initial cost contrasted with other surface treatments (e.g., microsurfacing or chip seals), nevertheless TAOs provide an increased smoothness with a calmer ride than the other mentioned surface treatments in the short term. Moreover, the durability of TAO is higher in the long term, along with a slight structural improvement to the asphalt pavement (Newcomb, 2009).

TAO applications are the best solution for roads in good structural condition or that need resurfacing because of raveling, rutting, cracking, aging, oxidation, or minor deteriorations. It is noticeable that TAOs are not viewed as an answer for roadways requiring critical structural restoration, however they are common procedures for asphalt protection (Im *et al.*, 2015).

1.3 Advantages and Disadvantages of TAO

Seeking the potential of TAOs is important to draw the highway infrastructure agencies goal to set up the surface treatment alternative. Among other surface treatment alternatives, the National Asphalt Pavement Association (NAPA) revealed many advantages of TAO applications (Newcomb, 2009), including:

1. Service life is long.
2. Decrease life cycle cost.
3. Ability to protect the slope and grade of road.
4. Ability to resist substantial movement and manage high shear stresses.
5. Surface is smooth.
6. Prevent raveling.
7. Reduce traffic delays.
8. Minimize noise generation.
9. Ignoring the asphalt runoff and curing time.
10. Easy to maintain TAO and used during the construction stage.
11. At low and medium speeds, provide high skid resistance.
13. When reconstruction is in progress, the roadway can be used.
14. Saving on the development time.
15. It can be recycle.

On other hand, of course TAOs have some distinguished disadvantages. The three most important disadvantages are:

1. When laying TAO, Weather conditions are more critical.
2. Dissociation by milling infers downgrading the material.
3. Susceptible to cracking identified with substrate lacks.

There are other disadvantages such as susceptibility to delamination, raveling and frost damage, plate (1-1) shows two problems that can occur in TAO.

Plate 1-1 Most common problems with TAO: raveling (left) and delamination (right) (Sandberg et al., 2011)

1.4 Problem Statement

Currently, the culture of maintenance and rehabilitation of local highway infrastructure is developing day by day, with absent of local guideline for surface treatment alternative. Thus, characterizing and optimizing different surface treatment alternatives are in high demand, especially with available local experiences and materials.

1.5 Research Aim and Objectives

The main aim of this research is to characterize thin asphalt overlay mixture suitable for local infrastructure highways network that provide acceptable resistance to pavement rutting, cracking and wet weather skid resistance. This will be achieved through the following objectives:

1. Optimizing thin asphalt mixture performance with different variables include: filler types, percent of asphalt content, and different percent of modified SBS polymer.
2. Characterizing the volumetric, mechanical, and durability properties for the optimized mixtures in terms of :

- Mechanical and performance properties (Marshall Stability, Marshall Flow, IDT, Creep, resistance to permanent deformation and skid resistance test).
- Durability properties (Tensile strength ratio, and Cantabro abrasion test).
- Volumetric properties (air void, VMA, VFA, and density).

3. Modeling some important properties for prediction purpose. This modeling includes the correlation of these properties with some mix indices such as (IDT, TSR and bulk density).

1.6 Scope of the Research Work

Within the wide range of conditions, materials, testing methods, and design methods, this research work was achieved under the following scope:

1. All main raw materials used in this research were local.
2. New type of additives was selected and investigated. Modified SBS polymer with silica was nominated to disclose the double effect of polymer and fine silica on TAO performance.
3. Mixtures were evaluated in the lab in terms of mechanical, volumetric, and durability properties. No site evaluation was obtained during research work.
4. All tests were performed at the University of Kerbala (UOK) laboratories.

Some testing devises have locally manufactured, including shear mixer that used in mixing polymer (SBS), indirect tensile strength test (IDT), creep compliance test (CC), and wheel track test (WTT). These manufactured apparatus were erected according to standard specifications. Devices were programmed and computerized locally with the help of an experienced programmer.

1.7 Thesis Structure

This thesis consists six chapters which demonstrate the study work outcomes as listed below:

Chapter 1 Introduces the background of the research, its statement of the problem, aim and objectives, scope of the research work, and finally the thesis structure.

Chapter 2 Reviews thin overlay technology, types, classifications and mix design methodology and its performance.

Chapter 3 Describes materials properties that used in the research, the adopted TAO mixture design procedure, the adopted tests to examine mix properties, and finally research methodology.

Chapter 4 Demonstrates the results of the study with extensive discussion

Chapter 5 Discloses the predictive models that correlate the depended variable with independent variable.

Chapter 6 Presents the main conclusions and recommendations for future work.

Chapter Two

LITERATURE REVIEW

2.1 Introduction

The utilization of bituminous asphalt as a construction material is backed to pre-historic times. Bituminous asphalt is associated with the development of roads and airfields, which have the essential role of the world economy system (Krishnan and Rajagopal, 2003).

The design of pavement structures has developed over the years from purely empirical to mechanistic-empirical in nature. However, the design idea has been to minimize the potential failure of the pavement structure because of distress. In specific, cracking is a main distress in pavements. Low temperature cracking (because of thermal stresses), reflective cracking (propagation of existing cracks through the overlay) and fatigue cracking (because of repeated wheel loads), are the main cracking distresses in pavements. Although all three cracking distresses (thermal, reflective, fatigue) have different driving forces, the rate and potential magnitude of cracking in all three cases is greatly influenced by the fracture resistance of the surface layers in the system. A better understanding of these pavement and overlay deterioration mechanisms will enable enhanced future design and performance. Pavement preservation continues to gain importance as means to delay costly rehabilitation and reconstruction alternatives with ever escalating cost of materials. In the recent years, many cost-effective and efficient maintenance technologies have been developed and implemented to address these issues (Krishnan and Rajagopal, 2003), (Moulthrop and Smith, 2000), (Corley-Lay and Mastin, 2007). The assessment of these technologies included visual performance for raveling, weathering, delamination, surface roughness (IRI), skid resistance testing, surface macrotexture depth measurements, and noise measurements. In view of these investigations, TAO provides a riding surface with a high degree of macrotexture, good aggregate retention, and well bonded to the underlying pavement. Many studies (Bellanger, Brosseaud and Gourdon, 1992), (Hanson, 2001), (Corley-Lay and Mastin, 2007) found that TAO represents an efficient treatment option for deteriorated rigid and flexible pavement systems and often hold advantages over other alternatives.

The objective of this chapter is to provide a background of information about TAOs. It summarizes the benefits and limitations, the factors affecting the application of TAOs, the functional and structural characteristics provided by its use, the treatment life, the materials used for recently developed mix designs and the construction procedures.

2.2 Outline of TAO System

There are various protection maintenance strategies (slurry seals, chip seals, fog seals, microsurfacing, crack treatment and TAO). These techniques designated to extend service life of pavement, improve safety, and save the public budgets. All of which focus on preserving a pavement's structure by improving functional deficiencies without significantly affecting the structural capacity of the pavement.

Thin asphalt overlays are characterized as surface courses typically with thickness no more than 1.5 in (38.1 mm) (Hajj, Sebaaly and Habbouche, 2016) for more than 86% of the survey participants. Over 15 years in Europe and abroad, TAOs have been utilized broadly and with promising results (Sandberg *et al.*, 2011). They appeared to be cost effective pavements, fast to construct and may have good surface properties. In recent years, many studies proved that TAOs lead to reduced traffic noise levels, good skid resistance and durable surface layers compared with traditional alternatives.

TAOs have been performed by numerous transportation agencies with differing achievement. A recent study, which was made by AASHTO over 25 States, have used thin HMA overlays. Only eleven reports stated that the thin HMA overlay has problems with reflective cracking, low durability, de-lamination and poor friction (Chou, Datta and Pulugurta, 2008b). Charles Jahren and Cliff (2007) proposed a decision matrix to select an appropriate preservation treatment for various distress types and conditions. Table (2-1) demonstrates the decision matrix, as seen from this table, it is obvious that the thin asphalt overly is the best Preservation Treatments when compared with other techniques. Thus it is recommended in all conditions excluding the case of alligator cracking.

Table 2-1. Decision Matrix (Jahren, C., Smith, D. E., and Plymesser, 2007)

Factor		Preservation Treatments				
		Fog seal	**Seal coat**	**Slurry seal**	**Microsurfacing**	**Thin asphalt overlay**
Traffic volume	AADT<2,000 (low traffic)	R	R	R	R	R
	2,000>AADT>5,000 (medium traffic)	R	M	M	R	R
	AADT>5,000 (heavy traffic)	R	NR	NR	R	R
Bleeding		NR	R	R	R	R
Rutting		NR	NR	R	R	R
Raveling		R	R	R	R	R
Cracking	Few tight cracks	R	R	R	R	R
	Extensive cracks	NR	R	NR	NR	R
	Alligator cracking	NR	M	NR	NR	NR
Low friction		I	I	I	I	I

R=Recommended NR=Not Recommended M=Marginally Recommended I=May

Brown and Heitzman (2013) assessed several pavement preservation techniques including cheap seals, fog seals, crack treatment, microsurfacing, slurry seals, and thin asphalt overlay. Their research conducted for FHWA over five selected states to investigate several cost effectiveness parameters, namely: initial costs, expected extended life of pavement, and an annualized cost. The results of this search are summarized in Figure (2-1). It is clear from this figure that the crack treatment, fog seals, and chip seals had the lowest annualized costs than TAO. These last techniques could provide limited advantages comparatively, while TAO can resist rutting, improve smoothness, and skid resistance with long expected pavement life extension and inexpensive annualized cost. Chen, Lin and Luo (2003) concluded that the chip seal was the best preservation technique in most cases, nonetheless, thin overlay was the most effective treatment in tending to rutting issues, and it should be used on high traffic roads where rutting is the main concern. Pavement Preventive Maintenance Guideline for Oregon Department of Transportation (ODOT) concluded that pavements that treated with a thin HMA overlay are structurally sound, their durability are higher in the long term and are expected to serve perfectly 8 to 12 years (Newcomb, 2009).

Im *et al.*(2018) compare between TAO of 25mm thickness and the traditional rehabilitation of 50mm thickness. They found that the behavior of TAO mixtures are similar to mixture of coarser-graded conventional overlay in terms of the resistance to cracking, rutting and stiffness of mixture.

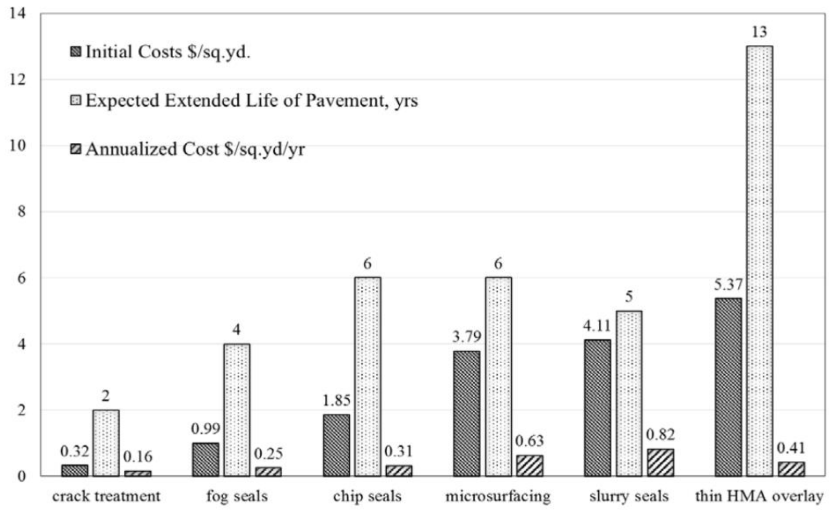

Figure 2-1 Typical Unit Costs and Pavement Life for Specific Maintenance and Preservation (Brown and Heitzman, 2013).

2.3 Characteristics of TAO

TAO provides some functional and structural characteristics, in terms of functional characteristics, the following have been proven (Hajj, Sebaaly and Habbouche, 2016):

a) Smoothening of the pavement surface which result in improving the ride quality.

b) High skid resistance due to the use of polish-resistant aggregates.

c) Lower tire-pavement noise generation due to the use of smaller NMAS.

In terms of the structural characteristics, TAO can add an extra potential to the structural capacity of the existing pavement. Whereas, the tensile strain at the bottom of the existing asphalt layer decreases and the fatigue life repetitions to failure increases when the thickness of additional thin asphalt overlay increase (Hajj, Sebaaly and Habbouche, 2016), as shown in Figure (2-2).

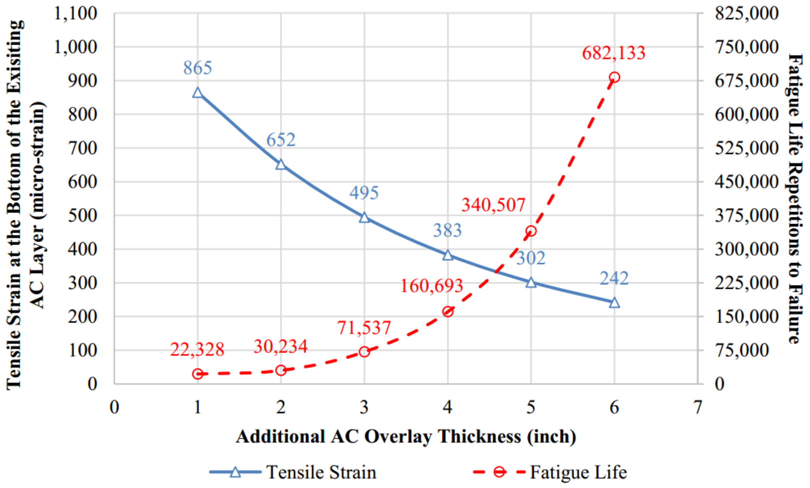

Figure 2-2 Example for Tensile Strain and Fatigue Life Repetitions Variations (Hajj, Sebaaly and Habbouche, 2016)

2.4 TAO use limitations

Like any construction materials, TAOs have some problems and limitations, which can be summarized as follows (Sandberg *et al.*, 2011):

1. The bearing capacity of thin asphalt overlay is peripheral in many cases.
2. Large maximum aggregate sizes are required to resist wear from studded tires.
3. Open-textured or porous types of thin asphalt overlay may offer great noise reduction, but this lead to reduction durability under heavy traffic load.
4. Another problem that the sensitivity of thin asphalt overlay to weather conditions during paving which has been specified as a noteworthy disadvantage.

2.5 Types of TAOs

Many kinds of mixtures are utilized effectively as TAO. The most widely applications in highways constructions are the stone matrix asphalt and dense graded Superpave mixtures with NMAS of (12.5mm and 9.5mm). These types of blends provide durability and they are having a good resistance to cracking and rutting as a result of their load carrying mechanism of stone to stone contact. These mixtures are cost-effective which withstand for a long period of up to 20 years (Newcomb, 2009). Ultra-thin bonded wearing course is another type of mixtures which developed in France in 1986 (Attoh-Okine and Park, 2007). Ultra-thin bonded wearing course is a gap graded mixture and polymer is used to modify asphalt. Many states of U.S are using this type routinely as a pavement preservation.

Another type of mixtures which has gained acceptance and popularity within many agencies is dense graded mixes with 4.75mm NMAS. In 2002 AASHTO added 4.75mm NMAS mixes to its specifications (West, Rausch and Takahashi, 2006). In 1990, when stone matrix asphalt (SMA) was used in U.S, many experimental projects were conducted with 19mm and 12.5mm NMAS (Cooley and Brown, 2003), Developmentally, The National Center for Asphalt Technology (NCAT) in 2003 made research used stone matrix asphalt mixtures with 9.5mm and 4.75mm NMAS (Cooley and Brown, 2003).

Thin asphalt overlays are not limited to dense graded and SMA mixtures, but also open graded friction course mixtures have been applied as TAO. The temperature of open graded friction course (OGFC) layer is lower compared to dense graded mixtures and this returned to its open structure. Watson, Zhang and Powell (2004) made a comparison between OGFC and dense graded mixtures in terms of layer and they observed that the temperature of OGFC layer is lower about (2°C) than the layer underneath dense-graded mixes.

Plate 2-1 Thin Hot Mix Asphalt (HMA) Overlay (http://fp2.org/)

Plate 2-2 Paving Ultra-Thin Hot Mix Asphalt in Salisbury, Maryland (http://www.ejbreneman.com/Ultra-Thin-Hot-Mix.html)

2.6 Specifications of TAOs' Materials, Mixtures, and Structures

2.6.1 Aggregates

Many types of aggregate can be used in TAO mixture; natural or synthetic materials which can be used individually or collectively to produce a suitable mix gradation. Natural aggregates involved limestone, granite, syenite, sandstone, dolomite, crushed gravel, natural sand and crushed stone. Synthetic material involved blast furnace slag, steel furnace slag and taconite tailings. The type of used aggregate in the mixtures is mainly rely on the available aggregate in the construction area.

Two important issues in fine aggregate should be controlled to guarantee good internal friction and help in rutting resistance, they are the amount of natural sand and Fine aggregate angularity (FAA) (Zaniewski and Diaz, 2004). Cooley Jr, James and Buchanan (2002) reported that the high percentage of natural sand significantly affect the 4.75mm NMAS mixtures performance. They recommended limits for the amount of natural sand used in mixtures; for low/ medium trafficked highway they suggested (20-25%), where (15-20%) were suggested for high trafficked highways. These limitations could assist to take control on adversely effect of natural sand. It was also noted in the same study that the percent of natural sand above 15% having negative impact on permeability, rutting and moisture susceptibility.

Cooley Jr, James and Buchanan (2002) suggested that the FAA should be at least 40% when the value of design Equivalent single axle loads ESALs lower than 0.3 million and 43% or greater when the value of design ESALs (0.3-3) millions. This assist to ensure that the rounded particles do not make up the whole amount of aggregate in mix.

The compatibility between aggregate and asphalt binder should be considered in the case of selecting aggregate. Determination this affinity produces good adhesion between aggregate and asphalt binder therefore raveling resistant is ensure. This in turn leads to improve durability. The volumetric properties of mixture and the stability, cohesion of the skeleton are influenced by aggregate grading and shape, thus the aggregate grading and shape should be as constant as possible (Sandberg *et al.*, 2011).

Many researches were made up to conclude that the thickness of TAO are ranged (0.75-2 in) (Cantrell, 2013). Walubita and Scullion (2008) reported that the thickness of TAO using 12.5 mm NMAS in U.K and Australia are ranged from (0.8 to 1.6 in) and the thickness of SMA overlays in New Zealand are ranged from (0.5-1.2 in) with predicted service lives of 15 years or more. The thickness of thin asphalt overlays are associated with NMAS. The desired thickness of TAO without aggregate crushing under heavy traffic loads are obtained by using smaller NMAS (Hajj, Sebaaly and Habbouche, 2016). The relationship between the thickness of TAO and NMAS as follow:

$$t = n * S \qquad \text{Equation (2-1)}$$

Where, t is the thickness of TAO, S is NMAS, and (n) is an integer scaling factor. Based on many previous studies, the (n) value between (1-3) (Hajj, Sebaaly and Habbouche, 2016).

In order to ensure adequate compaction, the thickness of TAO to NMAS should be preserved in the range of 3:1 to 5:1 (Brown *et al.*, 2004). Given the fact that the thickness of thin asphalt overlays is generally less than 38.1 mm (1.5 inches), NMAS must be 12.5 mm or less. As shown in Table (2-2), most states used aggregates with NMAS of 4.75 mm to 12.5 mm for thin asphalt overlays (Im *et al.*, 2015).

Several state highway agencies have put many limitations for the thickness of TAO based on a survey performed by the National Cooperative Highway Research Program, synthesis 464 (Hajj, Sebaaly and Habbouche, 2016), as shown in Table (2-3) and demonstrated in figure (2-3).

Table 2-2 NMAS Requirements for a Variety of States (Im et al., 2015)

State (mixture)	*NMAS (mm)*
Nebraska (SLX), Nevada, Utah, Mississippi (Mix 1), Massachusetts, Indiana, Missouri, Michigan	9.5
Alabama, North Carolina, Ohio (Type B)	12.5
New York, Maryland	6.3
Georgia, Mississippi (Mix 2), Ohio (Type A)	4.75

Table 2-3 State Survey for Thin Asphalt Overlay Thicknesses (Hajj, Sebaaly and Habbouche, 2016).

Thickness Limit (in inches)	*Percentage of answer*
more than 2.0	3 %
Between 1.5 and 2.0	11 %
Between 1.0 and 1.5	24 %
Between 0.75 and 1.5	25 %
Between 0.75 and 1.0	28 %
Less than 0.75	9 %

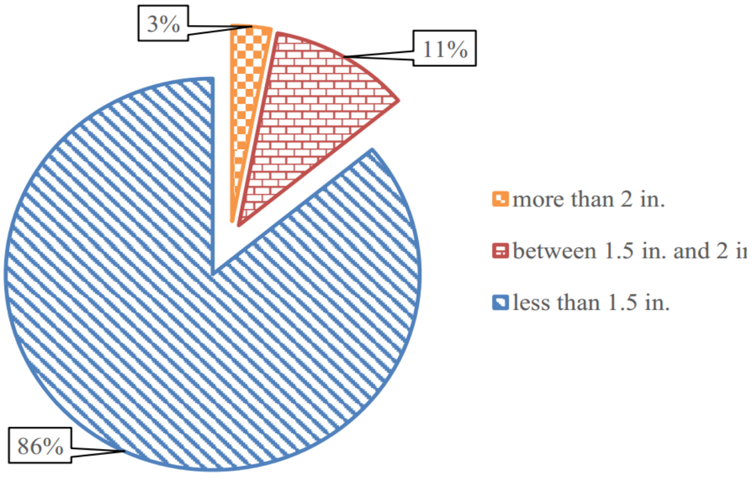

Figure 2-3 Summary of States Responses for TAO Thickness (Hajj, Sebaaly and Habbouche, 2016)

Plate 2-3 TAO Commonly Measure 1.5 inches or less, Like This Dense-Graded Asphalt Overlay in Reno, NV (Accelerated Implementation and Development of Pavement Technologies 2017)

The quality of aggregates is also specified based on predicted traffic, vehicle speed, and the type of overlaid pavement. For coarse aggregate, the quality is tested depending on many tests such as sulfate soundness, aggregate shape and angularity, and Los Angeles abrasion test While, for fine aggregates measures of cleanliness, such as sand equivalent values, are typically measured and specified (Newcomb, 2009). Aggregate properties can affect mix properties in different ways (Ahlrich, 1996; Bahia and Stakston, 2003). For example, if the used aggregates are weak they may disintegrate easily under the action of Marshall Hammer during the mix design process.

Gradation is defined as the distribution of particle sizes expressed as a percent of the total weight. If the used aggregates have similar specific gravities, the gradation in weight and volume will be similar. Many studies reported the impact of aggregate gradation on the binder content (Elliott *et al.*, 1991; Matthews and Monismith, 1992; Kassem *et al.*, 2012). Matthews and Monismith (1992) seek the relationship between aggregate gradation and asphalt content for wearing and binder mixes based on regression analysis. For the wearing mix, they claimed that there is no relationship between the percent passing of the 4.75mm and 2.36mm aggregates and asphalt content. Inversely for binder mixes, they found a correlation between asphalt content and gradation changes. Roberts *et al.*(1991) stated that the aggregate gradation has a significant impact on principle properties of asphalt mixtures; such as stability, durability, stiffness, workability, permeability, resistance to water damage and frictional and fatigue resistance. Large size aggregate has led to lower the binder content, high density, satisfying voids in mineral aggregate. (Amy , Lounsbury and Huck, Gary, 2013) studied the effect of aggregate gradation on the performance of bituminous mixture, the study was conducted by using two types of asphalt content and three types of aggregate gradations, it was concluded that the upper gradation (finer) mix has higher IDT and less horizon TAO tensile strain, while the lower (coarser) gradation mix has higher shear strength and less rut depth.

Button, Perdomo and Lytton (1990) pointed out the nine possible factors cause rutting, but stated that the aggregate characteristics is the primary material quality factor influencing rut susceptibility. Stakston and Bahia (2003) also indicated that rut resistance is highly dependent on aggregate grading, and that mixes made with the best possible materials, which would fail without a proper gradation. Golalipour *et al* (2012) also found that the result seems to indicate that when the gradation is near to the lower limit curve, the permanent deformation is increased and the rutting resistance will be decreased. Also several studies have found that the mixture with finer graded reduced rut potential (Eliana, 2006).

Moisture damage is recognized by loss of strength or durability in an asphalt pavement due to the effects of moisture, and may be measured by the mixture’s loss of mechanical properties (Kumar, Chandra and Bose, 2006). Pan and White (1999) noticed that the main factor in the adhesion loss of asphalt film was fine aggregate. They noticed that the aggregate gradation and maximum aggregate size have an important effect on permanent deformation, and also observed that moisture damage could be reduce by using crushed sand. Kandhal (1992) explained that fine aggregate stripping is more critical than coarse aggregate.

Abo-Qudais and Al-Shweily (2007) found that the conditioning of HMA specimens has a significant effect on the creep deformation. Aodah, Kareem and Chandra (2012) used three aggregate gradation and two binders, they found that the creep ratio was affected by aggregate gradation, and they also observed that the highest value of creep ratio was obtained with coarser gradation.

According to ASTM standards, filler is the graded fine aggregate material that passing from sieve # 200 sieve (0.075 mm), while according to the European Standard EN12620 (BSI, 2013) it is defined as fine grained portion which pass from sieve (0.063 mm) at percentages (70-100%). The purpose of using filler in the mixtures of asphalt binder is to enhance binder paving mixture properties (Tunnicliff, 1962). The role of mineral fillers in asphalt mixture was summarized in two points, the first: strengthen the mixture of asphalt binder by filling the voids between the coarser aggregate particles in the mixtures and it acts as a part of the mineral aggregate, the second: fillers form mastic when mixed with asphalt, a large portion of the mineral filler stay suspended in asphalt while a smaller portion of filler becomes part of the load bearing framework (Harris and Stuart, 1995; Kollaros, Kalaitzaki and Athanasopoulou, 2017b). Muniandy, Aburkaba and Taha (2013) mentioned that the filler which form the mastic (filler finer than asphalt film) is improved the stiffness of asphalt mixture. While the larger was participated in improving the contact point between particles of individual aggregate. The mechanical properties of bituminous road pavement were decisively depended upon the properties of its filler-bitumen (Huschek and Angst, 1980). Filler affects the optimum asphalt content in bituminous mixtures by increasing the surface area of mineral particles, also the surface properties of the filler particles significantly modify the rheological properties of asphalt (such as penetration, ductility), and those of the asphalt mixture, (such as resistance to rutting) (Kandhal, 1981; Muniandy, Aburkaba and Taha, 2013).

Usually, coarse and fine aggregates will be brought in the asphalt mixture production plant in two or more separate fractions. Filler has to be brought and added separately. Thereby, the asphalt mixture stability in filler content is ensured (Mahan, 2013; Area, 2015). Filler particles are beneficial because they increase resistance to displacement due to the large area of contact between particles. It was found that fillers increase compactive efforts that required to compact specimens to the same volume or air void content. This effect becomes more pronounced with increasing concentration of fillers (Asmael, 2010). The properties of asphalt mixture influenced by the type and percent of mineral filler used in mix (Muniandy, Aburkaba and Taha, 2013). Adding filler to asphalt mix lead to increase density and reduce voids between aggregate which increase stability and toughness. The asphalt pavement become more brittle and more exposed to cracks as the amount of filler increases (Harrigan, 2011). The characteristics of mineral filler material have been investigated to determine their potential in upgrading performance of asphaltic concrete, especially by increasing hot mix stability and durability to alleviate problems with rutting and shoving. The use of certain mineral fillers offer enhanced opportunity for increased stiffness and strength in asphalt concrete (Benson and Martinez, 1984). Lime is often used as mineral filler in asphalt mixtures. It reduces the design asphalt content; improves cracking resistance at low temperatures; reduces age hardening of the asphalt binder; and increases mixture durability and stability (Kollaros, Kalaitzaki and Athanasopoulou, 2017a). Cement is also used as a filler material in asphalt mixture and it found improving stiffness, strength and anti-stripping properties of asphalt mixtures (Likitlersuang and Chompoorat, 2016).

2.6.2 Binder

The purpose of asphalt binder in the mixture is to bond the aggregate together, where represent the glue of the aggregate structure. Asphalt binder reduced the void between aggregates and acts as a lubricant aiding in consolidation during compaction (Rausch, 2006). The optimum binder content should be determined to get acceptable performance with regard to multiple failure situations. According to general specifications for roads and bridges (GSRB) in Iraq, the asphalt content is between (4-6) for surface course using 9.5 mm NMAS. Table (2-4) shows the rang of asphalt content for various states in US using different NMAS (Newcomb, 2009). (Walubita and Scullion, 2008) reported that in Texas, typically the asphalt content is between (6-8.5) in their study of 9.5mm NMAS mix design. According to traffic level and climate, the asphalt grade was determined in most cases (Cantrell, 2013). Also according to ESAL level and low and high temperature, the performance grade binder system permits to select asphalt binder. Table (2-5) showed different binder types used in TAO mixtures in various states of US (Im *et al.*, 2015). The visco-elastic behavior of asphalt mixture is a result of the bituminous binder rheological properties, it has an important effect on road performance, especially resistance to cracking and permanent deformation (Read and Whiteoak, 2015).

Table 2-4 Different States Using Different NMAS and Different Asphalt Content (Newcomb, 2009)

Agency	***Alabama***	***North Carolina***	***Maryland***	***Georgia***	***Ohio***
NMAS (mm)	12.5	12.5	4.75	4.75	4.75
Asphalt content %	5.5 min	4.6 - 5.6	5.0 - 8.0	6.0 - 7.5	6.4 min

Table 2-5 Comparative Listing of Bitumen in Different States (Im et al., 2015)

State	***PG***	***State***	***PG***
Nebraska	64-34	Mississippi	76-22
Alabama	76-22 M*	Missouri	64-22
California	Depend on Climatic Region	New Jersey	76-22
Florida	67-22, 76-22 M	New York	64-22 M, 76-22 M
Georgia	64-22	North Carolina	76-22 for high ESAL§ Indiana 70-28 64-22 for low ESAL
Indiana	70-28		
Iowa	70-22, 64-22	Ohio	76-22 M
Massachusetts	52-28	Texas	70-22, 76-22
Michigan	64-28 M, 70-22 M	Virginia	64-22

* Modified Binder § Equivalent Single Axle Loads

2.6.3 Polymer Modified Binder

Asphalt binder has been used in the construction of modern asphalt pavements for more than a century. The behavior of asphalt binder in service is governed by their initial engineering properties as well as by the mechanical and environmental conditions to which they are subjected. Special asphalt binders or asphalt binder with high quality are needed to make pavement having ability to accommodate traffic load in different climatic environments and the rise in traffic intensity (Isacsson and Lu, 1995; Awanti, Amarnath and Veeraragavan, 2008).

For many years, polymers have been incorporated into asphalt as a way to mitigate the major causes for asphalt pavement failures, including permanent deformation at high temperatures and cracking at low temperatures (Chen, Liao and Shiah, 2002). Polymer Modified Asphalt (PMA) binder has been used with success at locations of high stress such as interstates, intersections, and airports. It has proven itself to be another essential element in the paving process. When a polymer and virgin asphalt are blended, the polymer strands absorb part of the low molecular weight oil fraction of the virgin asphalt and become swollen. When the polymer-rich phase becomes the continuous phase (due to the relatively higher fraction of swollen polymer), the swollen strands connect together and forms a three dimensional network. This network provides the physical properties of elasticity, plasticity, and elongation of asphalt binder (Wekumbura, Stastna and Zanzotto, 2007). Ultimately, PMA binders become more viscous and tend to improve the binder coating (i.e., by increasing its film thickness) on aggregates and this holds the aggregate particles together more effectively.

The extension of the pavement service life or reducing the thickness of asphalt concrete layer is one of the advantages obtained when modifying the asphalt mixtures by polymers. Therefore, there is great potential for the introduction of polymers in the design of flexible pavement (Al-Hadidy and Yi-qiu, 2009). For the purpose of enhancing the cohesion and adhesion properties of asphalt mixture, the use of polymer modified bitumen has become mandatory in Austria (Litzka, Pass and Zirkler, 1994). In France, the utilization of polymer modified bitumen is increased, because it permits for an even more discontinuous mix design (high bitumen content and low sand) (Brosseaud, Abadie and Legonin, 1997). Several asphalt modifiers play an important role in improving the resistance to permanent strain at high pavement temperatures and they do not have negative effect on the properties of the bitumen. The resistance to permanent deformation of asphalt mixture is achieved either by stiffen the asphalt binder so that lead to reduce the total visco-elastic response of the asphalt mixture, or increase the elastic component of the asphalt binder, thereby reducing the viscous component (Read and Whiteoak, 2015). Increasing the elastic component of the asphalt binder will improve the flexibility of the mixture and this is important where high tensile strains are induced (Read and Whiteoak, 2003). Improving asphalt binder stiffness is likely to improve the stiffness of asphalt mixtures and this help to increase the service life and strength of the pavement and improve the capacity of load spreading. Instead, it may be possible to achieve the same structural strength but with a thinner layer. Polymer modified binder is often the best choice for binder modification (Kragh et al., 2011). Particularly for TAO, a polymer modified binder offers important advantages as compared to unmodified binder with regard to resistance to binder drainage, raveling, and durability (Sandberg *et al.*, 2011). States agencies like New York, North Carolina and Ohio utilized polymers to improve the performance of TAO mixtures (Hajj, Sebaaly and Habbouche, 2016).

There are several types of polymers used in asphalt binders today, currently, the most commonly used polymer for asphalt modification is the SBS (styrene butadiene styrene) followed by other polymers such as crumb rubber, SBR (styrene butadiene rubber), EVA (ethylene vinyl acetate) and polyethylene (Sengoz and Isikyakar, 2008). Walubita and Scullion (2008) illustrated that some polymers such as latex rubber, SBS can be used to modify TAO mixtures to improve the mechanical and durability characteristics of these mixtures.

In the United States, the SBS is the choice that used frequently. According to a modified asphalt market survey in 2005-2006, 80% of states across the country used SBS as a modifier (Casola, 2006). The use of the SBS as an asphalt modifier was developed by Shell chimerical company - It has been recognized that the physical and mechanical properties and rheological behavior of conventional asphalt compositions can be improved by the addition of SBS (Lu and Isacsson, 1997). SBS exhibits a two-phase morphology consisting of glassy polystyrene (PS) domains connected together by the rubber polybutadiene (PB) segments at the temperatures between glass transition temperatures of the PB and PS. Therefore, SBS exhibits cross-linked elastomer network behavior. Above the glass transition temperature of PS, the PS domains soften and SBS becomes melt-process able. This behavior of thermoplastic elastomer has allowed SBS to become usable for extensive applications in asphalt modification. In structural terms, its backbone chain is made up of three segments as shown Figure (2-4) (Rajpal, 2005). Polystyrene is a hard plastic which provides durability at high temperature, while butadiene is a rubber which contributes to the elasticity of the binder at low temperature. Figure (2-5) shows a schematic of the interaction between the SBS network and the asphalt fractions (Shull, 1995). It is envisioned that the SBS network interacts with the asphaltene and resin micelles (Rozeveld et al., 1997).

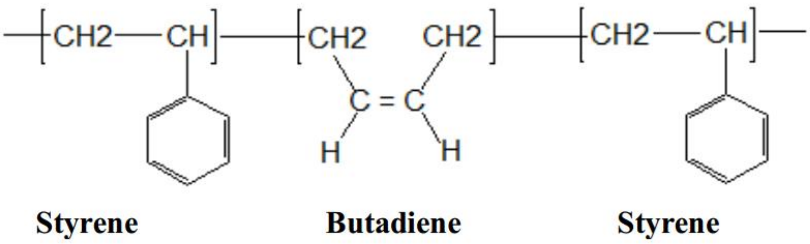

Figure 2-4 Structure of SBS Polymer (Rajpal, 2005).

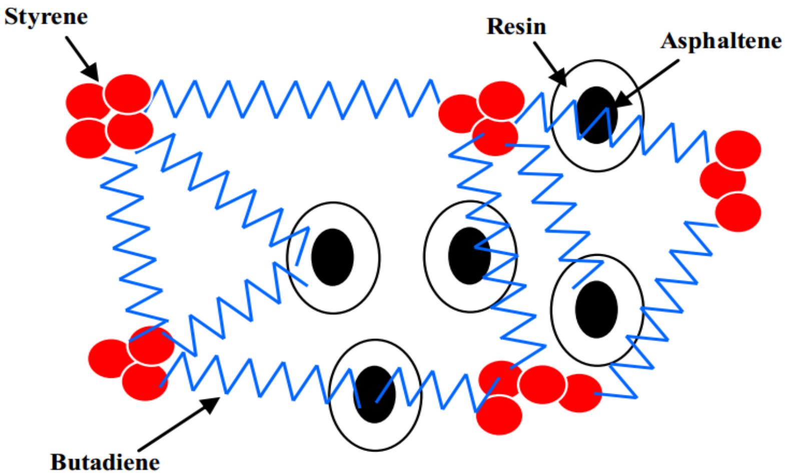

Figure 2-5 A Schematic of The SBS Interaction with Asphalt Fractions (Shull, 1995)

With the modification of asphalt by SBS, the high temperature rutting resistance and temperature susceptive of asphalt, as well as its low-temperature flexibility, were improved effectively. Airey (2003) studied the effect of SBS polymer modification on the conventional asphalt content. He stated that, although the decrease in penetration is relatively uniform with increasing polymer content but there is a significant increase in softening point at high polymer content of 5% and 7%. In addition to the increase in stiffness, the increase in penetration indices a significant reduction in temperature susceptibility with polymer modification particularly at higher polymer content.

A large number of research works on the performance of asphalt mixtures were performed when modified by SBS polymer, e.g., (Airey, 2003) found that modified asphalt binder with SBS led to improve the rheological properties of asphalt pavement, offer higher modulus than the net mixtures, which that helpful with regard to resist to permanent deformation. Hanyu et al (2005) and Zhao et al (2016) focused on the rheological properties of SBS polymer, the mechanism of SBS polymer modified binder, and also explain that the performances of mixtures are greatly affected by the morphology of SBS. Good improvement in stability of asphalt mixture was achieved when using SBS modifiers in asphalt binder (Fu *et al.*, 2007; Ou and Li, 2015). Chi and Liu (2017) have confirmed that adding the SBS to asphalt binder plays an important role on performance of asphalt mixture, which can enhance the resistance to permanent deformation, stripping, fatigue damage, temperature susceptibility and thermal cracking. Awanti, Amarnath and Veeraragavan (2008) investigated the effect of SBS polymer on asphalt mixture and they found that, firstly: the values of penetration and temperature susceptibility of polymer modified binder are lower than those of neat asphalt while higher values of viscosity and softening point, which were obtained when SBS polymer was used, secondly: the Marshall stability and indirect tensile strength (IDT) values of mixtures modified by SBS polymer at optimum binder content are higher when compared with unmodified mixture, thirdly: resistance to moisture damage was improved when utilizing polymer SBS in asphalt mixture. Romeo *et al.*(2010) studied the effect of SBS polymer in Superpave mixtures in case of cracking resistance and healing. Their results showed that using SBS polymer in Superpave mixtures led to an increase in cracking resistance and has no effect on healing or aging.

2.6.4 TAO Mix Design

Asphalt mixture design of TAO has been studied worldwide, highlighting on the advantages and disadvantages of different approaches with regard to durability problems and functional properties of TAO. In France the very thin asphalt (BBTM) mix design is depending on: a gyratory compaction test, rutting resistance and water sensitivity of the mixture (Kragh *et al.*, 2011). As defined in NF EN 13108-2 (EN, 2006) and based on the gyratory compaction results, mixtures are classified into two classes. First: corresponds to mixtures distinguished by a voids content of (12–19) % (following 25 gyrations) for a BBTM 0/6 or in case of a BBTM 0/10, voids content of 10 – 17 %. Second: mixtures correspond to a void content of (20–25) % after 25 gyrations for a BBTM 0/6, or in case of a BBTM 0/10 void content of 18 – 25 %. The most commonly used mixtures are those that meet the criteria of the first category. The second category for the determination of the minimum binder content.

In the past, French identified the minimum value of asphalt content according to NF P 98-137 is (3.5 %), while at the present time the lowest value of asphalt content according to EN 13108-2 is (5 %) (Sandberg *et al.*, 2011). De Larrard and Hu (1993) explained that the gyratory compaction of BBTM is an indicator of surface texture than for the void content in France .

In the case of very thin asphalt mixtures, not only the purpose of permanent deformation test to assess the resistance to rutting, but it is used for the development of surface texture as a function of the number of wheel passes. In France, the design of ultra-thin asphalt mixture is not specified. The mix composition is normally derived from very thin asphalt formulations with minor adjustments such as a small reduction in the percentage of asphalt content and filler and also the percentage of sand fraction has decreased by (5-15%) (Brosseaud, Abadie and Legonin, 1997).

In Austria, the TAO mix design began with a constant discontinuous grading curve and the optimal asphalt content of TAO mixtures was specified depending on Marshall Stability and void content (Litzka, Pass and Zirkler, 1994).

In U.S, to meet the structural and functional requirements of TAO, mix design specifications were designated. As shown in Table (2-6), N design, air voids, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and asphalt content were specified by different states (Newcomb, 2009). It is noted that only Ohio is used Marshall Method to design TAO mixture, while the rest of states designed the mixture using Superpave mix design.

Table 2-6 Mix Design Requirements In Different States (Newcomb, 2009; NDOR, 2013).

State	N_{design}	***Design Air Voids***	***VMA (%)***	***VFA (%)***	***Binder content %***
Nebraska	50	4	16	--	5.3
Alabama	60	--	15.5	--	5.5
Georgia	50	4-7	--	50-80	6-7.5
Maryland	65	4	--	--	5-8
Massachusetts	75	4	15	65-78	--
Michigan	--	4.5-5	15.5	--	--
Mississippi	50-75	4-5.5	16-19	--	6.1
Nevada	--	3-6	12-22	--	--
New York	75	4	16	70-78	--
North Carolina	--	--		--	4.6-5.6
Ohio	50-75	3.5	15	--	6.4
Texas	50	--	16	--	6.8-8
Utah	50-125	3.5	--	70-80	--

in U.S, report described the design of ultra-thin asphalt mixture by using the Superpave gyratory compactor to determine the optimum asphalt content for a given grading, the voids content after 100 gyrations are 10% (Hanson, 2001). Also Texas Department of Transportation described the mix design procedure for ultra-thin hot mixtures.

There are some general paths that can be followed in the design of TAO (Kragh *et al.*, 2011):

- First: Often the grading curve is sporadic. The relation between performance of TAO mixture and exact grading is poor, therefore, there are broad limits on the grading curve.
- Second: The different types of asphalt mixtures lead to different asphalt content. Asphalt content is a function of mortar film thickness, and it is necessary to ensure that the aggregate having sufficient coating.
- Third: using void content in design of TAO as a means of classification of mixtures.

2.7 Laboratory Performance Tests

Table (2-7) shows various laboratory tests for some countries and states in US to assess TAO mixtures and to predict the distress of asphalt pavement like cracking, moisture damage and rutting. Walubita and Scullion (2008) and Scullion et al.(2009) used different types of TAO mixtures to assess the performance of these mixture with regard to cracking and rutting resistance when subjected to various environment conditions and traffic by using overlay test and Hamburg wheel tracking test. They found that the mixtures with 9.5mm NMAS and over 7% binder content was promising mixture for use of TAO mixtures. Study was made to evaluate the rutting resistance of TAO mixtures with (12.5, 9.5, and 4.75mm) NMAS by using Asphalt Pavement Analyzer (APA). It was concluded from this study that the rutting resistance of mixture with 4.75mm NMAS was comparable to that mixtures with 12.5mm and 9.5mm NMAS (Powell and Buchanan, 2012). (Mogawer *et al.*, 2013) found after conducting many laboratory tests on trial field TAO mixtures to measure moisture damage, stiffness of mixture, cracking and rutting resistance that the mixtures had a high cracking resistance including resistance to low temperature cracking and reflective cracking.

Table 2-7 Summary of The Laboratory Tests (Im et al., 2015)

Country	***Testing method***	***To identify***	***Reference***
South Africa	Model Mobile Load Simulator	rutting	Pretorius, Wise and Henderson (2004)
	Pendulum Friction	Skid resistance	
Australia	Cantabro	Durability	Walubita and Scullion (2008)
		Binder Film Thickness	
Unite Kingdom	Indirect Tensile Stiffness Modulus	Mixture Stiffness	Nicholls, Carswell and Langdale (2002)
	Dynamic Creep		
State	**Testing method**	**To identify**	**Reference**
Alabama	Asphalt Pavement Analyzer	Rutting	Powell and Buchanan (2012)
Minnesota, Vermont	Dynamic Modulus test	Mixture Stiffness	Mogawer et al (2013)
	Hamburg test	Moisture Susceptibility	
	Overlay Tester	Reflective Cracking	
	Asphalt Concrete Cracking Device	Low Temperature Cracking	
	Semi-Circular Bending test	Fatigue Cracking	
Texas	Hamburg Wheel Tracking	Rutting	Walubita and Scullion (2008) and Scullion et al.(2009)
	Overlay Tester	Cracking	
Virginia	Model mobile load simulator	Rutting	Druta, Wang and McGhee (2014)
		Fatigue	

2.8 Performance of Thin Overlay Pavement

Thin asphalt overlay pavement performance is affected by several factors. The main distresses of TAO involve: cracking, raveling, stripping, rutting, friction, roughness and traffic noise according to report made by (Cantrell, 2013). This section includes the performance of TAO with respect to these failures.

2.8.1 Cracking

Preventive maintenance should be applied in the early stages of cracking to be more cost-effective. Life cycle costs are high and may reach 14% for states that are delayed in crack maintenance when compared with those implement maintenance in early stages (Harvey, 2009). With respect to medium and high fatigue cracks, preventive maintenance treatments are not applied. Corrective maintenance should be used to treat the severity fatigue cracking. Newcomb (2009) reported that the block, transverse and longitudinal cracking can by corrected by TAO. Figure (2-6) shows that the chip seals and TAO were high performance with respect to resistance of fatigue cracking when compared with other preventive techniques (Shirazi et al., 2010).

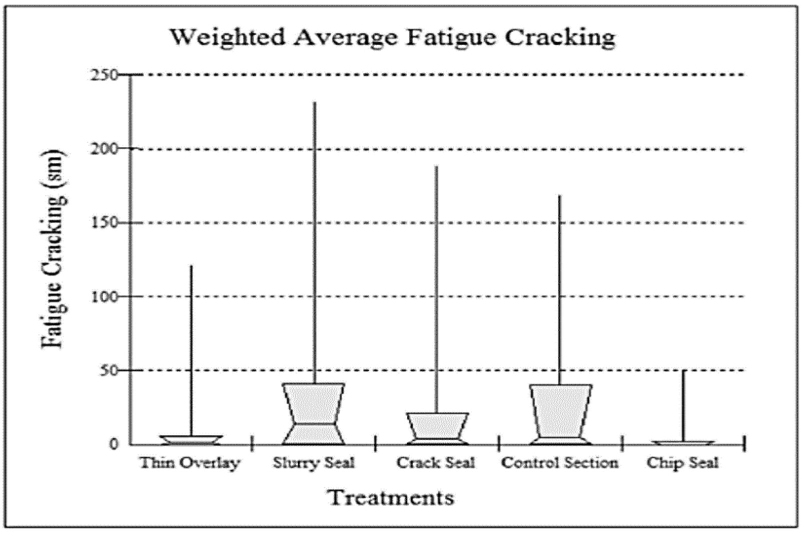

Figure 2-6 Weighted Average Fatigue Cracking (Shirazi et al., 2010).

Powell and Buchanan (2012) conducted a comparison study between three experiment TAO pavements (4.75 mm, 9.5 mm, and 12.5 mm NMAS surface mixes), all experiment TAO pavements were visually inspected for cracking on a weekly basis. Surface cracks are first painted then digitized, so that a record of each individual crack is recorded. The pairs of ordinate and abscissa measurements that define the shape of each crack were stored in a relational database such that the development of cracking as a function of traffic could be established. At the end of 20 million ESALs, no cracking was observed in any of the study mixes. A very small amount of longitudinal top-down cracking was first observed in the 9.5 mm NMAS surface after approximately 21 million ESALs. The crack map for the 9.5 mm NMAS surface near the end of the 2009 research cycle after approximately 30 million ESALs. No cracking has been observed in the 4.75 mm NMAS mix with the same level of traffic.

Qi and Gibson (2010) showed that the resistance to fatigue cracking for un aged and aged TAO with 4.75 mm NMAS were much better than untreated pavement but un aged perform better. Hall, Simpson and Correa (2002) demonstrated that the TAOs have a significant impact on the resistance to fatigue cracking because they noticed that the pavement which are (2-11) years in age had fatigue cracking more than 4 times than overlaid with TAO.

2.8.2 Raveling

Raveling happens when there is no adhesion between asphalt binder and aggregate. Raveling is an indicator of surface aging and it is caused by asphalt binder loss and aggregate particles displacement. Raveling may be the main reason of many distresses in pavement such as spray and splash, noise problem and low skid resistance if it occurs significantly (Cantrell, 2013). The raveling resistance of TAO mixtures with 4.75mm NMAS is better than the mixtures with 9.5 mm NMAS because the macro texture of mixtures with 4.75mm NMAS had less change and this refer to good durability and low raveling (Powell and Buchanan, 2012). Some materials are added to the pavement surface to cover the raveled surface and prevent it from growing. For this reason, most surface treatment techniques address some riskiness of raveling. Rausch (2006) demonstrated that TAO should be proper for raveling treatment if placed on structurally sound pavement. Table (2-8) suggests the use of various preventive techniques on different levels of raveling severity (Cantrell, 2013)

Table 2-8 Severity Level Surface Treatments (Cantrell, 2013)

Degree of severity	*Fog Seal*	*Chip Seal*	*Double Chip Seal*	*Slurry Seal*	*Microsurfacing*	*Thin Overlay*	*Cape Seal*
Low severity	*X*				*X*	*X*	*X*
Medium severity	*X*	*X*			*X*	*X*	*X*
High severity		*X*	*X*	*X*	*X*	*X*	

According to Caltrans (2007) many factors can cause raveling such as low asphalt content, low compaction, moisture damage and asphalt hardening. The permeability also has an effect on raveling as increased permeability leads to the asphalt mixtures aging, which in turn leads to increase raveling. It can improve the resistance of mixtures to raveling by modifying asphalt binder with polymer.

2.8.3 Stripping

Stripping is the reverse raveling which occurs at the bottom of the hot mix asphalt layer when the aggregates is separated from the asphalt. The prime cause of stripping is moisture damage (Wood et al., 2009). Caltrans (2007) explained that the stripping is considered to be one of the different distresses of dense graded TAO. For the purpose of reducing stripping (improving adhesion between aggregates and asphalt binder) some agencies add anti-stripping or anti-aging to the asphalt mixture. (West *et al.*, 2011) demonstrated that the TAO mixtures with 4.75 mm NMAS resist stripping due to their resistance to moisture induced damage. A study made comparison between TAO mixtures with 12.5mm NMAS and 4.75 mm NMAS and showed that the stripping resistance of mixtures with 4.75 mm NMAS similar and sometimes greater than mixtures with 12.5 mm NMAS (Williams, 2006).

2.8.4 Rutting

Rutting can be defined as a disfigurement of the surface layer in the wheel path. The main reason of rutting is one or more layers of the pavement suffering lack of shear strength (Hicks, Seeds and Peshkin, 2000). Rutting can also be occurred due to repeated traffic. asphalt content, dust content, type of aggregate and air void, which are the main factors in TAO that have an effect on rutting (Cantrell, 2013). Most preventive treatments techniques do not treat rutting issues. Hall, Correa and Simpson (2003) and Morian (2011) showed that the rutting can be reduced dramatically and immediately by utilizing TAO technique. NAPA (2009) explained the using of thin HMA overlay can reduce the depth of rut by (5-55%). Shirazi et al.(2010) showed that the weighted average rutting of various preventive treatment techniques as can be seen in Figure (2-7). It is clear that the weighted average rutting of TAO was lower than other techniques.

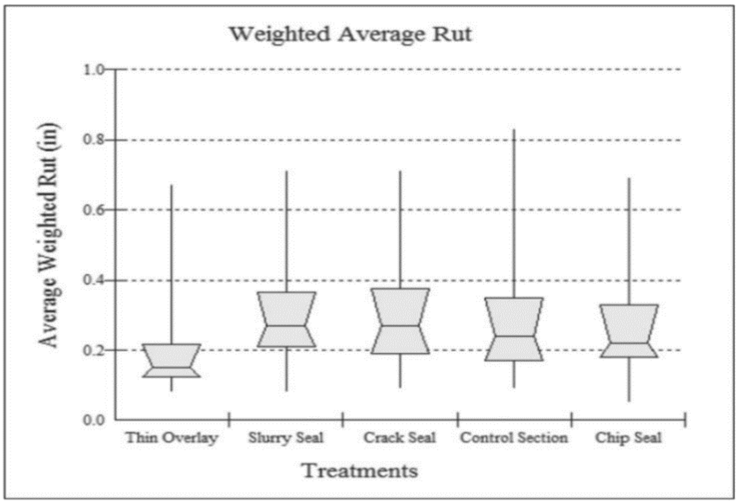

Figure 2-7 Weighted Average Rutting (Shirazi et al., 2010)

Powell and Buchanan (2012) investigated the performance of TAO with respect to rutting resistance using three aggregate gradations (12.5mm, 9.5mm and 4.75mm) NMAS. They found that the rut depth after 20 million ESALs of traffic were (4mm, 4mm and 6mm), respectively, but when using the asphalt pavement analyzer and after 8000 cycles, the values of rut depth were (3.4mm, 3.4mm, 2.2 mm), respectively.

2.8.5 Friction

There are many studies on getting good results in friction with the help of some instructions. For fine aggregate, FAA considers to be the most significant property to get a good degree of friction. Also in order to improve friction, aggregate with gradation should be falling below the line of maximum packing on the 0.45 power, and aggregate having good skid resistance are used (Newcomb, 2009). A study was conducted by West *et al* (2011) included that the establishment of projects in Missouri, Tennessee and Minnesota to evaluate the performance of 4.75mm TAO with respect to friction, by using dynamic friction tester and circular track meter (CTM) to measure the initial friction. The macro texture of 4.75mm thin HMA overlay measured by CTM and the properties of pavement surface can be quantified by Mean Profile Depth (MPD). The result of Missouri test in Mean Profile Depth for 4.75mm thin HMA overlay are normal (0.17-0.22). The Tennessee result for virgin mixture (without RAP) in MPD of (0.16- 0.33) mm, while the result of Minnesota test in MPA of (0.13-0.18) mm. The low friction is caused by the existence of high film of asphalt binder on the pavement surface, but friction characteristics can be improved when asphalt binder film get worn. The friction performance of TAO could be enhanced by utilizing aggregates that having high resistance to polishing. According to West *et al.*(2011), the texture of surface layer do not have a major impact on friction. This may be due to the fact that the thin asphalt film has a negative impact on friction until it is worn by traffic, then the value of friction depend on aggregate polish resistance. In dry and wet conditions, the fine aggregate having high angular can offer good friction. Li *et al.*(2012) showed the frictional characteristics of different types of surface layer as explained in Table (2-9).

Table 2-9 Frictional Characteristics of Various Pavement Surfaces (Li et al., 2012)

Surface Type	Friction	MPD (mm)
4.75-mm HMA on I-465, 36 months	16.7 (smooth tire)	0.24 (CTM)
4.75-mm HMA on US-27, 18 months	19.7/28.6 (smooth tire)	0.24/0.30 (CTM)
4.75-mm HMA on SR-227, 18 months	20.1/19.8 (smooth tire)	0.18/0.20 (CTM)
4.75-mm HMA on SR-29, 6 months	21.6/27.6 (smooth tire)	0.21/0.22 (CTM)
4.75-mm HMA, new (47)	62.5 (rib tire)	0.21 (CTM)
4.75-mm HMA, 15 months (47)	63.8 (rib tire)	0.26 (CTM)
12.5-mm HMA, new (47)	65.5 (rib tire)	0.39 (CTM)
12.5-mm HMA, 15 months (47)	45.9 (rib tire)	0.39 (CTM)
4.75-mm HMA, new, MODOT (51)	–	0.17–0.22 (CTM)
4.75-mm HMA, new, TNDOT (virgin mix) (51)	0.25–0.35 (DFT_{20})	0.16–0.33 (CTM)
4.75-mm HMA, new, TNDOT (15% RAP) (51)	0.28–0.33 (DFT_{20})	0.19–0.33 (CTM)
4.75-mm HMA, new, MNDOT (51)	0.34–0.49 (DFT_{20})	0.13–0.18 (CTM)
9.5-mm HMA (52)	42.5 (smooth tire)	0.59 (CTM)
9.5-mm Dense-Graded HMA (53)	–	0.53 (CTM)
12.5-mm SMA (53)	–	1.07 (CTM)
19.0-mm SMA (53)	–	1.11 (CTM)
12.5-mm OGFC (53)	–	2.31 (CTM)
Dense-graded HMA to OGFC (54)	32.5 (smooth tire)	1.63 (sand patch)
	27.4 (smooth tire)	0.53 (sand patch)
	41.4 (smooth tire)	1.57 (sand patch)
	33.4 (smooth tire)	2.19 (sand patch)
	37.8 (smooth tire)	2.97 (sand patch)
9.5-mm HMA (55)	61.9/64.3 (BPN)	0.62/0.78 (sand patch)
Polymer modified 9.5-mm HMA (55)	56.6/65.6 (BPN)	0.76/0.82 (sand patch)
Rubber modified 9.5-mm HMA (55)	60.6/64.5 (BPN)	0.78/0.73 (sand patch)
Polymer modified 12.5-mm SMA (55)	58.4/67.6 (BPN)	0.89/0.94 (sand patch)
12.5-mm SMA with fibers (55)	60.5/67.8 (BPN)	0.89/1.07 (sand patch)
19.0-mm HMA (55)	60.9/62.9 (BPN)	0.73/0.82 (sand patch)
9.5-mm PFC, new (56)	0.51 (DFT_{20})	1.37 (CTM)
9.5-mm PFC, 36 months (56)	0.52 (DFT_{20})	1.37 (CTM)
9.5-mm PFC, 60 months (56)	0.42 (DFT_{20})	1.48 (CTM)
9.5-mm SMA, newly constructed (56)	0.37 (DFT_{20})	1.17 (CTM)
9.5-mm SMA, 36 months (56)	0.61 (DFT_{20})	1.03 (CTM)
9.5-mm SMA, 60 months (56)	0.69 (DFT_{20})	0.93 (CTM)
9.5-mm HMA, newly constructed (56)	0.52 (DFT_{20})	0.30 (CTM)
9.5-mm HMA, 36 months (56)	0.39 (DFT_{20})	0.55 (CTM)
9.5-mm HMA, 60 months (56)	0.41 (DFT_{20})	0.63 (CTM)

2.8.6 Roughness

The TAO provides ride quality due to the smoothness of the surface, and this is one of the main reasons for the selection of TAO from other techniques. Peshkin and Hoerner (2005) explained that TAO has several advantages such as reduce reflective cracking, reduced rutting and enhanced ride quality. TAO had an important impact on long term roughness (Hall, Simpson and Correa, 2002). There are two factors that impact on the smoothness of a new TAO which include the condition of the existing pavement and the amount of surface preparation done prior to the application of a TAO. NAPA (2009) demonstrated that the utilizing of TAO improved the ride quality by (40-60%). International Roughness Index (IRI) used to measure the ride quality and its unit is m/km or in/mile. Good ride quality can be achieved when the value of IRI decrease (Chou, Datta and Pulugurta, 2008a).

Labi *et al.*(2005) found that IRI reduced by (18-36%) when applying TAO. In Ohio, Chou, Datta and Pulugurta (2008) reported that the initial IRI for four lane divided highways (priority system) reduced to (31%) and for two lane undivided highways (general system) decrease to 45%. According to different studies, the range of increasing ride quality is between (18-60 %). Figures (2-8) and (2- 9) explain that the using of TAO lead to great improvement in ride conditions, it found that the average IRI for priority system decreases from 98 to 68 and decrease from 140 to 78 for general system.

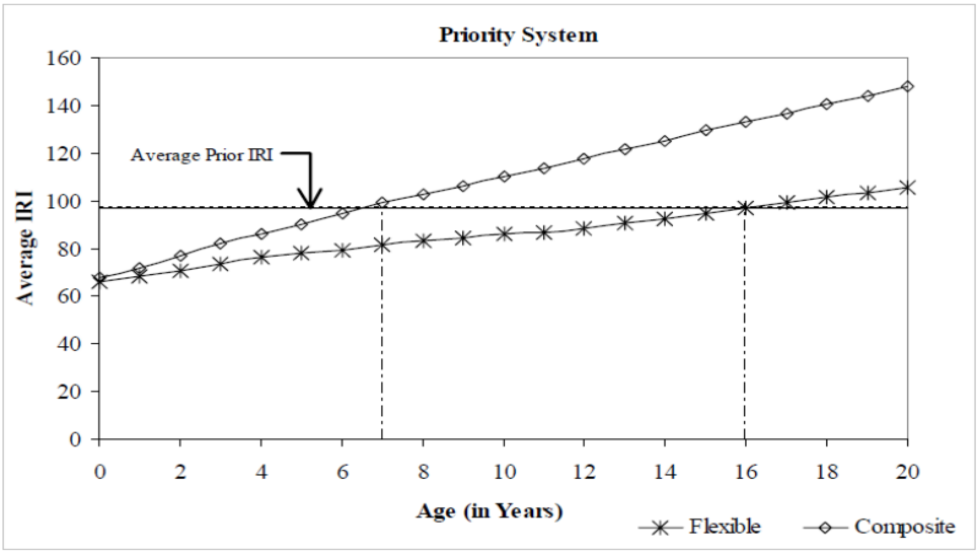

Figure 2-8 Average Ride Quality Deterioration Trend of Thin Overlay/Priority System (Chou and Pulugurta, 2008)

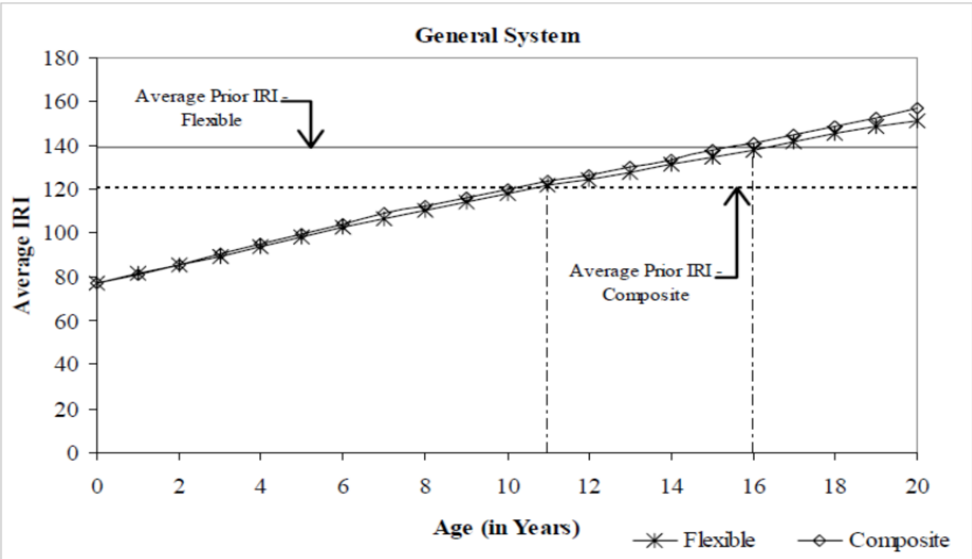

Figure 2-9 Average Ride Quality Deterioration Trend of Thin Overlay/General System (Chouand Pulugurta, 2008)

Morian (2011) summarized the potential maintenance techniques for different types of distresses as explained in Table (2-10). As shown, the only technique which can address stability related roughness was thin overlays. Also Table (2-11) shows maintenance treatments for different distress types (Hicks, Seeds and Peshkin, 2000).

From these tables, it can be recognized that only cape seal, microsurfacing and thin overlay whom can enhance ride quality.

Table 2-10 Possible Maintenance Treatments for Various Distress Types (Morian, 2011)

Pavement Distress		Thin Overlay	Milling and Overlay	Micro-surfacing	Chip Seal	Sand Seal	Fog Seal	Slurry Seal	Cape Seal
rough ness	Nonstability related	X	X	X					X
	Stability related	X							
Rutting		X	X	X					
Cracking		X	X	X	X	X	X	X	X
Flushing/bleeding			X	X	X				
Raveling and wear				X	X	X	X	X	X

Table 2-11 Possible Preventive Maintenance Treatments for Various Distress Types (Hicks et al., 2000)

Pavement distress		Crack sealing	Fog seal	Microsurfacing	Slurry seal	Cape seal	Chip seal	Thin HMA overlay	Mill or grind[a]
roughness	Nonsteability related			x		x		x	x
	Stability related							x	
rutting				x				x	x
Fatigue cracking[b]			x	x	x	x	x	x	
Longitudinal and transverse cracking		x		x	x	x	x	x	
bleeding				x			x		x
raveling			x	x	x	x	x		

Key: appropriate strategy

[a] This is a corrective maintenance technique

[b] for low severity only; preventive maintenance is not applicable for medium to high severity fatigue cracking

As shown in Figure (2-10), the lower weighted average IRI between treatment techniques (chip seal, control section, slurry seal and thin overlay) was thin overlay (Shirazi *et al*., 2010). From this research, high traffic, poor pavement condition and freezing conditions were factors that having impact on roughness. It was found that the thin asphalt overlay was the best option when compared with other treatments in these factors.

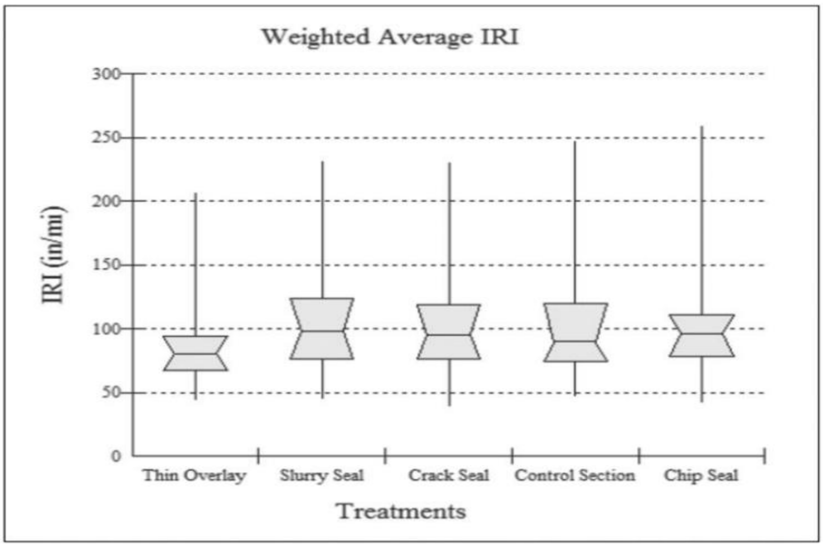

Figure 2-10 Weighted Average IRI (Shirazi et al., 2010)

Plate 2-4 Placement of Thin Asphalt Overlay (Top) and Surface Texture of New (Bottom Left) and Worn (Bottom Right) Dense Graded Asphalt Surfaces (www.fhwa.dot.gov)

2.8.7 Traffic Noise

Noise can be defined as the generation of unwanted sound (Hanson, James and NeSmith, 2004). Traffic noise where it happen can reduce living standard, for this reason is considered an environmental pollution. Since the 1970's in sensitive areas, the noise could be mitigated by using noise barriers or sound walls. Traffic noise can be reduced by enhancing the mixtures of pavement or using surface treatment techniques. Traffic noise generation can be affected by the properties of aggregate used in asphalt mixture. The interaction between tires of vehicle and pavement surface is influenced by the macrotexture of the road, this is why macrotexture is the main cause of tire noise generation. The traffic noise increased as the macrotexture became coarser (Newcomb, 2009). When the size of the aggregate NMAS is large it leads to increased macrotexture of the road and this in turn leads to increased traffic noise, as shown in the Figure (2-11). Al-Qadi (2011) noted that the level of noise influenced by NMAS instead of aggregate gradation. Little decrease in decibels (dB) can assist in reduce the level of noise, because it was observed that every 3 dB decrease in noise could reduce traffic noise to half.

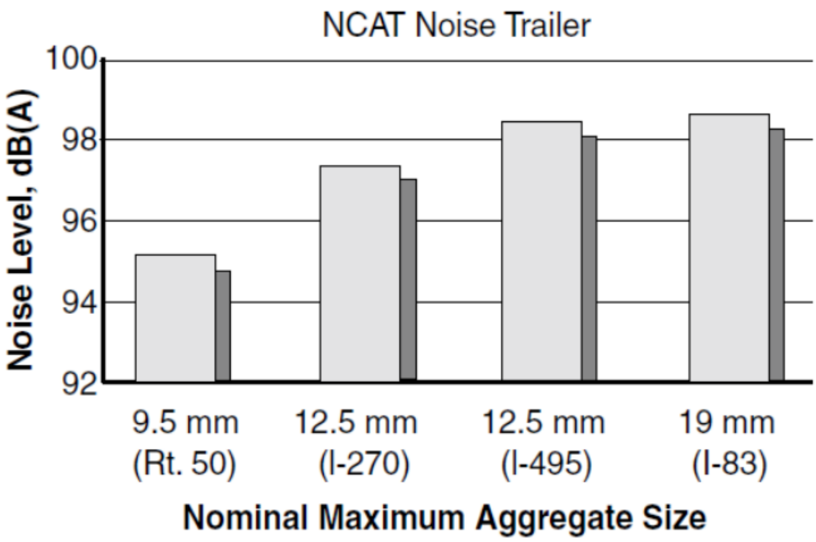

Figure 2-11 Relationship between NMAS and Tire-Pavement Noise Level (NAPA, 2009)

Table (2-12) shows different treatments techniques that having various impact on the characteristics of surface layer of pavement. As shown, many treatment techniques have improved the noise level such micro-surfacing, thin overlays, slurry seals and ultrathin friction course (Peshkin, Hoerner and Zimmerman, 2004).

Table 2-12 Primary Benefits of Different Maintenance Treatments (Peshkin, Hoerner and Zimmerman, 2004)

Treatment	Roughness	Friction	noise	Life Extension	Moisture reduction
Bituminous surface pavements					
Crack sealing				X	✓
Fog seals				X	✓
Scrub seals				✓	✓
Slurry seals	✓	✓	✓	✓	X
Microsurfacing	✓	✓	✓	✓	X
Chip seals	✓	✓		✓	X
Ultrathin friction course	✓	✓	✓	✓	✓
Thin overlays	✓	✓	✓	✓	✓
PCC pavements					
Joint and crack sealing				X	✓
Diamond grinding	✓	✓	✓	✓	

✓= major effect ***X*** *= Minor effect*

Plate 2-5 Noise Absorption Measurement with The Extended (Sandberg et al., 2011)

2.9 Summary

Thin asphalt overlays are characterized as surface treatment typically with thickness no more than 1.5 in. Worldwide, the use of TAO has increased significantly, although it has become difficult to recognize between TAO and other HMA. The conditions for applying TAO different from country to other. Among the advantages of TAO, the most important seem to be the long service life, noise reduction, the smaller working space, fast construction, higher skid resistance, and higher fatigue cracking resistance. TAO are more sensitive to weather conditions and this is considered to be the important disadvantage. The design of TAO mixtures is subjected to prior experience and materials used in design. Many types of aggregate can be used in TAO mixture such as natural and synthetic materials individually or collectively. Two important things in fine aggregate should be controlled to guarantee acceptable internal friction and help in resist rutting namely, natural sand and FAA value. Gradation has a great effect on the performance of thin asphalt overlay. TAO pavement performance is affected by several factors. Better improvements observed when applying TAO with respect to main distress such as: cracking, raveling, stripping, rutting, friction, roughness and traffic noise.

Taken into account all advantages and disadvantages of TAO, it seems to be that one of the best solution for maintenance and preservation of the existing highway infrastructure, especially, as current practice of other surface treatment locally not well common. Therefore, more details of the characteristics of TAO using local material is in high demand.

Chapter Three

MATERIALS, TESTING, AND METHODOLOGY

3.1 Introduction

To achieve the main aim of this research work which characterizing TAO mixtures using unique modified polymer (SBS with silica), selected local materials, standardized and non-standardized testing methods, and systematic methodology were planned and then conducted. Therefore, this chapter introduces these stuff for the next step in the follow chapter where result details analyzed and discussed.

3.2 Materials

Principally, the used material in this research were almost supplied locally to ensure economic consideration, and to explore their potential in developing the paving industry in Iraq.

3.2.1 Aggregates

Due to the limitation of time and resources, one type of virgin aggregate, one NMAS and dense graded mixture was nominated in this study. The selected crushed limestone aggregates and natural sand were supplied from Karbala quarries. The aggregate were sieved, separated and graded in the lab to meet the specified gradation for surface course type III B (9.5 mm NMAS) according to the General Specification for Roads and Bridges (GSRB, 2003), section R9. Moreover, three types of filler were selected from local market. Plate (3-1) and Table (3-1) show the particle size distribution of the nominated aggregates gradation. However, the mid-range of the GSRB specification was specified to produce the tested gradation for TAO mixtures, as can be seen in Table (3-1) and Figure (3-1).

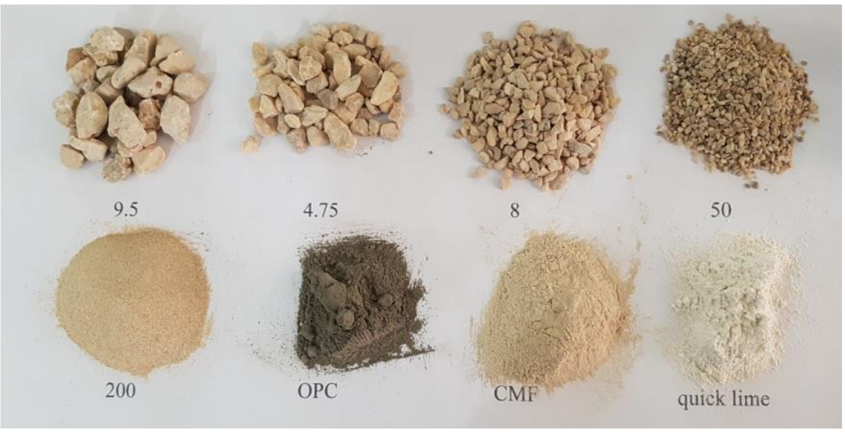

Plate 3-1 Nominated Crushed Aggregates Size with the Three Type Fillers.

Table 3-1 Gradation of Virgin Aggregate for Surface Course Type IIIB (GSRB, 2003)

Sieve size	mm	% passing by weight according to GSRB	Selected % passing by weight for tested TAO (mid-range of
¾	19	-----	-----
½	12.5	100	100
3/8	9.5	90-100	95
No. 4	4.75	55-85	70
No. 8	2.36	32-67	49.5
No. 50	0.3	7-23	15
No. 200	0.075	4-10	7

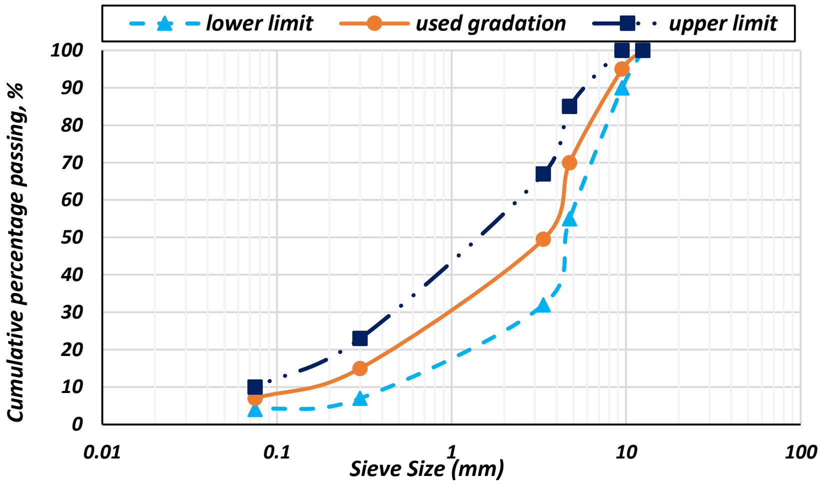

Figure 3-1 Distribution of Particle Size of the used Gradation for Virgin aggregate (Dense Graded Wearing Course)

3.2.1.1 Coarse and Fine Aggregates

The physical properties of coarse and fine aggregate were subjected to (GSRB) requirements, while the other fundamental tests were conducted to characterize the used materials, as shown in Tables (3-2), and (3-3) for coarse and fine aggregate, respectively. The results were gained from experiments that accomplished in the laboratory of University of Kerbala. It is worth mentioned that the used fine aggregate in this research were crushed sand and natural sand and the natural sand was always checked to be less than 25% of the total fine aggregates weight.

Table 3-2 The Physical Properties of Virgin Coarse Aggregates.

Property	***ASTM designation***	***Obtained value***	***GSRB Specification, (surface course)***
Bulk specific gravity, gm/cm^3	C127 (ASTM, 2015a)	2.6	-
Apparent specific gravity, gm/cm^3	C127	2.64	-
Water absorption, %	C127	1.36	-
Percent wear by los Angeles abrasion , %	C131 (ASTM, 2014a)	9.1	30% Max
Soundness loss by sodium sulfate ,%	C88 (C. ASTM, 2013)	4.1	12% Max
Clay lumps, %	C142 (ASTM, 2010)	0.05%	-
Flat and elongated particles, %	D4791 (ASTM, 2011b)	0.6%	10% Max
Passing sieve NO.200, %	C117 (ASTM, 2013b)	0.91%	-
Degree of crushing, %	---	94%	90% min

Table 3-3 The Physical Properties of Fine Aggregates.

Property	*ASTM designation*	*Obtained value.*	*GSRB Specification for surface course*
Bulk specific gravity, gm/cm^3	*C128 (ASTM, 2015)*	*2.64*	-
Apparent specific gravity, gm/cm^3	*C128 (ASTM, 2015)*	*2.65*	-
Water absorption,%	*C128*	*0.7*	-
Clay lumps , %	*C142*	*1.9%*	-
Passing sieve NO.200,%	*C117*	*3.52%*	-
sand equivalent,	*D2419 (ASTM, 2014b)*	*49%*	*45% min*

3.2.1.2 Filler

The main purposes of filler are to reinforce the asphalt mastic (when it mixes with the bitumen and this leads to increase the stability and stiffness of the mixture), acting as a packing mineral (to control the void structure of the mixture), and sustain the mixture durability (under water and aging actions are attacked the asphalt mixture). Therefore, three types of filler were used in this research, namely, conventional mineral filler (CMF), ordinary Portland cement (OPC) and quick lime (QL) to explore the potential of these fillers in achieving the mentioned purposes. The portion of crush aggregate and natural sand that passed from sieve NO. 200 was used as CMF filler, normally as it happened in asphalt plant. While the OPC and QL were provided from Karbala Cement Plant, and Karbala Lime Plant, respectively. Table (3-4) illustrates the physical and chemical properties of the used three types of filler.

Table 3-4 Properties of the Utilized Fillers.

Physical Properties			
Property	*Filler type*		
	CMF	*OPC*	*Quick lime*
Specific surface area (m^2/kg)	225	410	3050
Density (gm/cm^3)	2.61	2.987	3.4
Chemical testing			
SiO2	81.89	25.41	2
Al2O3	3.78	2.324	1.35
Fe2O3	1.92	1.125	0.76
CaO	7.37	65.148	85.5
MgO	3.45	1.326	0.34
K2O	0.73	0.760	0.3
Na2O	0.19	1.714	0.12

3.2.2 Asphalt Binder

The used asphalt binder was supplied from AL-Daurah refinery with grade of (40-50), the properties of this asphalt was tabulated in Table (3-5), whereas all the tests were carried out in the laboratories of Kerbala University according to GSRB specification.

Table 3-5 Properties of Grade Asphalt Cement.

Property	***ASTM designation***	***Test results***	***GSRB requirements***
Penetration,100gm., 25°C, 5sec (1/10 mm)	D5 (ASTM, 2015e)	41	40-50
Specific Gravity, 25 °C (gm/cm3)	D70 (ASTM, 2009a)	1.03	-
Ductility, 25 °C , 5 cm/min (cm)	D113 (ASTM, 2007a)	135	>100
Flash point, (°C)	D92 (ASTM, 2005)	313	>232
Softening point (°C)	D36 (ASTM, 2015d)	47	-
Solubility in trichloroethylene, (%)	D2042 (ASTM, 2015c)	99.5	>99
After Thin Film Oven test			

Penetration of Residue (%)	D 1754 (ASTM, 2015)	69	>55
Ductility of Residue, (cm)		68.5	>25

3.2.3 Modified Polymer

The Styrene Butadiene Styrene (SBS) Kraton D1192 E (which is a clear linear block copolymer based on styrene and butadiene with bound styrene of 30% by mass) was nominated in this study. Two unique properties in the used polymer type; they are polymer gradation and inclusion of silica in such polymer. However, this polymer comparatively has small particle size, its gradation is presented in Table (3-6). This property is facilitating the desperation of the polymer within the asphalt binder effectively. The other property is the inclusion of the silica as a modifier of the SBS polymer, which will affect positively on the binder and then on mixture properties as will see hereafter. The properties of the modified SBS polymer are demonstrated in Table (3-7).

Plate 3-2 Styrene Butadiene Styrene Powder.

Table 3-6 Kraton D1192 ESM Polymer Gradation.

Sieve size (mm)	***Passing%***
NO.20 (850 µm)	100
NO.30 (600 µm)	93.5
NO.40 (425 µm)	69.5
NO.50 (300 µm)	34.2
NO.60 (250 µm)	15.7
NO.80 (180 µm)	8
NO.100 (150 µm)	3.8
NO.200 (75 µm)	0

Table 3-7 Kraton D1192 ESM Polymer Properties.

Property	***Test Method***	***Unit***	***Tested Value***	***note***
Specific Gravity	SO 2781	-----	0.94	
Melt Flow Rate, 200°C/5kg	ISO 1133	g/10min.	<1	
Bulk Density	ASTM D 1895 method B	kg/dm3	0.4	
Hardness, Shore A (15 sec)	ASTM D 2240	Hardness, Shore A (15 sec)	70	a
Apparent Molecular Mass of Triblock	KM 01	kg/mol.	150	
Polystyrene Content	KM 03	%m	30.5	
Vinyl Content	KM 03	%	35	
Triblock Content	KM 01	%	90	
Total Extractable	KM 05	%m	1.0	
Volatile Matter	KM 04	%m	0.3	
Antioxidant Content	KM 08	%m	0.16	
Ash (ES, ET)	ISO 247	%m	0.25	
Ash (ETM)	BAM 908	%w	5	
Ash (ESM)	ISO 247	%m	3.75	

a *Measured-on compression molded slabs*

3.3 Preparation of the Modified Asphalt Binder

SBS is used as an effective modifier for neat binder. However, following the previous research recommendations (Jin *et al.*, 2002; Wen *et al.*, 2002; Al-Hadidy and Yi-qiu, 2010; Dong *et al.*, 2014; Shirini and Imaninasab, 2016), the modified SBS polymer were added to neat binder with three percent (2%, 4% and 6% by weight of the asphalt binder). A mechanical mixer was manufactured with high shear mixing force and a multi-mixing speed up to 3500 rpm. Also a heating system was erected to conserve the heating temperature of the binder during mixing process. The mixer and the heating system are shown in Plate (3-3). Preparation method was developed in the laboratory to maximize the rheological properties and to minimize the asphalt degradation. The asphalt was heated to become a fluid in an iron container, then upon reaching about 180 ºC, the certain amount of heated SBS was added into asphalt gradually. The blend of asphalt and SBS are subjected to continuous shear mixing at 3500 rpm for 60 min, at the same time the heating system stabled the iron container temperature at 180 ºC. After completion, the blend was removed from the iron container and stored in smaller containers for further tests. Properties of the modified bitumen is presented in Table (3-8), whereas Figure (3-2) shows the viscosity property of neat and the three modified binders.

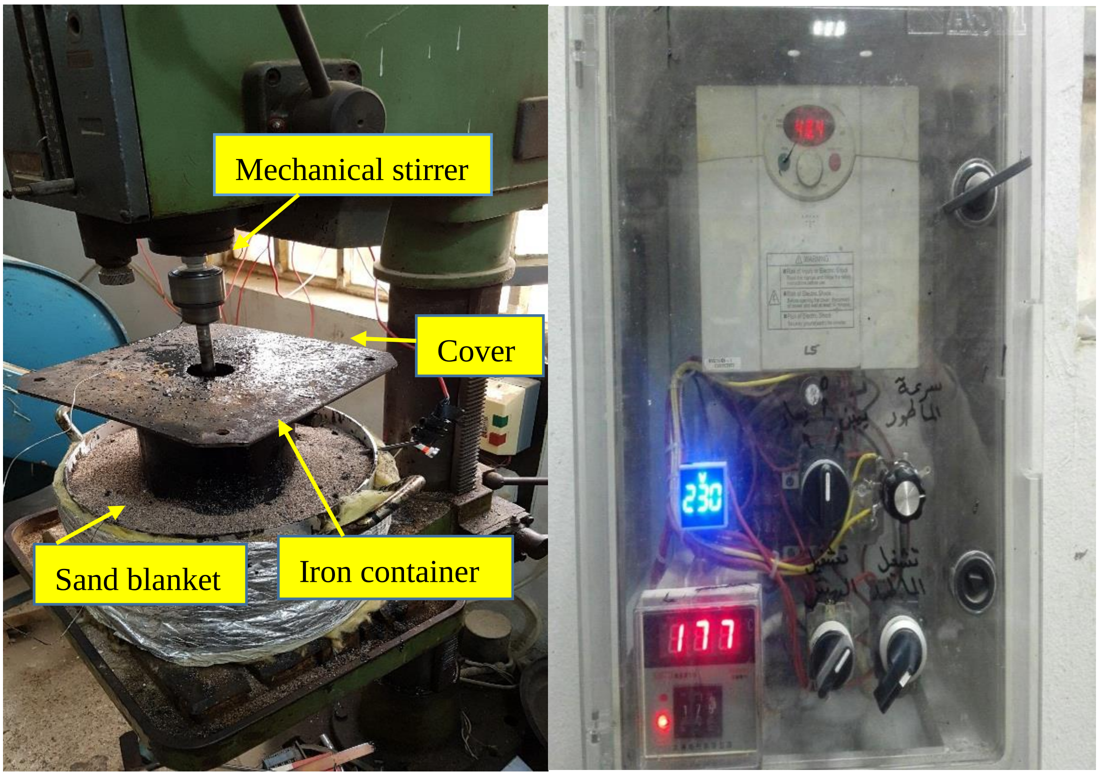

Plate 3-3 Shear Mixer and Heating System.

Table 3-8 Neat and Modified Bitumen Properties.

Properties	***Standard (ASTM)***	***0 SBS***	***2 SBS***	***4 SBS***	***6 SBS***
Penetration at 25 °C (0.1 mm)	D5-73	40.7	27.2	23.5	22
Softening point (R&B °C)	D36-76	48	59	62	64
Ductility at 25 °C (cm)	D113-79	>100 cm	>100 cm	85	78
Penetration index	D5	-2.1	-0.48	-0.22	-0.03
After thin-film oven test (TFOT)					
Penetration at 25 °C (0.1 mm)	D5-73	32	29	26	25
Softening point °C	D36-76	50	60.5	64	66

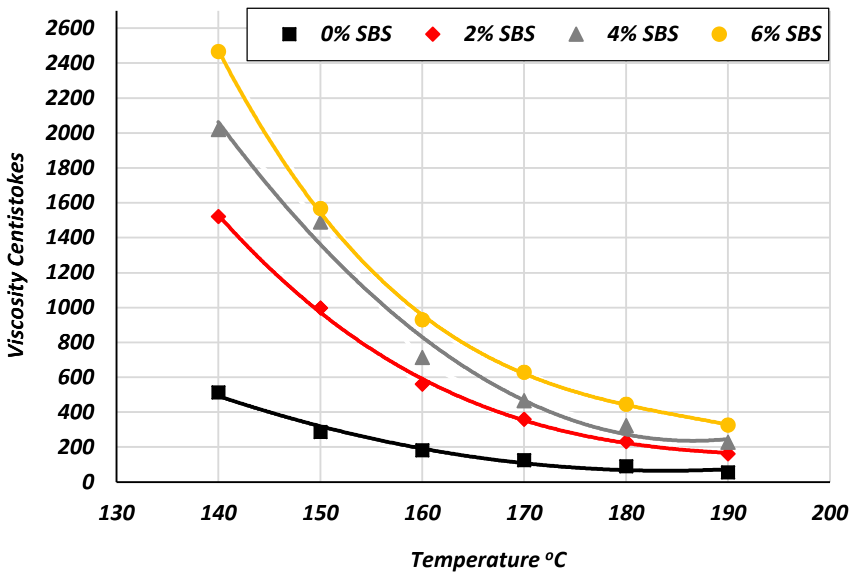

Figure 3-2 Kinematic Viscosity of the Binders

3.4 Hot Mix Asphalt Design

The adopted method for the design of TAO is a traditional procedure for the determination of optimum asphalt content (OAC) for wearing course using Marshall design method. This method was performed as follows:

- Selecting the NMAS: 9.5 mm NMAS was selected to fulfill the thin asphalt overlay requirements (3 times x 9.5 (NMAS) = 28.5 mm < 38.1 mm (the upper limit of TAO thickness).
- Selecting the gradation: dense graded gradations which is based on Iraqi standard specification (GSRB) (9.5 mm NMAS), as mentioned previously, was selected; this gradation is well known in Iraq, while stone mastic asphalt and porous gradations are recommended for future research studies.
- Determining OAC: five percentages of asphalt content (namely, 4, 4.5, 5, 5.5, and 6 %) were specified to determine the OAC for the conventional mix with neat asphalt binder. To ensure the reliability, at least three compacted specimens for each percentage were prepared according to (ASTM D 6926, 2015). Then, specimens were subjected to curing protocol by leaving the specimen to cool down after compaction by Marshall Hammer (75 blows each face were adopted to simulate mixture suitable for heavy traffic load). After that, the specimens were de-molded using manual extractor jack. Finally, specimens were immersed for 30-40 mins in water path at 60 °C to control the requested testing temperature. Three types of filler

were used (CMF, OPC, and QL), therefore, three OAC were determined accordingly.

3.5 Testing Methods

Volumetric, mechanical and durability properties are the important indexes for characterizing the TAO properties, which then used extensively to describe the variation produced TAOs. Standardized and non-standardized, empirical, simulative, and fundamental test methods, were all nominated to determine TAQs properties. Table (3-9) shows a summary of the experimental tests and their significant, which used in this research to evaluate the performance of TAO mixture.

Table 3-9 Test Methods Utilized for Analysis of Samples.

Property	*Test Method*	*Standard*	*Function of Tests*
Mechanical properties	Marshall Stability and Flow	ASTM D6927 (ASTM, 2015b)	Evaluating the plastic deformation
	Indirect Tensile Strength	AASHTO T283 (AASHTO, 2003)	Evaluating the cracking potential
	Creep Compliance	AASHTO T322 (AASHTO, 2003)	Indicating the crack progression and fatigue characteristics
	Skid resistance test	ASTM E303 (ASTM, 2013c)	Evaluating the sliding resistance
	Wheel track test	EN BS 12697-22 (BSI, 2003)	Evaluating the rutting resistance
	Cantabro test	ASTM D7064M (ASTM, 2013a)	Assessing the resistance of a mixture to surface abrasion
Volumetric Properties	Air void	ASTM D2041 (ASTM, 2015b) ASTM D3203 (ASTM, 2011a)	Giving an indications that help significantly in evaluate the bleeding, ageing, degree of compaction, etc.
	V.M.A		
	V.F.B		
	Bulk density		
Durability properties	Tensile strength ratio	AASHTO T283 (AASHTO, 2003)	Assessing water susceptibility
	Cantabro abortion ratio	ASTM D7064M (ASTM, 2013a)	Assessing resistance of a mixture to surface abrasion after ageing

3.5.1 Mechanical Properties Testing

In this research, the mechanical properties of TAO were evaluated via several tests. Such test methods were adopted depending on the recommendations of the design method, while others were adopted to sustain clear details of the fundamental properties of the mixes performance under loadings.

3.5.1.1 Marshall Test

Marshall test is a common well-known empirical destructive test, which measures the mixture resistance to plastic deformation and flow. The maximum capacity of the specimen to resist the applied load, the resistance of the specimen for deformation at maximum applied load and volumetric properties of the specimens (density-voids) are provided by Marshall Test. Marshall Test was performed according to ASTM D6927. Test conditions are cleared in Table (3-10), while the limitations of the Iraqi specification (GSRB) for the surface layer are demonstrated in Table (3-11) for comparison purpose late on. Plate (3-4) shows Marshall Device computer screen and lab view program package.

Table 3-10 Marshall Test Conditions based on ASTM D6927

<table>
<tr><th colspan="2">Parameter</th><th>Standard</th><th>Used Value for thin asphalt overlay</th></tr>
<tr><td colspan="2">Asphalt temperature ℃</td><td>150-165</td><td>150</td></tr>
<tr><td colspan="2">Aggregate temperature ℃</td><td>170</td><td>170</td></tr>
<tr><td colspan="2">Mix temperature ℃</td><td>130-180</td><td>140</td></tr>
<tr><td colspan="2">Number of specimens</td><td>3</td><td>3</td></tr>
<tr><td colspan="2">The load Application Rate mm/min</td><td>50 ± 5</td><td>50</td></tr>
<tr><td colspan="2">Measuring device accuracy</td><td>Min. 0.01 N</td><td>0.01 N</td></tr>
<tr><td rowspan="2">Specimen conditioning before test min</td><td>water bath</td><td>30-40</td><td rowspan="2">30 mins in water bath</td></tr>
<tr><td>in oven</td><td>120-130</td></tr>
<tr><td colspan="2">Test temperature ºC</td><td>60 ± 1</td><td>60</td></tr>
<tr><td colspan="2">Specimen compaction</td><td>75 below each face</td><td>75 below each face</td></tr>
<tr><td colspan="2">Specimen diameters mm</td><td>101.6-101.7</td><td>101.6</td></tr>
<tr><td colspan="2">Specimen thickness mm</td><td>63.5 ± 2.5</td><td>63.5 ±2.5</td></tr>
<tr><td colspan="2">Curing</td><td>24hr at Lab temperature</td><td>24hr at Lab temperature</td></tr>
</table>

Table 3-11 GSRB Limitation for Surface Layer, Section R9 (GSRB, 2003)

property	GSRB limits
Stability, kg.	>800
Flow, 1/10mm	2-4
Air Void, %	3-5
VMA, %	>14

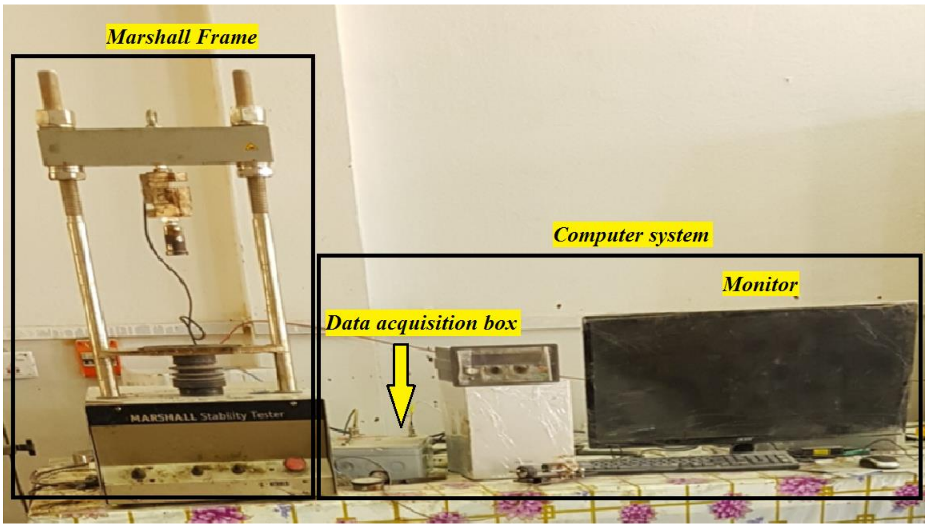

Plate 3-4 Configuration System for Marshall Test

3.5.1.2 Creep Compliance Test

AASHTO-T322 (AASHTO, 2003) defined the creep compliance test as the time dependent strain divided by applied stress, this test describes the crack developing with time in pavement mixture. It considers as a primary input parameter for thermal cracking analysis or low temperature cracking in terms of empirical mechanistic pavement design method. Also, same test could give an indication for fatigue cracking of the asphalt mixtures. On the other hand, creep compliance value is the inverse of the stiffness properties against cracking. The test conditions are explained in Table (3-12), while Plate (3-5) shows the apparatuses of Creep Compliance Testing. The creep compliance values were determined by equation (3-1)

$$D(t) = \frac{\Delta X \times D_{avg} \times b_{avg}}{GL \times P_{avg}} \times C_{Cmpl} \qquad \text{Equation (3-1)}$$

Where:

D(t) = creep compliance at time t ,1/KPa

ΔX = trimmed mean of the horizontal deformations, mm

Davg = average specimen diameter, mm

bavg = average specimen thickness, mm

Pavg = average force during the test KN,

GL = gage length, mm

Ccmpl= creep compliance parameter at any given time, computed as:

$$C_{Cmpl} = 0.6345 \times \left(\frac{X}{Y}\right)^{-1} - 0.332$$ Equation (*3-2*)

Where:

X/Y is the ratio of horizontal to vertical deformation, taken at mid testing time.

The limitations of the Ccmpl value as shown in the following equations

$$\left[0.704 - 0.213\left(\frac{b_{avg}}{D_{avg}}\right)\right] \leq C_{Cmpl} \leq \left[1.566 - 0.195\left(\frac{b_{avg}}{D_{avg}}\right)\right]$$ Equation (*3-3*)

Table 3-12 Test Conditions of Creep Compliance.

Item	***standard***	***Used conditions***
Ram movement (vertical) mm/min	12.5	12.5
Device accuracy	0.001N	0.001N
stain Rate, mm	0.00125–0.019	within rang
Testing time, sec	100 ± 2 or 1000±20.5	100 ± 2
Testing temperature	0, -10, -20 °C	10, 0, -20
No. of specimens	3	3
Specimens diameter, mm	150±9	101.6
Specimens height, mm	38-50	63.5 ± 2.5
Compaction (Marshall hammer)	Compacted to 7 ± 0.5% air void	Vary within air void limits

In creep compliance test, many adjustments on this test were adopted due to limitations of resources, as follows:

1. Specimen diameter: AASHTO T322 is recommended to use 150 mm diameter for specimen in creep compliance test.
2. Gauge length, 101.6 mm gauge length was used to calculate horizontal deformation instead of 38 mm as recommended by the specification.
3. The load was applied in this test manually to generated stress with a tolerance 0f ± 2% from the total load. But it is worth mentioned that the load was controlled to produce a horizontal deformation between (0.00125 - 0.019 mm) in order to retain strain of specimens within linear viscoelastic limits as recommended by AASHTO T322.
4. Repeating the test for many times to obtain the acceptable level of the applied load because this test is very sensitive. Horizontal deformation indicates the acceptable level of the applied load, which was selected with three colors for this reason, as can be seen in Plate (3-6). The black color is an indication of horizontal deformation less than the minimum limit of 0.00125 mm. Green color is an indication of horizontal deformation within the acceptable limit (0.00125 to 0.019 mm). Whereas the red color is an indication for the horizontal deformation high than 0.019 mm. In case, the reading of horizontal deformation is unsatisfied to limits, the test was repeated after exiting the specimen to rest for 5 min.

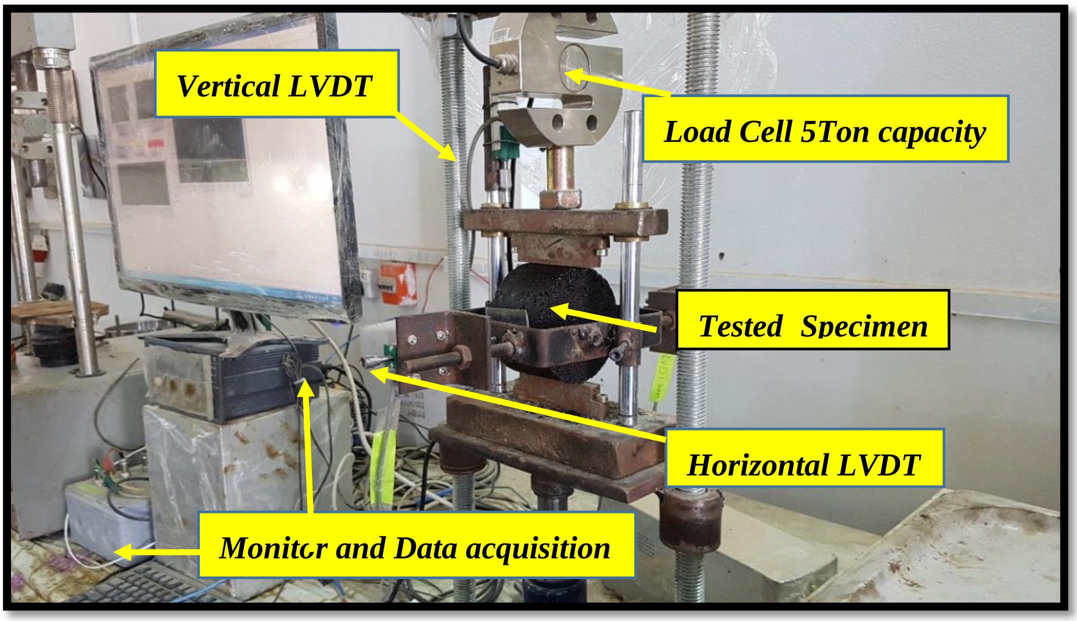

Plate 3-5 Apparatuses of Creep Compliance Testing

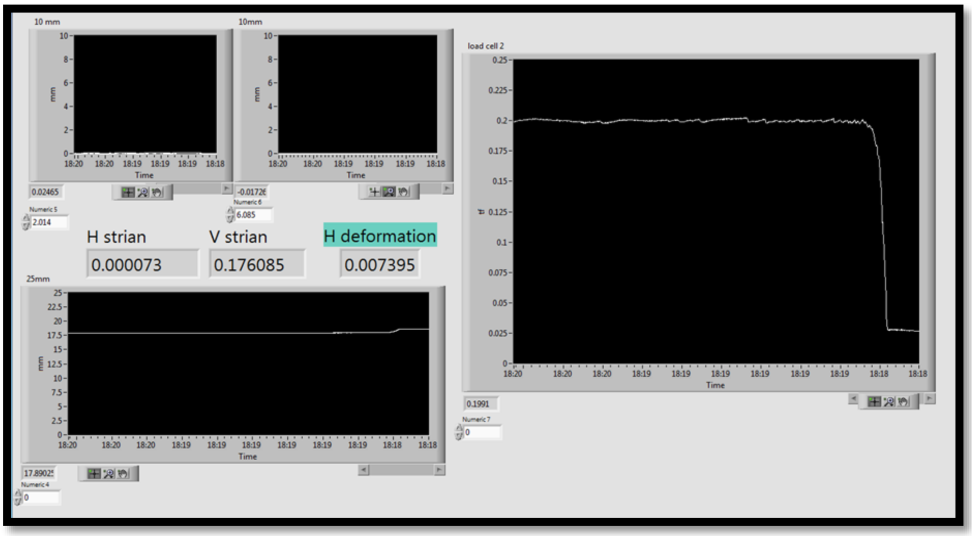

Plate 3-6 Screen Capture of Used Creep Compliance with Lab View Program Package.

3.5.1.3 Indirect Tensile Strength Testing

The tensile properties of bituminous mixtures are of interest to pavement engineers because of the problems associated with cracking. The indirect tensile strength test (IDT) is used to determine the tensile properties of the bituminous mixture which can further be related to the cracking properties of the pavement. The evaluation of tensile characteristic is achieved by applying a constant rate of compressive load on the specimen of Marshall acting parallel to and along the vertical diametrical plane of the specimen through two opposite loading strips. The test procedure was accomplished according to AASHTO T283, whereas test conditions are shown in Table (3-13). Three trail mixes for each optimal asphalt content were made to determine the optimal number of compaction that achieve the target air void (7%) according to (AASHTO T283). Equation (3-4) is used for calculate IDT

$$IDT = \frac{2P}{\pi . D . t}$$ Equation (3-4)

Where:

IDT = indirect tensile strength, KPa
P = maximum load, N
t = specimen height immediately before test, mm
$D = specimen\ diameter$, mm

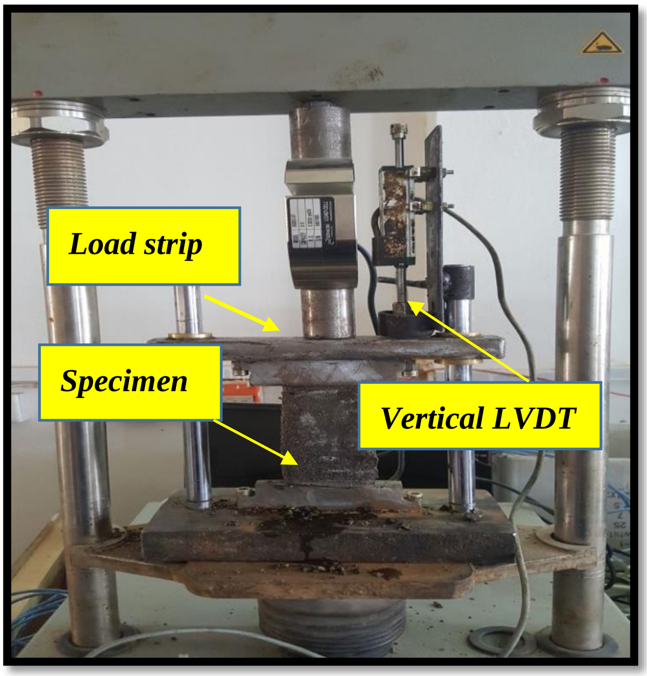

Plate 3-7 IDT device

Table 3-13 Test Conditions of IDT

Item	*AASHTO T283*	*Used condition*
No. of specimens	3	3
Rate of loading, mm/min	50 ± 5	50
Accuracy of device	Min. 0.01 N	0.01 N
Test temperature, ºC	25 ± 2	25 ± 2
Specimen diameters, mm	100, 150	101.6
Specimen thickness, mm	63.5±2, 95±5	63.5 ± 2.5
Compaction(Marshall Hammer)	Compacted to 7 ± 0.5% air void	Depended on the required air void 7%
Specimen conditioning before test	2 hr at 25°C	2 hr. at 25°C
Curing	Placed in over for 16 hr at 60 ^{O}C	Placed in over for 16 hr at 60 ^{O}C

3.5.1.4 Skid Resistance Test

Skid resistance is the force developed when a tire that is prevented from rotating slides along the pavement surface. Skid resistance is an important parameter in pavement assessment and this is due:

1. High incidence of skid accidents due to lack of sufficient skid resistance.

2. Providing users with safe roadway is what most agencies are committed to.
3. Different types of materials and construction practices can be assessed by skid resistance measurements.

Skid resistance relay on two important factors: Microtexture and Macrotexture of the pavement surface (Corley-Lay, 1998). Microtexture refers to the small-scale texture of the pavement aggregate component (which controls contact between the tire rubber and the pavement surface), while the Macrotexture represent the whole arrangement of aggregate particles in the pavement surface that having large scale texture and which control the escape of water from under vehicle tire. Over time, there is a change in the skid resistance, usually after two years of construction, Skid resistance increases as a result of worn the roadway by means of traffic loads and the surface of the aggregates becomes exposed and then the skid resistance begins to decrease over the pavement life (Kumar, 2014). Under the same surface condition (degree of wetness), it was observed that the skid resistance is low in spring and summer and it is high in autumn and winter (Jayawickrama and Thomas, 1998).

The British Pendulum skid resistance tester was utilized to measure the surface skid resistance of the molded mixes in the laboratory. This measurement was achieved through testing under dry and wet conditions of the surface of the wheel track specimens prior to actual wheel track testing. Plate (3-9) shows the British pendulum.

The test was conducted in accordance to (ASTM E303). British pendulum procedure was Execute one swing without recording and Rewet and execute four more times and record, then Calculate the average for dry and wet surface. The skid resistance value (SRV) is the mean of four readings or the constant of three readings.

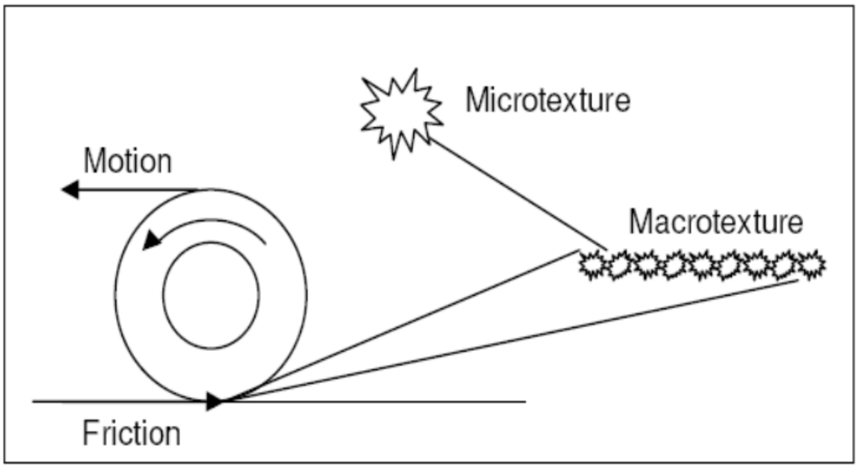

Plate 3-8 Schematic Plot of Microtexture/Macrotexture (Noyce et al., 2005).

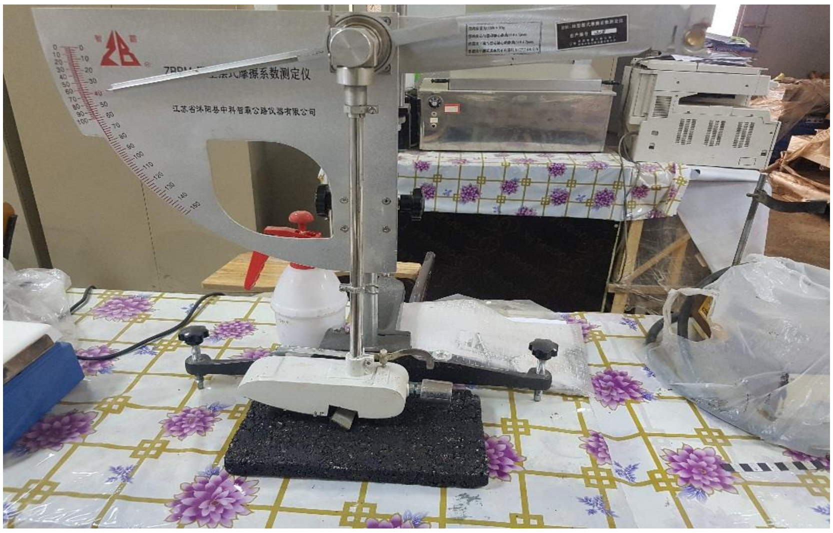

Plate 3-9 The British Pendulum Skid Resistance Tester.

3.5.1.5 Wheel Track Test

The performance test has become a common way to evaluate the asphalt mixture behavior and a tool to assist in the mixture design. Performing the wheel tracking test (WTT) is used to evaluate the rutting performance in the laboratory. Wheel track test is a simulative test that measures hot mix asphalt (HMA) qualities by supplying a prepared (HMA) specimens to a rolling repeatedly of small loaded wheel device. Different types of devices were developed to carry out this test under the principle of measuring the permanent deformations that occur in the mixture when it is subjected to a loaded wheel. In this study, rectangular slabs samples with dimensions (300x165x25 mm) were made to be tested for performance in the wheel track, whereas vibratory compaction was used to an air void of 7% according to BS EN 12697-32 (BSI, 2003), Trial mixes with different compaction efforts were carried out to determine the specified air void as shown in Figure (3-3)

In this research, WTT device was manufactured locally according to BS (EN 12697-22) (BSI, 2003) for small wheel track device. Conditions of this test are summarized in Table (3-14). Plates (3-10, 11, 12) explain the wheel track device and specimens

Also, wheel track test can provide many indications for resistance of rutting deformation of asphalt mixtures, namely, rut depth, rate of rut, and dynamic stability (DS). DS refers to the number of wheels passes that required to cause a unit rut depth in asphaltic mixtures (Read and Whiteoak, 2015). DS values can be obtained by the following formula:

$$DS = \frac{N15}{D60 - D45}$$ Equation (3-4)

Whereas:

DS: Dynamic stability (passes/mm)

N15: Number of wheel passes after the first 15 minutes of testing (passes).

D60-D45: The change in the rutting depth at the last 15 minutes of testing (mm)

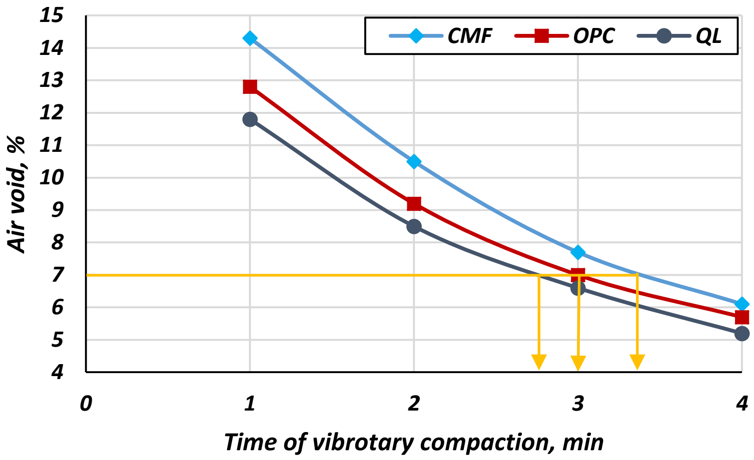

Figure 3-3 Time of Compaction vs. AV% Content

Table 3-14 Conditions for Wheel Track Testing

Parameter	***Standard***	***Used Value for TAO***
No. of Required Specimens	2	2
Diameter of Wheel	200-205	200
Width of Wheel, mm	50±5	50
No. Wheel Pass per min.	50±5	50
Speed of Wheel, m/min	26.5	28
Load on the wheel	700 ±10 N	700
Dimensions of specimens	300 x 260 mm	300 x 165 mm
*Specimen Thickness**	38 -100 mm	25 mm
Air Void Content Specimens	4 or 7 %	7%
Compaction effort to air void 7%, min	Depended on the required air void 7% as critical case	Depended on the required air void 7% as critical case
Test Temperature ºC	60 ± 2	60
No. of Conditioning Cycles pre-test	5	5

*The specification recommends 38-100 mm, or the expected depth of the paved layer, thus 25 is selected.

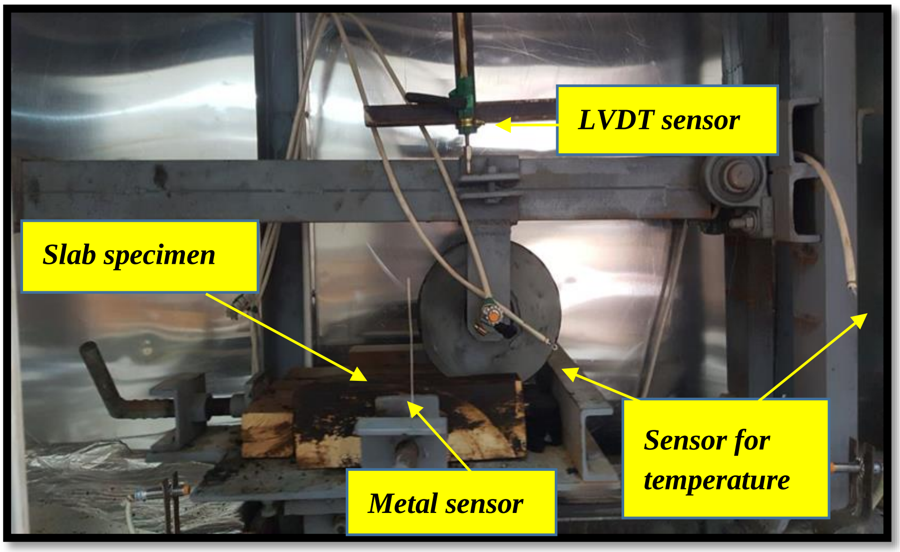

Plate 3-10 Apparatuses for Wheel Track Device.

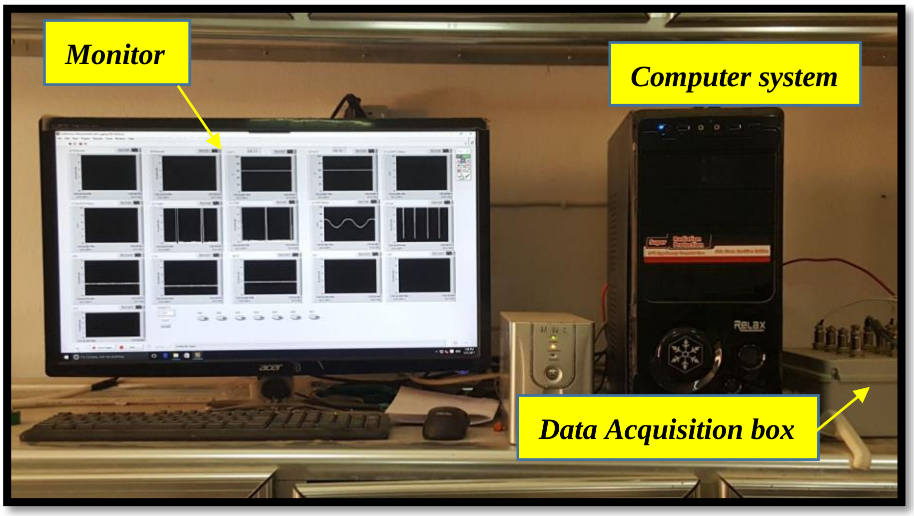

Plate 3-11 Computer System for Wheel Track Device.

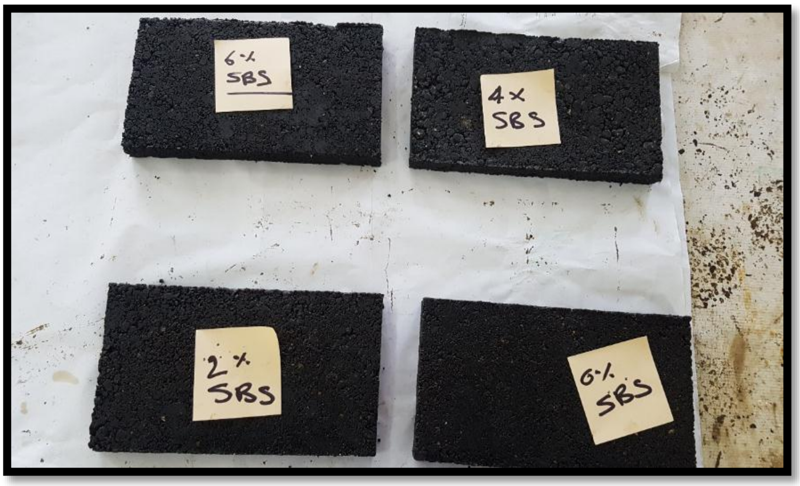

Plate 3-12 Specimens of Wheel Track Test.

3.5.2 Volumetric Properties

One of the main elements in the design of asphalt mixtures is the volumetric characteristics. In most cases, asphalt mixtures are considered in terms of weight proportion of bitumen and/or aggregate. However, for the design of asphalt mixtures it is very important to consider the three main components in asphalt mixtures, namely bitumen, aggregate and air. Understanding the behavior of asphalt mixtures, whether in laboratory or in service, depends on the complex interaction between the three mentioned components. The asphalt mixture composition can be stated in terms of volume or weight. Since the air does not have a mass, if three components are taken into consideration, the asphalt mixture composition are expressed in terms of volume. The asphalt mixture consists of 95% aggregate and 5% of bitumen by the total weight, but this will change when the asphalt mixture composition is take into account to be volumetrically (Hislop and Coree, 2000).

Volumetric properties are determined according to the ASTM D3203 (ASTM, 2011a) and ASTM D2041 (ASTM, 2015b) using the equations, as follow:

$$Gmm = \frac{\mathrm{A}}{\mathrm{A + D - E}} \quad \text{Equation (3-5)}$$

$$Gmb = \frac{\mathrm{A}}{\mathrm{B - C}} \quad \text{Equation (3-6)}$$

$$VTM = 100 * (1 - \left(\frac{\mathrm{Gmb}}{\mathrm{Gmm}}\right)) \quad \text{Equation (3-7)}$$

$$VMA = 100 * (1 - (\frac{\mathrm{Gmb} * (\frac{\mathrm{Ps}}{100})}{\mathrm{Gsb}}) \quad \text{Equation (3-8)}$$

$$VFA = 100 * (\frac{\mathrm{VMA - VTM}}{\mathrm{VMA}}) \quad \text{Equation (3-9)}$$

Where:

G_{mb} = bulk specific gravity of asphalt mixture

G_{mm} = theoretical maximum specific gravity of asphalt mixture

G_{sb} = bulk specific gravity of aggregate

P_s = percentage of aggregate in total mixture

A = the mass of specimen in air.

B = mass of specimen in saturated surface-dry (SSD) condition, gm.

C = the mass of the specimen in water

D = mass of container filled with water at 77°F (25°C)

E = mass of container filled with sample and water at 77°F (25°C)

3.5.3 Durability Properties

The premature failures of Asphalt Concrete Pavement (ACP) have several reasons. Most of these reasons are related to environment conditions and/or traffic loads. Some of the environmental conditions such as water or moisture, temperature and air have detrimental effects on the pavement performance of ACP. However, water damage and ageing effect are normally characterized through specified testing to identify the potential of HMA to resist these long term or durable effects.

3.5.3.1 Tensile Strength Ratio

The most environmental factors that influencing the durability of Hot Mix Asphalt (HMA) are the moisture induced damage and the stripping of its components due to loss bitumen- aggregate adhesion (Gorkem and Sengoz, 2009). Moisture damage represents the action of degradation of HMA strength and their durability due to the presence of moisture or water, and it may be evaluated by losing of mechanical properties of HMA. The phenomenon of moisture damage in HMA can generally be categorized in two mechanisms:(a) loss of adhesion between the aggregate and the bitumen due to presence of water at aggregate-binder interface,(b) loss of cohesion of bitumen itself due to the softening action (Lottman, 2001). The amount and types of moisture damage are affected by several factors; some of these factors are associated with components of HMA such as bitumen and aggregate. Others factors are associated with the processes of design, production and construction of HMA.

The indirect tensile strength ratio (TSR) of conditioned samples to dry samples is measured as a criterion for moisture damage resistance assessment. The typical TSR values from 0.7 to 0.9 are recognized as accepted values. The test procedure was accomplished according to (AASHO T283) by curing the mixtures in an oven at 60 ^{o}C for 16 h, another curing at compaction temperature for 2 h before compacted. The mixtures are divided into two subset unconditioned (tested in dry state) and conditioned (tested in saturated state). The conditioned samples were saturated with water to between (70-80%) by applying a vacuum of (13-67 KPa absolute pressure). After that, the conditioned samples are freezed for 16 hrs. At -18^{o}C. Then they are immersed for 24 hrs. in water at 60°C, which apparently reduces the tensile strength.

The test was accomplished for both conditioned and un conditioned sample using IDT as described previously. Plates (3-13, 14, and 15) show unconditioned and conditioned specimens.

Plate 3-13 Curing of IDT Specimen in an Oven at 60 ºC for 16 hr.

Plate 3-14 Un conditioned specimens.

Plate 3-15 Conditioned Specimen

3.5.3.2 Cantabro Abrasion Test

Scraping, skidding, rubbing or sliding of vehicle tires on the surface of asphalt pavement are factors that cause abrasion wear. Many factors affect the resistance of asphalt mixtures to abrasion of surface like: properties of aggregate, compaction procedure, toppings type, mixtures stiffness and surface finishing. The resistance of TAO mixtures to abrasion loss was analyzed by means of the Cantabro test. This test carried out in the Los Angeles abrasion machine according to (ASTM D7064) by placing the specimens into the Los Angeles machine without inserting the iron balls and rotate them at 30 rpm and until the number of revolutions to 300 cycles. It is worth mentioned that this test is designated as mechanical properties test, but at the same time it can be used to identify the durability when two sets of samples are prepared. The first tested without ageing process, while the second set is aged before test. The aging process was achieved by putting the specimens after compaction in a forced draft oven set for 168 hr. at 60 ^{o}C and then the specimens are cooled to 25 ^{o}C and stored for 4 h prior to conducting the Cantabro test.

Two specimens were prepared to test for each type of mixes. Before the test, the asphalt specimens are weighed and after testing, the specimens is cleaned and then weighed again. “Cantabro loss” is defined as the percentage of mass loss due to abrasion, which is the percentage of mass difference before and after the test as shown in equation (3-10). Plate (3-16) shows Los Angeles abrasion specimens.

$$P = \frac{\mathrm{P1} - \mathrm{P2}}{\mathrm{P1}} * 100$$ Equation (*3-10*)

Where

P = Cantabro abrasion loss,

P_1 = initial weight of the sample, and

P_2 = final weight of the sample.

Plate 3-16 Los Angeles Abrasion Specimens before and after Abrasion.

3.6 Methodology

As mentioned previously, the main aim of this study is to characterize the thin hot mix asphalt mixture. Figure (3-4) shows a schematic diagram of the proposed research methodology. While, Table (3-15) includes the testing matrix. However, the characterizing of TAO achieved through optimizing different thin asphalt mixtures by:

1. Design of traditional thin HMA control mix using (aggregate gradation of 9.5mm NMAS) and different filler types (CMF, OPC and QL) and identifying the volumetric, mechanical, and durability properties of traditional thin mixtures.
2. Using polymer modifier (SBS) as additive for asphalt to improve the volumetric, mechanical and durability properties.
3. Modeling some of the properties using statistical technique for good prediction and best practice

Table 3-15 Tests on Different Mixture Type.

Mixture type	***SBS %***	***Volumetric properties***				***Mechanical properties***						***Durability properties***	
		VTM	***VMA***	***VFB***	***BD***	***MS***	***MF***	***CC***	***IDT***	***SRV***	***WWT***	***TSR***	***Cantabro loss***
M1	0	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2	✓	✓	✓	✓	✓	✓	✓	✓	---	✓	✓	✓
	4	✓	✓	✓	✓	✓	✓	✓	✓	---	✓	✓	✓
	6	✓	✓	✓	✓	✓	✓	✓	✓	---	✓	✓	✓
M2	0	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
M3	0	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2	✓	✓	✓	✓	✓	✓	✓	✓	---	✓	✓	✓
	4	✓	✓	✓	✓	✓	✓	✓	✓	---	✓	✓	✓
	6	✓	✓	✓	✓	✓	✓	✓	✓	---	✓	✓	✓

M1, M2, and M3 are mixture include CMF, OPC, and QL, respectively

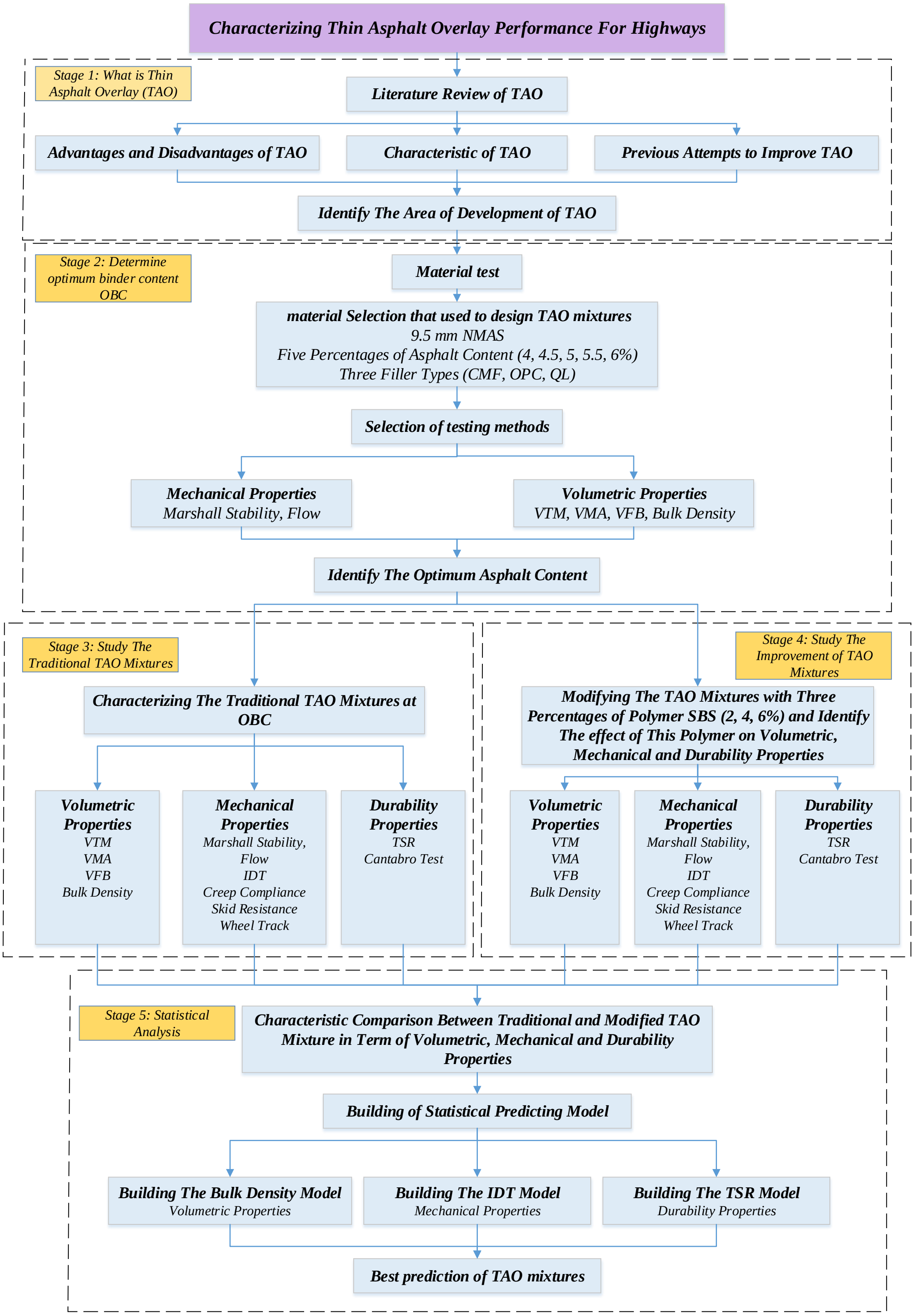

Figure 3-4 schematic diagram of the research methodology

3.7 Summary

This chapter explains the characterization of the materials used in this research, the methods used to test materials and mixtures, and the research methodology. Local source used to supply the materials in this study. On the other hand, tests are divided to mechanical, volumetric and durability properties. Mechanical properties include empirical tests such as Marshall Stability and Cantabro test fundamental tests such as creep compliance and simulative tests such as skid resistance and wheel track test. The durability tests, which include water damage (IDT) and cantabro test, were adopted to assess the performance of thin hot asphalt mixture. Asphalt Institute design method and GSRB standards were implement in this research to design the thin HMA mixture.

The methodology in this study included design of the thin HMA mixture (using aggregate gradation of 9.5 mm NMAS aggregate gradation and three filler types. Then modified asphalt binder of the optimized mixture by polymer (SBS) to improve the volumetric, mechanical and durability properties.

Chapter Four

TESTS RESULTS AND ANALYSIS

4.1 Introduction

With reference to the stated aim of this research work, the planned method to achieve this aim included a precise testing program to characterizing the potential properties of TAO, then analysis these properties and discuss the reasons of variation in different properties with different variables. However, this chapter presents the results and discussion for testing of compacted specimens with comprehensive analysis of the variables affected mix parameters.

4.2 Characteristics of TAO Comprising Neat Binder (Control Mix)

4.2.1 Determining the Optimum Binder Content for Controlled TAO Mixtures

To determine the OBC, the control TAO mixes preparation included blending of virgin coarse and fine aggregates using grading of 9.5 mm NMAS with two different variables, namely

- Three types of filler CMF, OPC, and QL.
- Five percent of asphalt contents ranging between (4%-6%) with 0.5% increment step, whereas three samples were prepared for each asphalt percent.

Different properties were based to determine the OBC as bulk density, air voids, voids in mineral aggregate (V.M.A), voids filled with asphalt (V.F.A), stability and flow. The results of these properties are:

- Density: is one of the most important parameter of asphalt mixtures. Within specific preparation, mixing and compaction condition, it reflects the characteristics of origin asphalt and aggregate characteristics and their abilities to interlock and pack. Figure (4-1) shows the relation of density with asphalt content for different filler types. In general, it can be observed that the density increases with increasing asphalt content until a maximum level, then the value of density starts to decrease with increasing in asphalt content. Increasing in asphalt content leads to increase in weight of mixture to a certain limit as a result of two issues; the asphalt cement fills the void (the volume of mixture is constant while the weight increase), and it facilitates the rolling over and lubricant of aggregates which result in better materials packing . Then, any increase in asphalt content leads to decrease in density because the volume of the asphalt increase instead of aggregate (asphalt has low specific gravity when compared with aggregate) as asphalt content increase.

On the other hand, TAO mixtures including different filler types showed various densities at the same asphalt cement content, which is a result of different characteristics of fillers especially the particle size distribution, density, and specific surface area, as can be seen from Table (3-4).

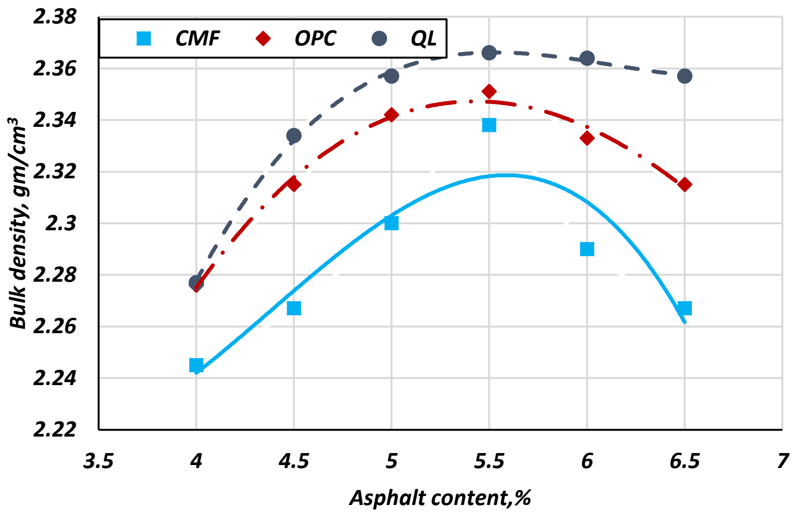

Figure 4-1. Bulk Density vs. Binder Content for Control TAO Mixture Comprising CMF, OPC and QL.

- Air voids: A mixture that is properly designed and compacted will, contains the optimum amount of air void. Within limited preparation, mixing, and compaction condition, the voids in an asphalt mixture are directly related to density; thus, density must be closely controlled to ensure that the voids stay within an acceptable range. Air voids can be defined as the air pockets located among the asphalt-covered aggregate particles throughout the compacted mixture. In dense graded mixtures, a certain proportion of the air voids must be required to allow some extra compaction under the traffic, as well as to provide spaces for small quantity of asphalt to flow during these spaces through the subsequent compaction. Figure (4-2) shows the relation of air void with asphalt content for various TAO mixture including different filler types. This figure exhibits that the air void decreases with increasing asphalt content. Whereas TAO mixtures comprising QL have the lowest air void at all asphalt content values in comparison with those including OPC or CMF. However, this is the result of the characteristics of filler type, as mentioned previously.

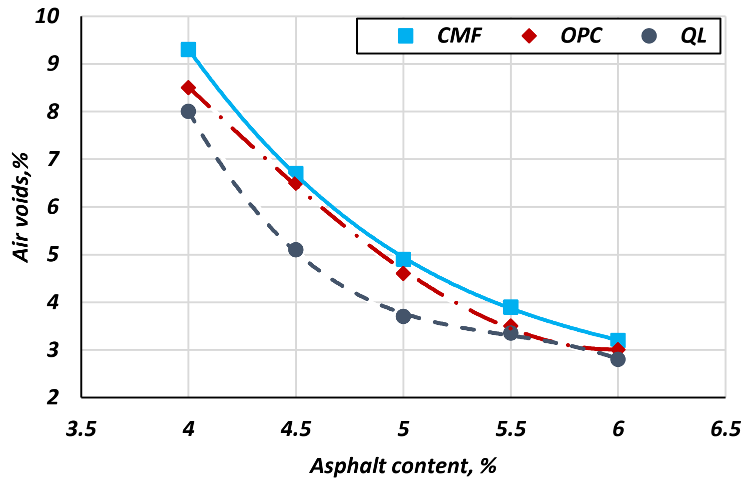

Figure 4-2. Air void vs. Binder Content for TAO Comprising CMF, OPC and QL.

- Voids in the mineral aggregate (V.M.A): These are the spaces in the compacted asphalt mixture between the aggregates, which includes the air voids in addition to the spaces filled with asphalt that are not absorbed by the aggregates particles. The space available for the asphalt film increases as the VMA increase. In most specifications, the minimum requirements for VMA have been specified depending on the fact that the durability of asphalt mixtures increase when the asphalt film covering the aggregates particles is thicker. Figure (4-3) demonstrates the ranges of (VMA) with different asphalt content. As expected, the filler type due to its physical characteristics leads to differences in VMA for various TAO mixtures at various asphalt content.

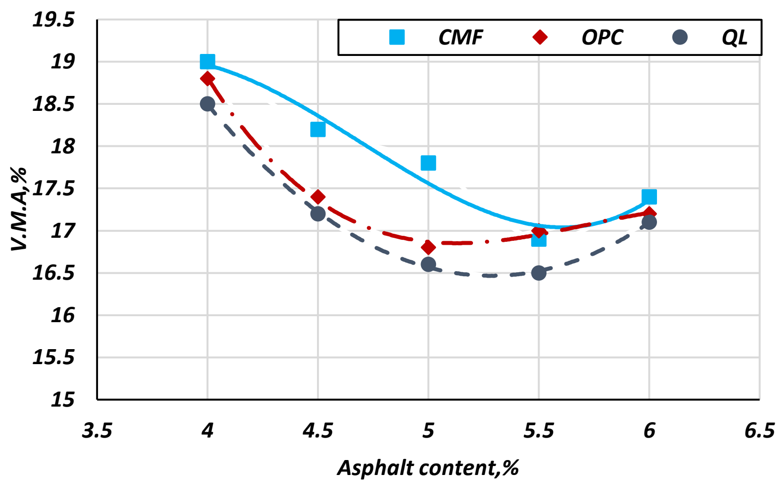

Figure 4-3. V.M.A vs. binder content for TAO comprising CMF, OPC and QL.

- Voids filled with asphalt (V.F.A): These can be defined as the air voids that occupied with asphalt in compacted mixture. When the thickness of the asphalt film is low, this reduces the durability of the asphalt mixture. For this reason the purpose of the VFA is to avoid it. As can be seen in Figures (4-4), VFA increases with increasing binder content gradually and this is a result of filling the air void with extra asphalt content. However, the higher surface area and particle size distribution of QL leads to higher agglomeration of asphalt binder with filler particles, result in lower VFA.

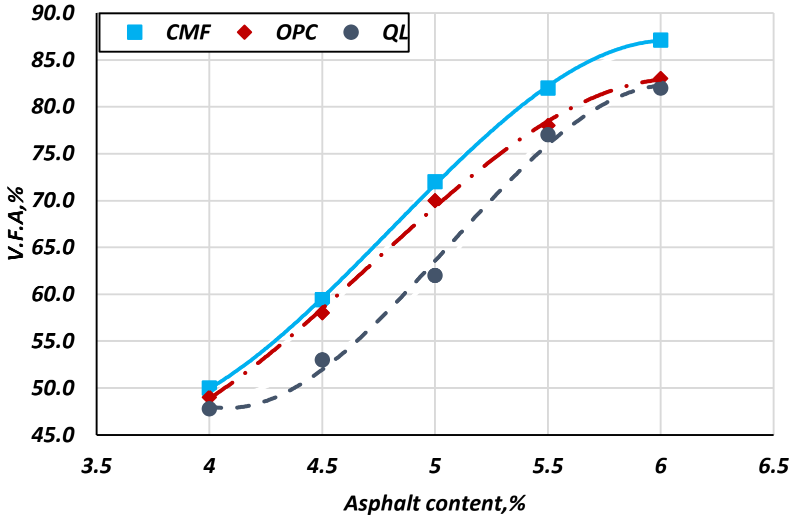

Figure 4-4. V.F.A vs. binder content for TAO comprising CMF, OPC and QL

- Marshall Stability: It is a very significant feature of the asphalt mixture in the surface layer design. Plastic deformation resistance can be assessed by the Marshall stability value of the asphalt mixture. Generally, the stiffness of asphalt mixtures increases when Marshall stability is high (Sarsam and Sultan, 2015). When Stiffness is high, this indicates that the pavement mixture withstand the traffic loads but the flexibility of the asphalt mixture which is required in the long term could be very low. Also, high Stiffness may lead to develop thermal cracks in the future. Figure (4-5) shows Marshall stability with various asphalt content for different TAO including various filler types. The results show that the stability increases with increasing asphalt content until a maximum value, then the stability decreases with extra asphalt content. The reason beyond that, when the asphalt content increases this lead to strengthen the connection between materials, initially. Furthermore, continuous increase in bitumen leads to separate aggregates while the interlock connection become weaker. It is worth mentioned that TAO mixtures with QL filler exhibit better Marshall Stability mainly because mixture volumetric improvements are reflected on stability, further to chemical characteristics of QL at the interface between filler and asphalt binder.

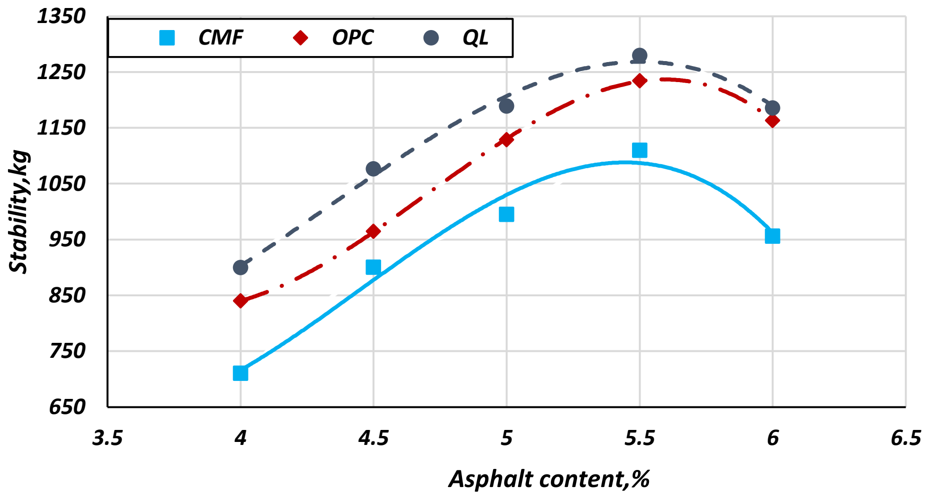

Figure 4-5. Marshall Stability vs. Binder Content for TAO Mixtures Comprising CMF, OPC and QL.

- Marshall Flow: When the flow value is high, it indicates that the mixture has plastic properties and therefore the pavement mixture is more exposed to permanent deformities, but when the values of flow is low, this refer to insufficient asphalt to maintain the durability of the mixture. Also low flexibility leads to early cracks due to brittleness of the mixture. As a result of asphalt nature to flow and loss of internal friction between the aggregate particles, the flow increases with asphalt content increase as shown in Figure (4-6). Obviously, TAO mixture comprising QL shows lower flexibility due to high surface area and particle size distribution, it is still within the limits specified by specification.

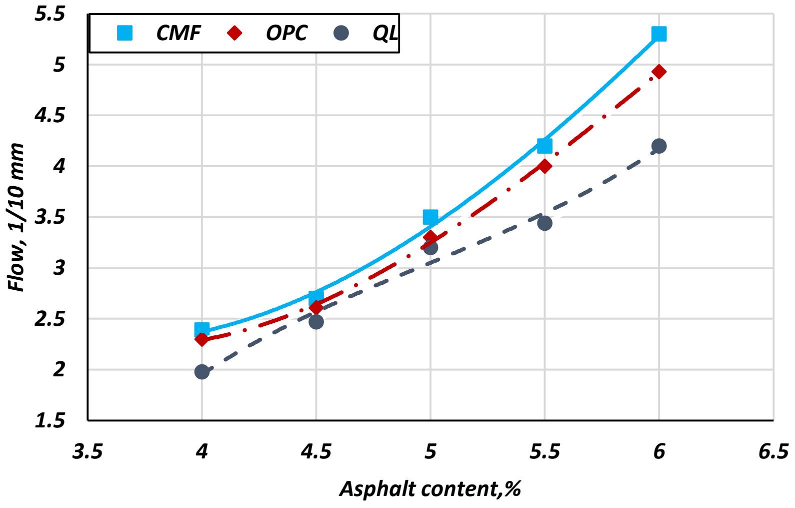

Figure 4-6 Marshall Flow vs. Binder Content for TAO Mixture Comprising CMF, OPC and QL.

From the obtained results for different TAO mixtures and with reference to the limitations of the specification, the OBC were determined depending on higher Marshall stability and density, limited Marshal flow (2-4) and air void (3-5) , limited VMA (higher than 14%). Figure (4-7) shows the OBC for 9.5 mm NMAS mixtures comprising CMF, OPC, or QL based on the properties mentioned above. However, the characteristics of filler type are reflected on OBC, where TAO with QL present lower value of binder content to maintain better mix characteristics, then TAO with OPC, and finally TAO with CMF.

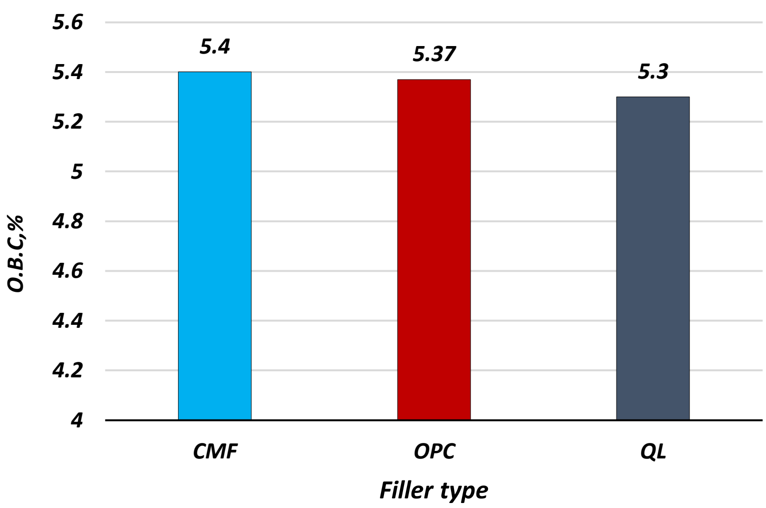

Figure 4-7. Optimum Binder Content for TAO Comprising CMF, OPC and QL.

4.2.2 Volumetric Properties of Controlled TAO Mixtures

In order to characterize the volumetric properties of TAO controlled mixes with various filler types at OBC, main indexes like bulk density, air void, VFA, and VMA were determined and analyzed as follows:

- **Bulk Density**

The filler type has an impact on bulk density at OBC as clearly shown in Figure (4-8). This figure illustrates that there is an increase in the value of bulk density when QL is utilized, the weighted bulk density of TAO mixes with CMF or OPC filler showed slight value. As mentioned previously, this is related to the characteristics of QL like specific gravity, surface area, particle size distribution, where all of them help in increase in bulk density.

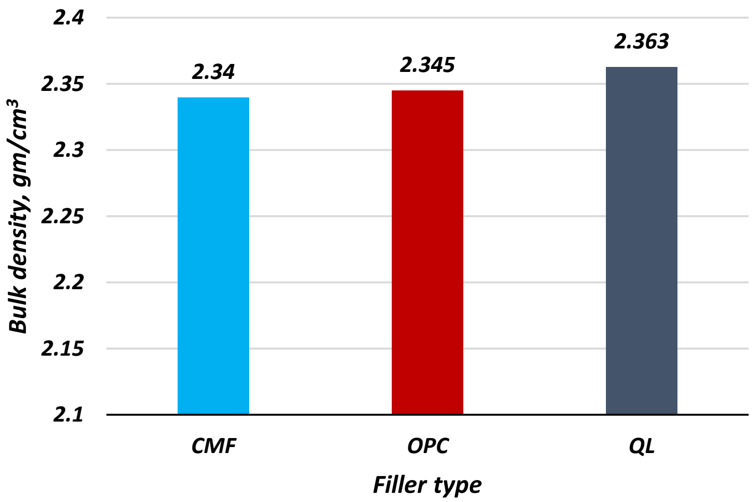

Figure 4-8. Bulk Density at O.B.C for TAO Mixes with Three Filler Types.

- **Air Voids**

Figure (4-9) shows that the air voids of controlled TAO mixes are affected by the type of filler. From this figure, it is clear that there is a decrease in the air void when utilizing QL compared with OPC and CMF and this is because of the fineness of QL. That filler is filling up voids among the aggregates, thereby decreasing the VTM. Also, the surface texture of the filler plays a vital role in resist the compaction effort.

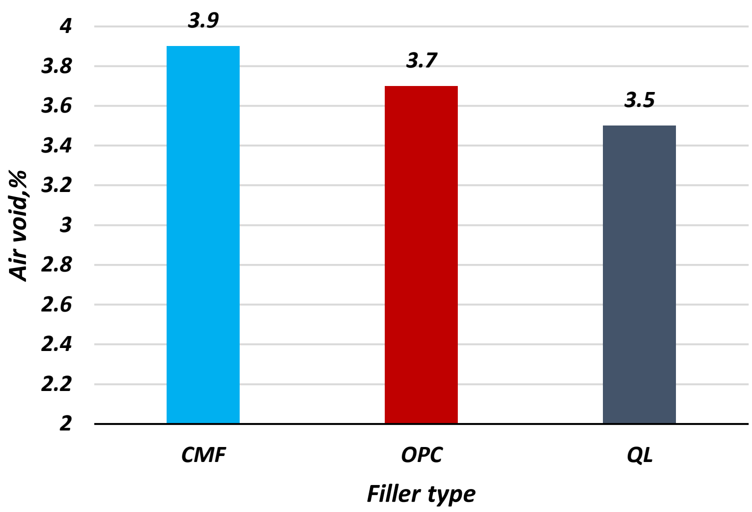

Figure 4-9. Air Void at O.B.C for TAO Mixes with Three Filler Types.

- **Void in Mineral Aggregate (V.M.A)**

Figure (4-10) demonstrates the values of V.M.A at O.B.C for different TAO mixes with various filler types. This figure shows that the VMA having a low value when QL is used compared with those mixes that include OPC or CMF. The particle size distribution and surface area of the filler are affecting this variation in VMA.

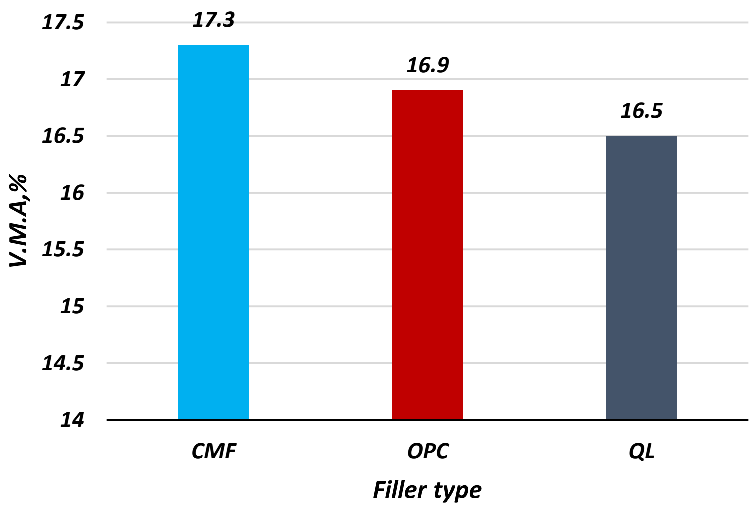

Figure 4-10. V.M.A at O.B.C for Three Filler Types.

- **Void Filled with Asphalt (V.F.A)**

The VFA is define as the percentage of voids in the compacted aggregate mass that are filled with asphalt binder. Figure (4-11) shows the impact of filler type on VFA. The results indicate that when QL or OPC are utilized in mixture, VFAs were decreased as a result of higher surface area and fineness of these filler, which might increase the asphalt film instead of filling the voids.

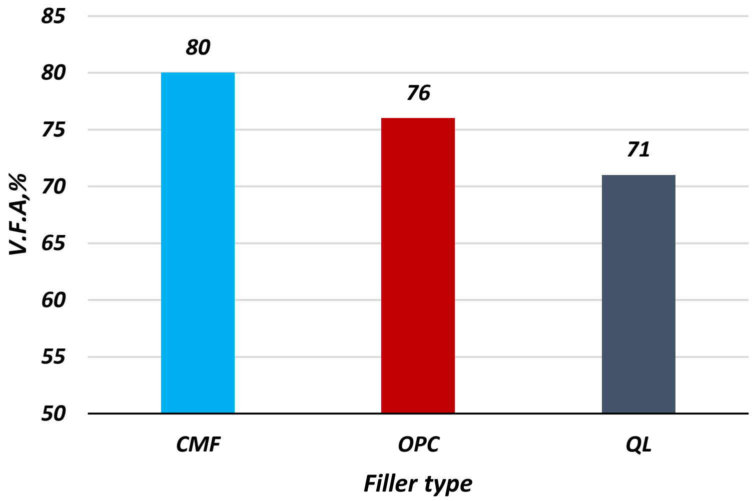

Figure 4-11. V.F.A at O.B.C for Three Filler Types.

4.2.3 Mechanical Properties

In order to characterize the mechanical properties of TAO controlled mixes with various filler types at OBC, main indexes like Marshall Stability and flow, IDT, creep compliance, skid resistance, and rut depth were determined and analyzed as follows:

4.2.3.1 Marshall Test

Figures (4-12) and (4-13) reported the Marshall stability and flow, respectively, which were obtained from each data set of TAO mixes with different filler types. It can be seen that the average stability values for TAO mixes comprising QL are approximately 2% and 12% higher, while the average flow values were approximately ١٣% and ١٨% lower than that TAO mixes comprising OPC and CMF, respectively.

This is related to the particle morphology and surface area, which introduce further reinforce to the asphalt mastic.

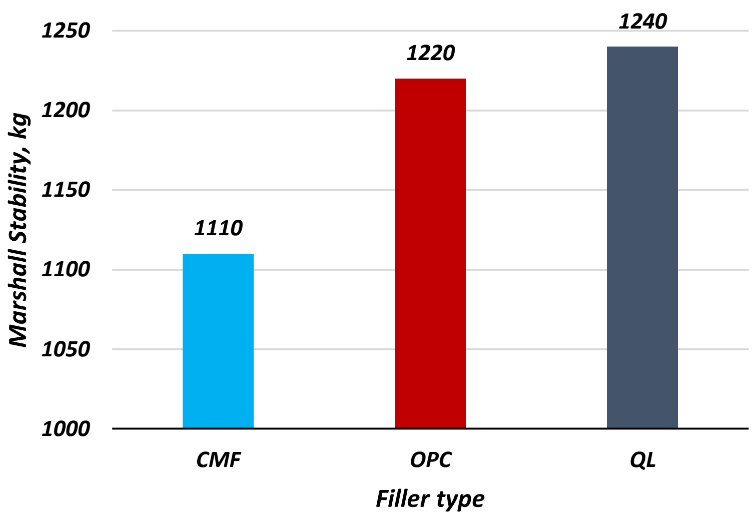

Figure 4-12. Stability at O.B.C for TAO Mixes Comprising Three Filler Types.

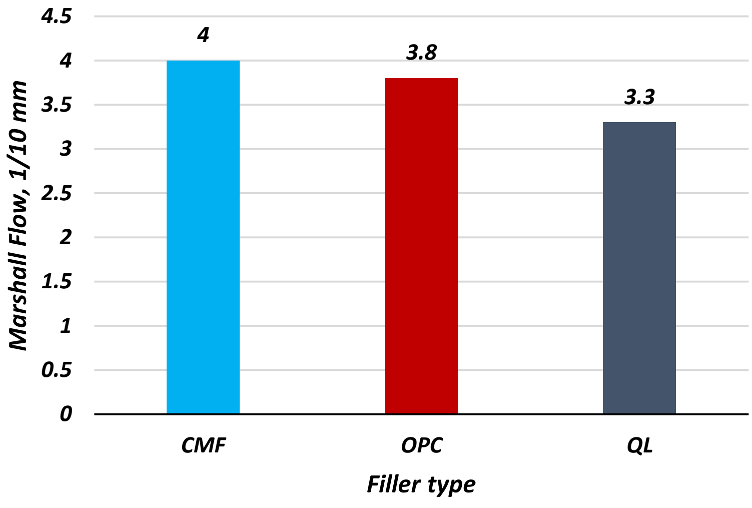

Figure 4-13. Flow at O.B.C for Three Filler Types.

4.2.3.2 Indirect Tensile Strength

Figures (4-14) shows the results of average IDT of TAO mixes with CMF, OPC and QL. The results show obvious higher cracking resistance of TAO mix including QL when compared with TAO mixes with OPC and CMF. This is returned to filler particle shape and surface area of QL, this characteristic helps in strengthen the asphalt mastic between aggregates, which reflects good tensile strength resistance. However, the higher cracking resistance can be seen from the cracking shape of different specimen, whereas the little distortion in the interface of stripes as can be seen in Plate (4-1).

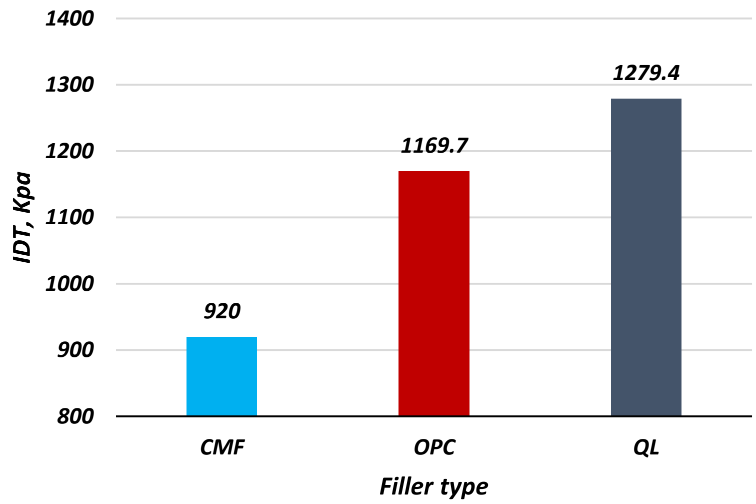

Figure 4-14. IDT for TAO Mixes with Three Filler Types.

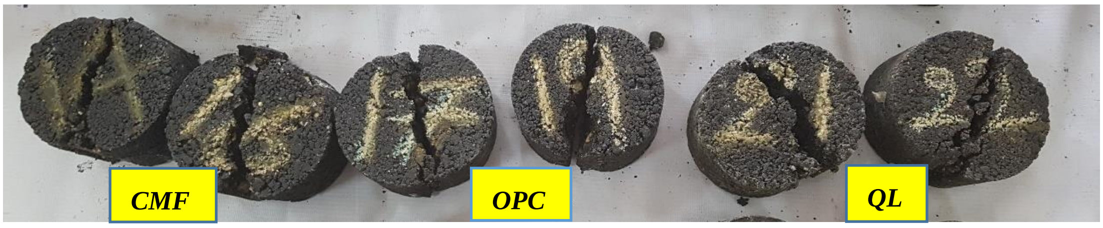

Plate 4-1 IDT for TAO Specimens after Test.

4.2.3.3 Creep Compliance

The creep compliance was calculated from the applied creep stress and the measured strain over time. The relationships between the creep compliance and time for each TAO mixes that including CMF, OPC or QL specimens, are shown in Figures (4-15,16,17). The test were conducted at different temperatures (-20, 0, 10 ^{o}C). It could be noted from these figures that mixtures with QL exhibit lower initial and lower total compliance. This might be for the same reasons that mentioned in explaining the IDT. Figure (4-18) explains the creep compliance values after 100 sec for various filler types. However, this implying that crack progression and fatigue life of TAO mixes that comprising QL offer superiority characteristics compared with OPC or CMF.

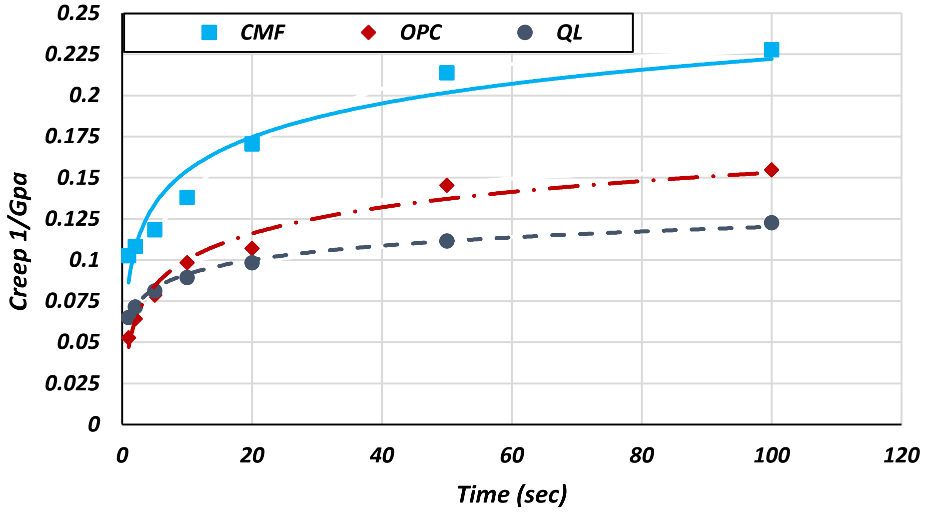

Figure 4-15. Creep compliance at -20 °C for TAO Mixes Comprising CMF, OPC, QL.

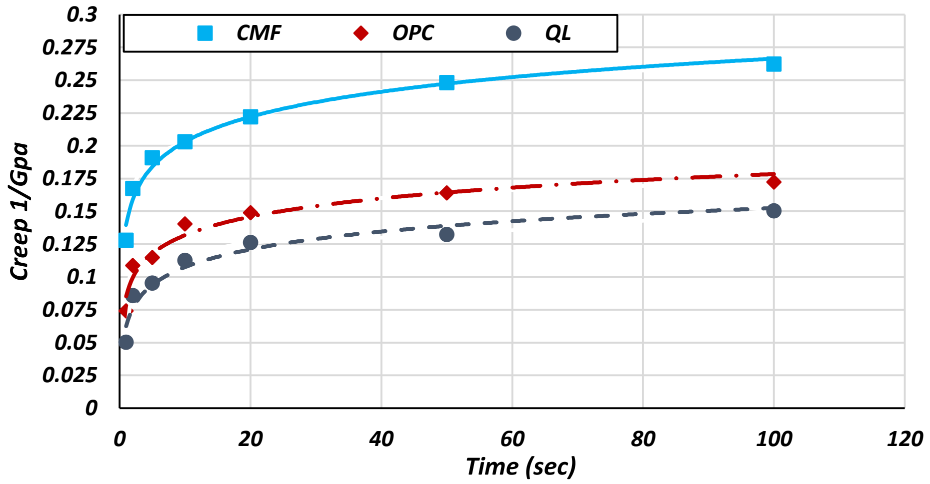

Figure 4-16. Creep compliance at 0 °C for TAO Mixes Comprising CMF, OPC, QL.

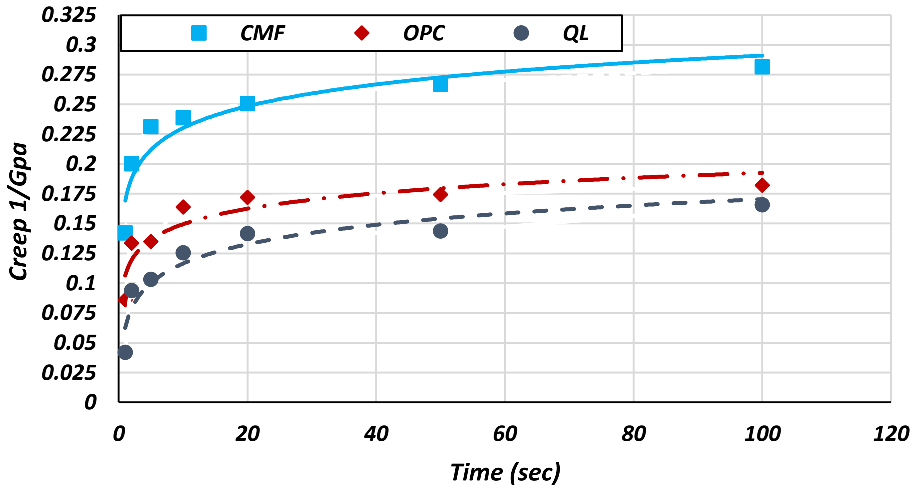

Figure 4-17. Creep compliance at 10 °C for TAO Mixes Comprising CMF, OPC, QL.

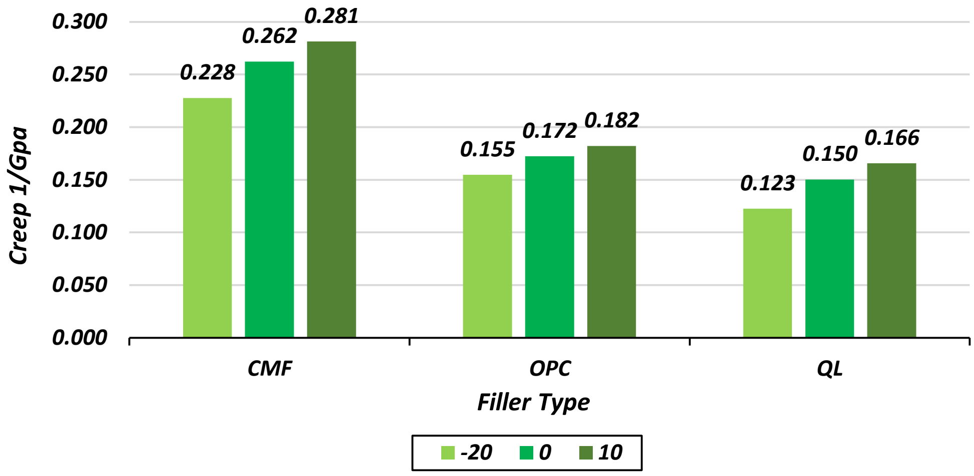

Figure 4-18. Creep Compliance after 100 sec at (-20, 0, 10 °C).

4.2.3.4 Skid Resistance Test

The British pendulum number (BPN) that results from the British pendulum skid test could be a good indication of pavement microtexture; it is related to the kinetic energy loss that occurs when the rubber slider is dragged on the surface of pavement. This test aims to measure the surface frictional property of field pavement or laboratory samples. Figure (4-19) demonstrates the results of skid resistance test for dry and wet condition of TAO mixes that comprising various filler types. The results showed that the mixtures were acceptable for heavy traveled roads in dry and wet conditioned (as SN $\geq$ 35). It is worth mentioned that the results proved there was a very little effect of filler type on skid resistance of the controlled mix. This is because skid is influenced by the aggregate grading and type.

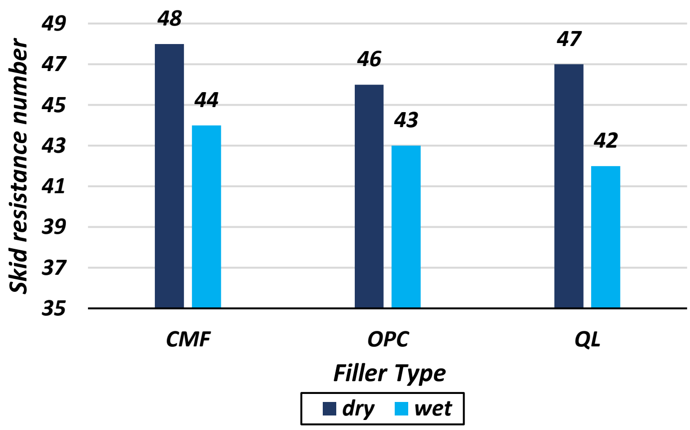

Figure 4-19. Skid Resistance for Dry and Wet Conditioned.

4.2.3.5 Wheel Track Test

Rutting is considered one of the major distresses that observed on asphalt pavement due to increasing traffic volume, heavy axle load, continuous hot weather, etc. Many factors would affect rutting resistance of TAO mixture, including material properties, climatic condition, traffic volumes, speed, and axle types. The main factors of rutting potential in thin overlay mixes are dust content, air voids, aggregate type, and binder content. The rutting depth increases with increasing the No. of repetition of wheel track load. Figure (4-20) illustrates the effect of filler types on rutting depth. Results showed that QL was helping for more resistance to rutting than OPC and CMF. The mixture with QL have changed mixture behavior and became more resistant to permanent deformation. Many reasons after that, the first reason is that a mixture with QL has showed comparatively low air void, which directly related to density. The second one is the stabile mastic, which forms from asphalt and QL comparatively with other filler, high surface area and particle size distribution of QL are significantly help in this stability. Simultaneously, Dynamic stability results, as illustrated in Figure (4-21), proven the same fact. QL filler has improved the dynamic stability of mixture efficiently, and made it stiff enough to resist applied repeated loads.

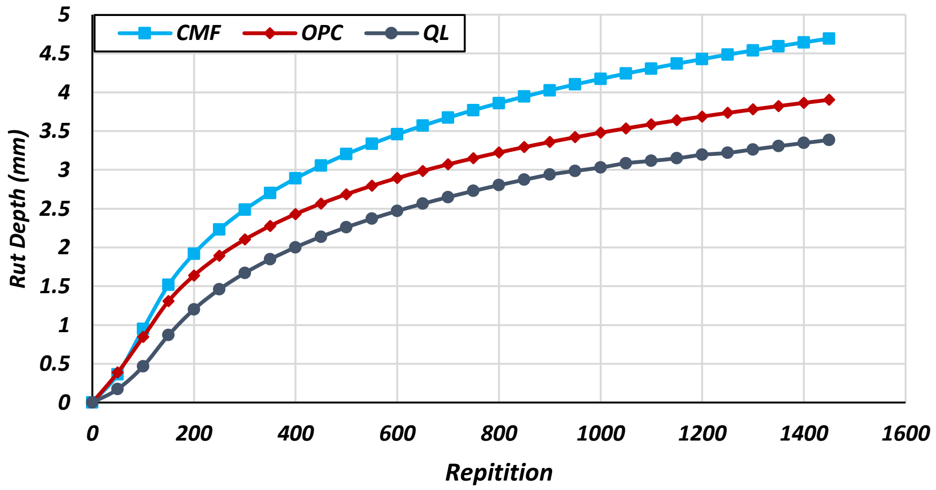

Figure 4-20 Rutting vs. Number of Cycle Curves for Control TAO Mixture Comprising CMF, OPC and QL

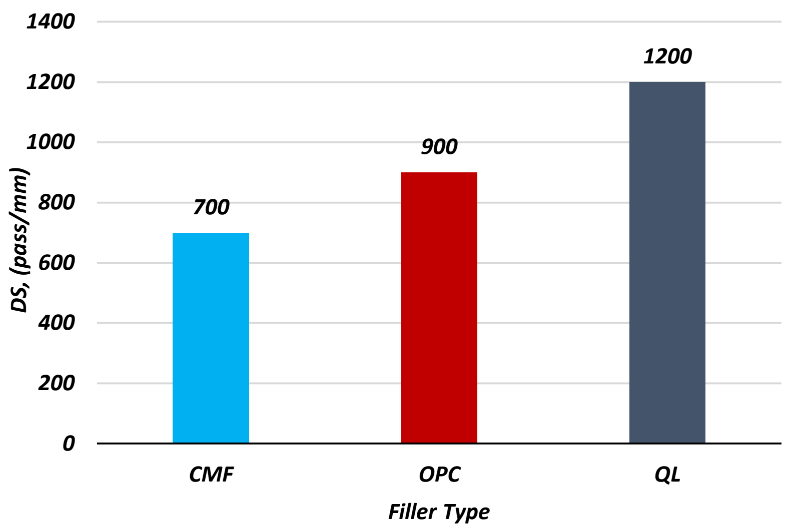

Figure 4-21. Dynamic Stability for Control TAO Mixture Comprising CMF, OPC and QL

4.2.4 Durability Properties

4.2.4.1 Tensile Strength Ratio

The IDT and TSR for both unconditioned and conditioned samples are shown in Figure (4-22). As indicated, unconditioned mixtures that containing QL exhibited the highest tensile strength values. Similar trends were observed for the IDT of conditioned mixtures. Those outcomes suggest that the IDT for conditioned samples is lower than the IDT for unconditioned samples. This observation indicates that deterioration occurred in the mixtures due to moisture conditioning exerts a significant effect on reducing the tensile strength of the mixtures. It was found that samples prepared with QL have greater IDT than those prepared with OPC or CMF. Simultaneously, samples incorporating QL exhibit greater resistance to moisture damage compared to those containing CMF or OPC. It believed that QL similar to OPC particles which in the presence of water, the hydration process is continue during specimens conditioning and that resulted in higher bonding property. In addition CA^{++} is free in the water, which prevent the stripping. As disclosed in Figure (4-22), slight differences in TSR values were observed among the mixtures prepared with OPC (79%), and QL (82%). While mixture with CMF showed unaccepted TSR value (57%). Results proven the superiority of hydraulic fillers (OPC and QL) over inert filler (CMF) in resist the water sensitivity.

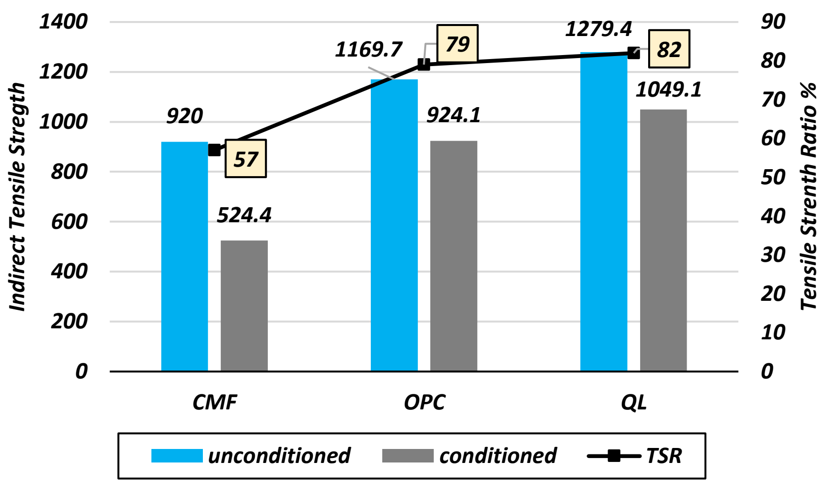

Figure 4-22. Indirect Tensile Strength and Tensile Strength Ratio Results.

4.2.4.2 Cantabro Test

Cantabro durability test is typically used for open graded asphalt mixtures and it has attracted little attention to use with dense graded mixtures. It is recommended that the abrasion loss from this test should not exceed 20% for un aged specimens and 30% for aged specimens (ASTM, 2013a) (Kandhal, 2002). Specimens of all three the mixtures, which were prepared at their respective design asphalt contents, were tested and results are summarized in Figure (4-23). The results explain the values of Cantabro loss for aged and un aged conditioned, Cantabro loss is reduced by (١٨%, ٣٠%) and (١٥%, ٢٤%) for aged and un aged when compared with OPC and CMF. whereas QL adds a noticeable improvement or noticeable adhesion and cohesion properties to TAO mixture. many reasons after this improvement, which are the decreased air voids, the higher density, and the expected thicker mastic film.

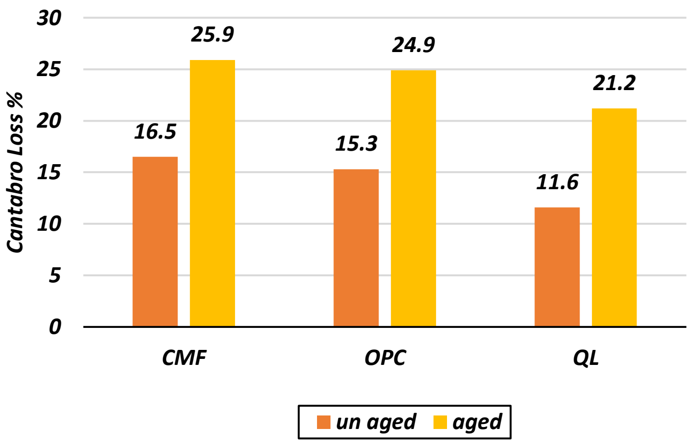

Figure 4-23. Cantabro Loss (Unaged and Aged Conditioned)

4.3 Characteristics of TAO with Modified Binder

Out of cost issue, to date, TAO represents the best performance asphalt mixtures technology worldwide in terms of mechanistic, volumetric and durability performance of surface treatment techniques. It is worth mentioned that TAO is subjected to heavy load and environmental conditions, which imply a serious superior mechanical, volumetric and durability properties requirements. On the other side, nowadays, modified binder is very common, where neat asphalt binder shows comparatively inferior characteristics. Therefore, extensive research works have continuous efforts to upgrade asphalt binder by polymers introduction. In this research and for comparison purpose, TAOs, which were prepared with three types of fillers, i.e., CMF, OPC and QL, are subjected to further investigation by the incorporating of modified binder.

4.3.1 Volumetric Properties of TAO with Modified Binder

4.3.1.1 Bulk Density

Figure (4-24) shows that the bulk density values increased when modifying the asphalt with SBS polymer. The higher value of bulk density was observed at 2% percent of SBS for all filler types. However, TAO mixtures with QL is still showing the superiority properties. This could be related to the increasing the mixing and compaction temperature due to the increase in binder viscosity to ensure 100% aggregate coating. While the extensive increment in viscosity with increase polymer limit the densification.

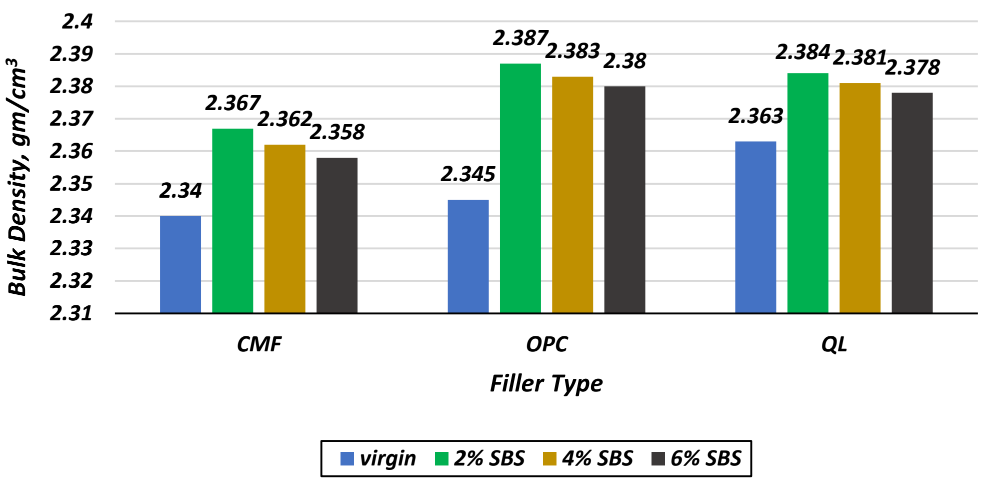

Figure 4-24. Bulk Density for Control TAO Mixture Modified with SBS (2, 4 And 6%).

4.3.1.2 Air Void

Figure (4-25) shows the air void contents of the SBS modified TAO mixtures, one can make the general observation that the air voids content decreased by adding 2% of SBS to asphalt binder and then the air voids content increase at 4% and 6% of SBS for all mixtures with different filler types, but still noticeable reduction in air void is recognized when compared with control TAO mixtures. The same explanation associated with density results can adopt here.

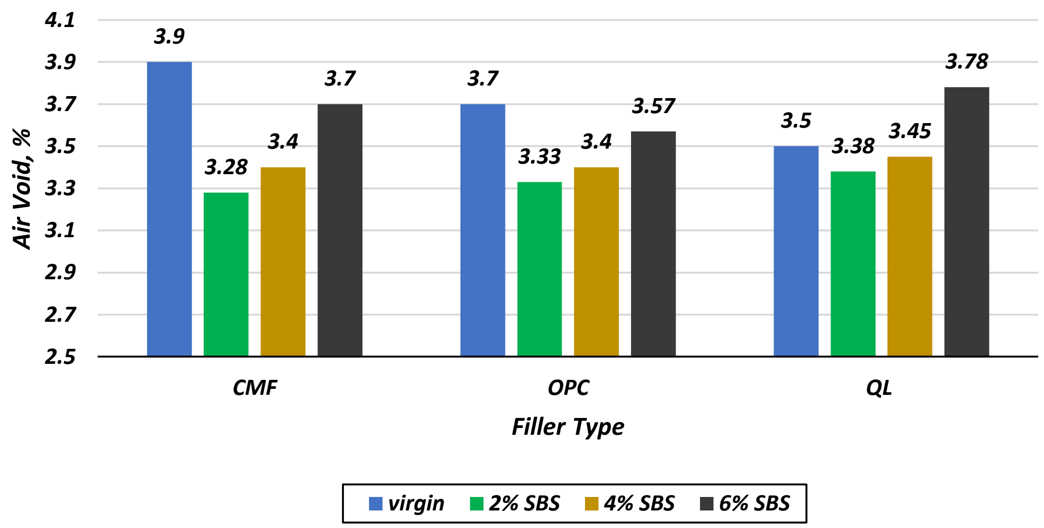

Figure 4-25. Air Void for Control TAO Mixture Modified with SBS (2, 4 And 6%).

4.3.1.3 Voids in Mineral Aggregate (V.M.A)

Figure (4-26) demonstrates that the VMA values of TAO mixture with modified binder shows the same trend of the air void results. Also, the VMA results pattern for the specimen using neat bitumen has higher VMA values compared to specimen that uses SBS polymer modified bitumen. This indicates that the viscosity characteristics of the modified binder play a vital role in controlling the volumetric properties of TAO mixtures.

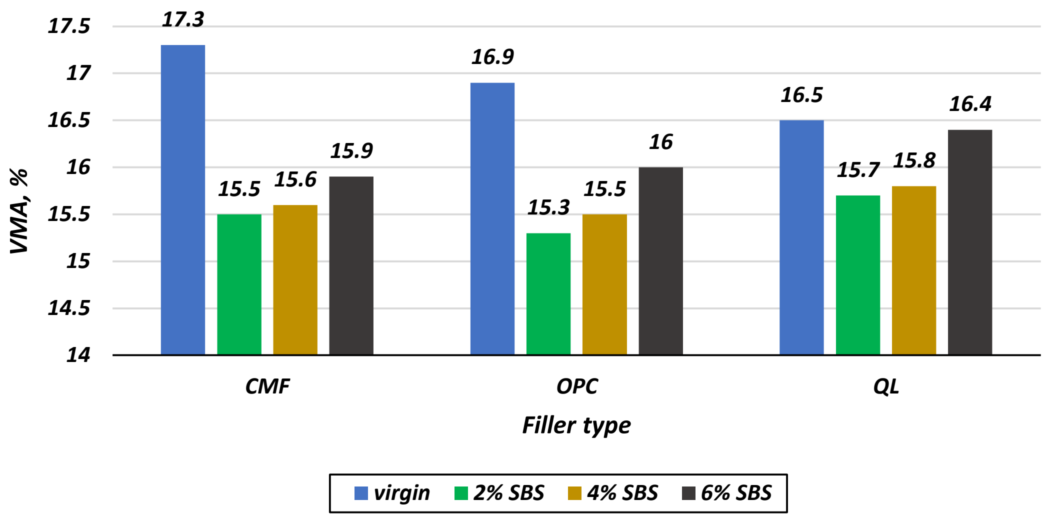

Figure 4-26. V.M.A for Control TAO Mixture Modified with SBS (2, 4 And 6%).

4.3.1.4 Voids Filled with Asphalt (VFA)

Figure (4-27) presents the result of VFA for TAO mixtures with modified binder and two significant indications can be drawn from these results. The first is the role of viscosity affects in preventing the fill of void while the second, is the role of filler type in controlling the fill of void, where QL with high SBS dosage are controlled the further filling of void with binder. The increase in viscosity of the asphalt mastic is a result of SBS and also the fineness of QL particles.

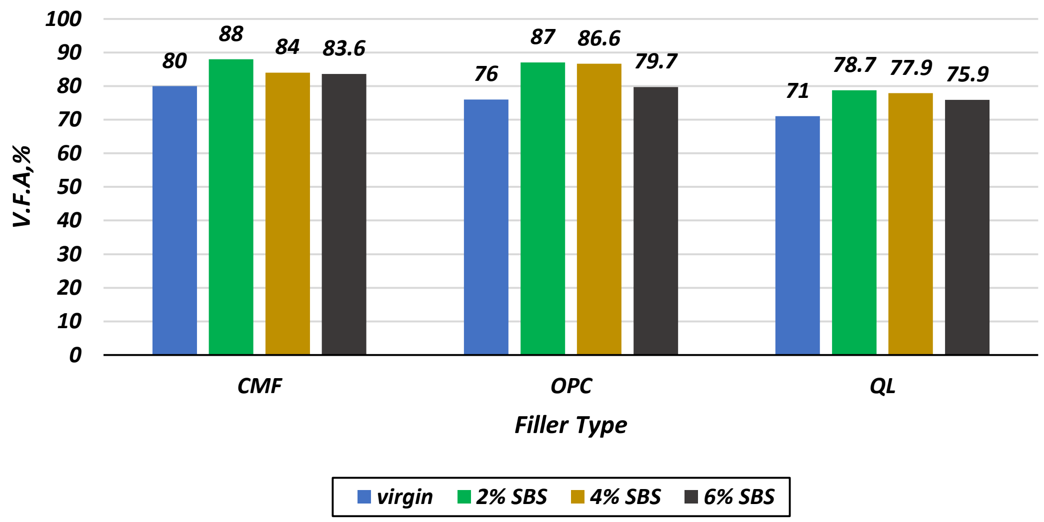

Figure 4-27. V.F.A for Control TAO Mixture Modified with SBS (2, 4 And 6%).

4.3.2 Mechanical Properties of TAO with Modified Binder

4.3.2.1 Marshall Test

Marshall Test results are summarized in Figures (4-28) and (4-29). When comparing the control TAO with TAO comprising polymer, adding (2, 4, and 6%) of SBS lead to increase the values of Marshall stability by (118, 102, and 89%) for TAO comprising CMF and Marshall stability increased by (72, 61, 55%) for TAO comprising OPC, while the Marshall stability increased by (25, 21, 18%) for TAO comprising QL respectively. While the values of flow decrease with the modifying the mixtures by this polymer. The high polymer dosage leads control the adhesion characteristics of the binder itself; polymer is reinforced the binder by introducing set of networks, which itself has no adhesion characteristics.

On the other hand, it is clear from the results that the mixtures with CMF are more affected by polymer SBS introduction, and they show higher values of stability when compared with mixtures prepared with OPC or QL. In other words, the polymer works more significant with less finer filler, which could control the dispersion of the networks. In addition, the results showed that the percentage of 2% SBS was the optimum percentage to be used for the modification of asphalt cement properties to enhance the pavement performance with the minimum modification cost.

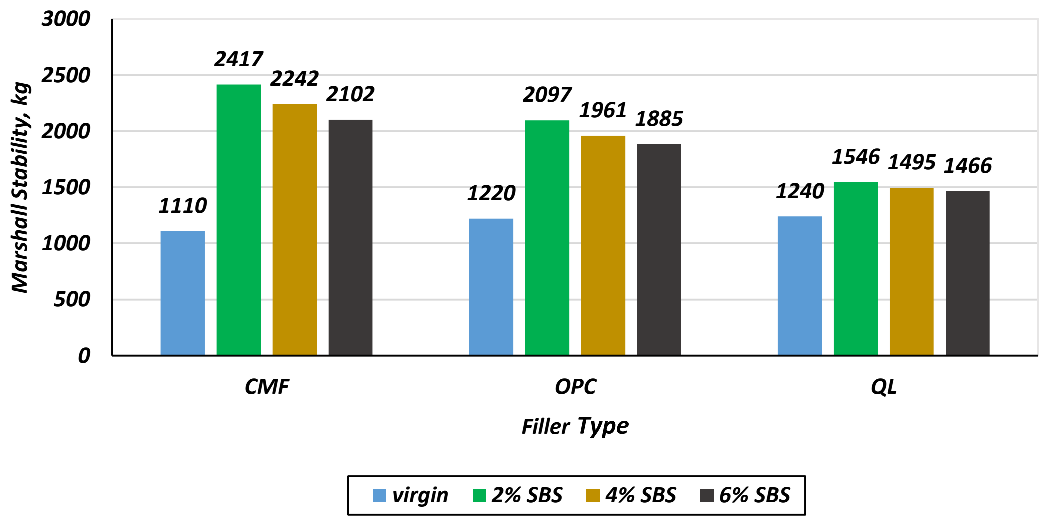

Figure 4-28. Stability for Control TAO Mixture Modified with SBS (2, 4 and 6%)

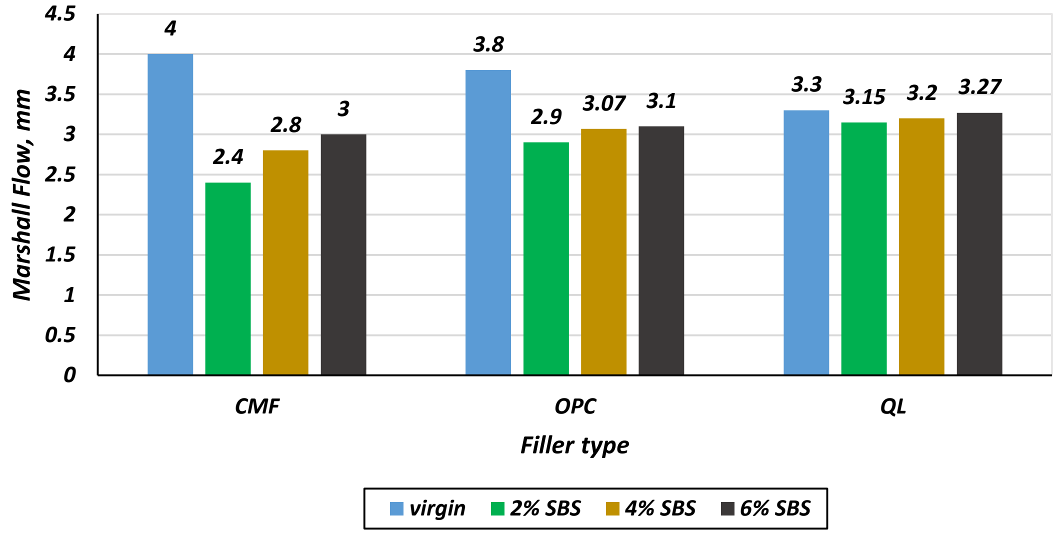

Figure 4-29. Flow for Control TAO Mixture Modified with SBS (2, 4 And 6%).

4.3.2.2 Indirect Tensile Strength

Figure (4-30) shows the result of IDT of TAO with different percentages of SBS. The results show that the IDT for TAO mixtures, which are modified by SBS at different content are greater than that of control TAO mixture. This means, that mixtures containing SBS have higher values of tensile strength at failure, which indicates greater cohesive strength of SBS modified mixtures, and improves the adhesion and cohesion of binder and don't allow the striping of asphalt from aggregate surface. In addition, the results explain that the mixture with modified bitumen having 2% SBS shows higher values of indirect tensile strength. The associated polymer networks and silica particle work to reinforce the binder in one hand, and extend a bonded load transformer between adjoin aggregate particles, from the other hand high dosage could affect the binder adhesion properties at the interface between binder and aggregates.

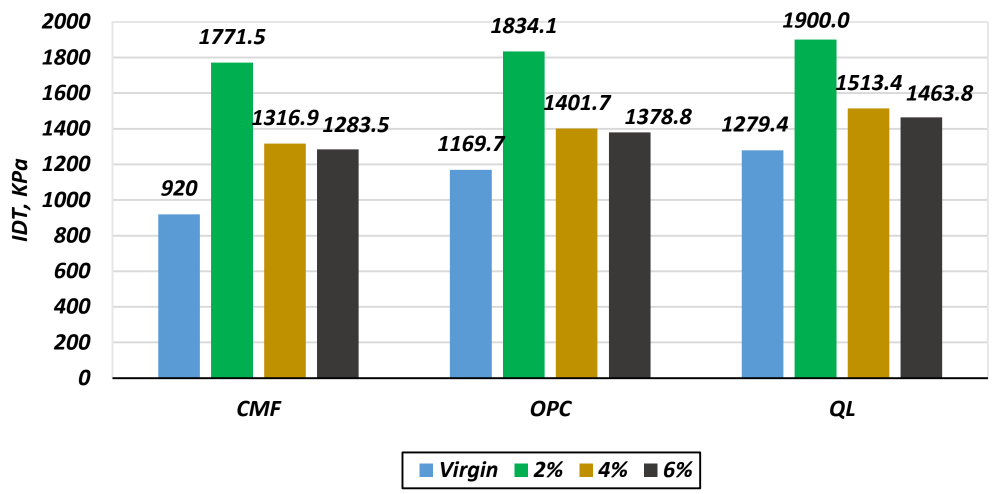

Figure 4-30. IDT for Control TAO Mixture Modified with SBS (2, 4 And 6%).

4.3.2.3 Creep Compliance

Results in Figures (4-31, 32, 33) demonstrate that the addition of SBS polymer leads to a significant decrease of the creep compliance. In other words, increase in TAO mixture stiffness and of course better resistance fatigue cracking. This could be because of the improving in binder characteristics due to cross-linking and micro silica particles that associate by the polymer. It is worth mentioned that the increase in the percentage of SBS leads to better improvement in creep compliance, especially for TAO mixture with QL. However, from Figure (4-34) it can be concluded that TAO mixture with QL shows the superior properties and this is as a result of both polymer and filler type and dosage. From the same figure, it is not surprising to notice that initiation extra network with higher SBS improve creep compliance.

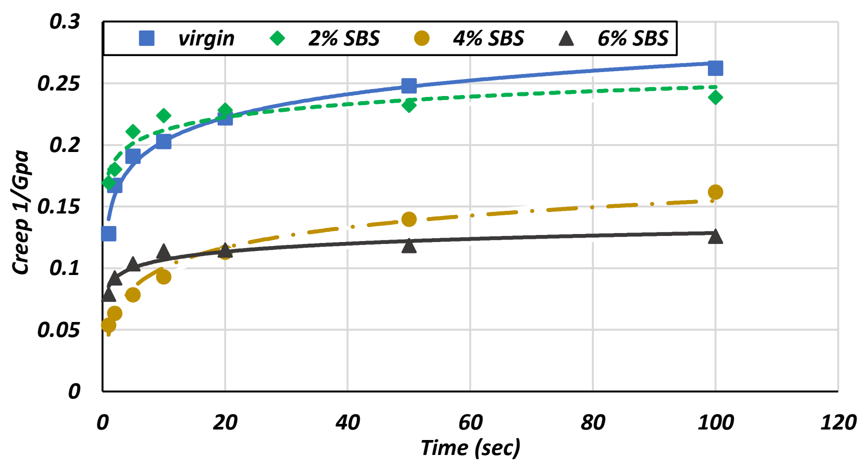

Figure 4-31. Creep Compliance for Control TAO Mixture with CMF Comprising Three Percentages of SBS (2, 4, and 6%)

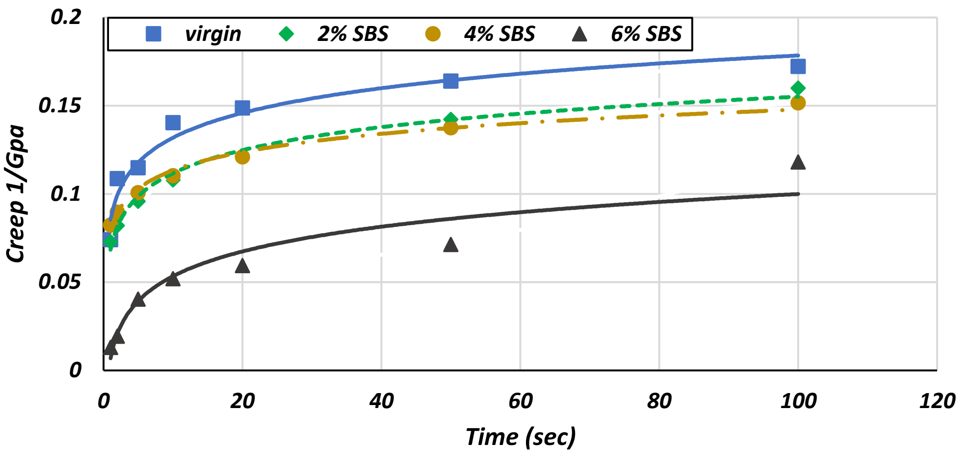

Figure 4-32. Creep Compliance for Control TAO Mixture with OPC Comprising Three percentages of SBS (2, 4, and 6%)

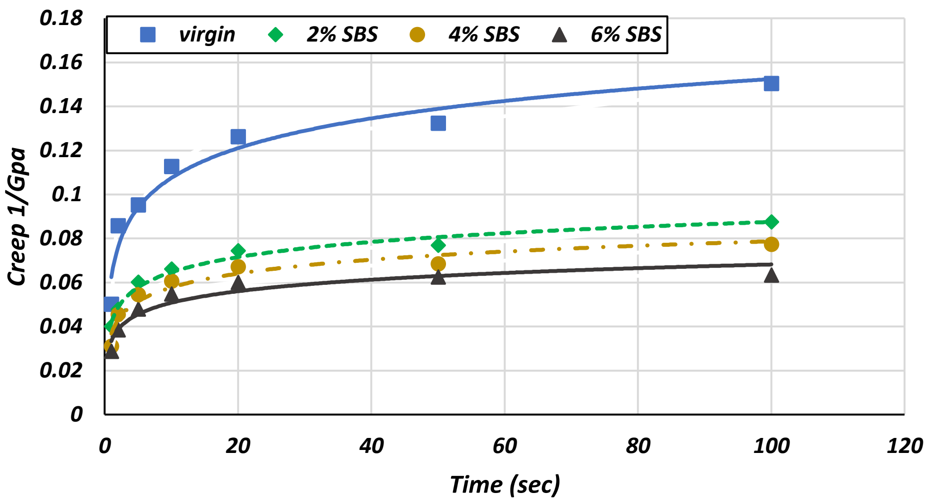

Figure 4-33. Creep Compliance for Control TAO Mixture with QL Comprising Three percentages Of SBS (2, 4, and 6%)

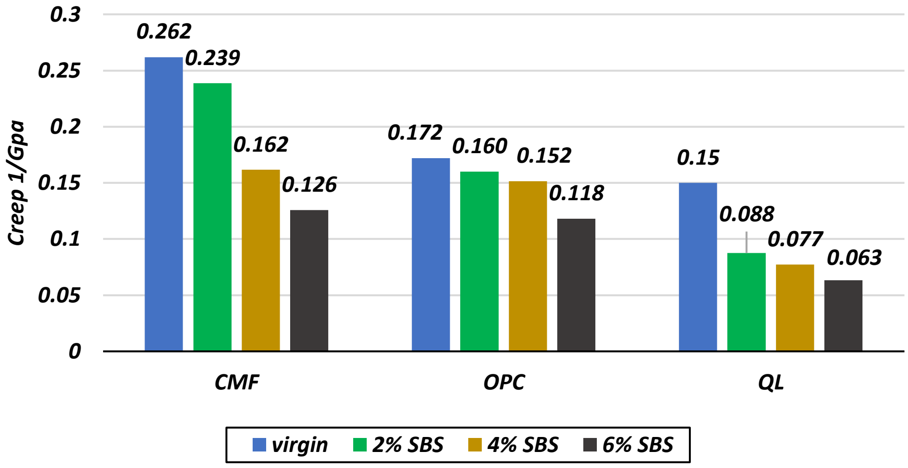

Figure 4-34. Creep compliance after 100 sec comprising three percentages of SBS (2, 4, and 6%)

4.3.2.4 Skid Resistance

Figure (4-35) demonstrates that the SBS polymer leads to increase the surface roughness of the modified TAO mixtures. It can proposed that SBS-binder combination locks the aggregate firmly in place, this creating an extremely rough, hard, durable surface. In other words, the increase in binder stiffness constrain the ability of the aggregate particles to sliding or moving even in micro scale. However, this improves the TAO layer capability of withstanding everyday roadway demands under heavy braking.

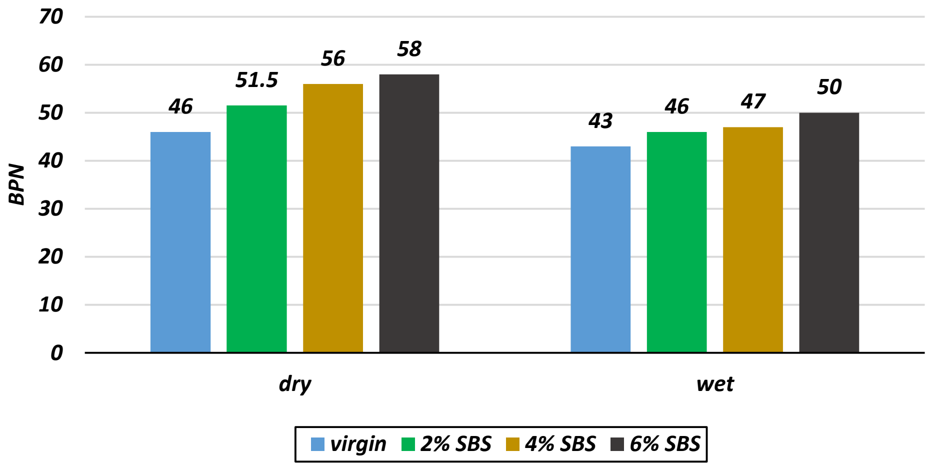

Figure 4-35 Skid resistance for dry and wet conditioned comprising three present of SBS (2, 4, and 6%)

4.3.2.5 Wheel Track Test

Wheel-tracking test results for conventional and modified mixture are presented in Figures (4-36, 37, 38). The TAO mixes with SBS showed the smallest rut compared to the TAO mixtures with neat binder. This result proved that modified mixtures have high resistance to rutting compared to controlled mixtures. The maximum displacement was recorded at (4.69, 3.9, 3.385mm) in controlled TAO mixtures with CMF, OPC, QL, respectively; while the TAO mixtures with the same filler types at 6% performed considerably well, in which the vertical displacements were (1.92, 1.76, 1.16mm), respectively.

On the other hand, Figures (4-39, 40, 41) explain the inverse relationship between dynamic stability and rutting increase rate. The results show that the dynamic stability increases with increasing the percentage of SBS while the rutting rate decreases with increasing the percentage of SBS. However, the presence of the polymer networks reinforce the binder and prevent the irrecoverable strain, which is the main cause of rutting. Also the presence of silica within the polymer increase the stiffness of the binder. Plate (4-2) shows the significance of polymer on rutting resistance.

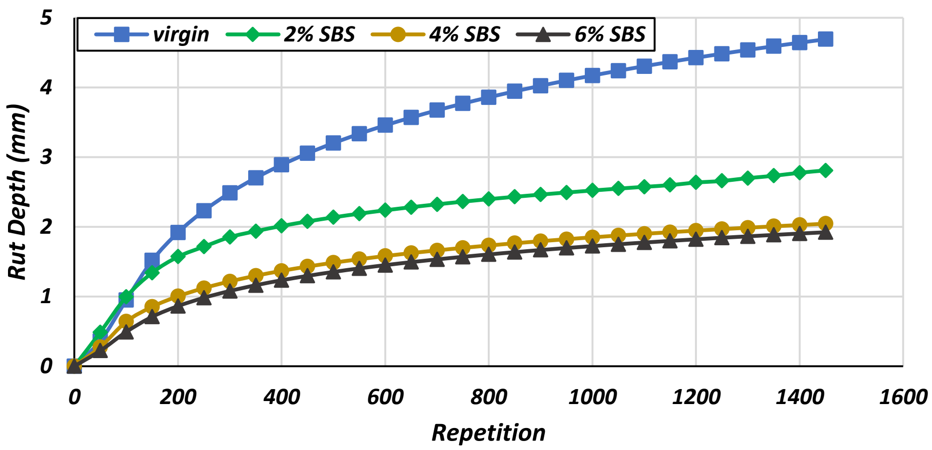

Figure 4-36. Rutting vs. repetition for control TAO mixture with CMF comprised different percentages of SBS (2, 4, and 6%).

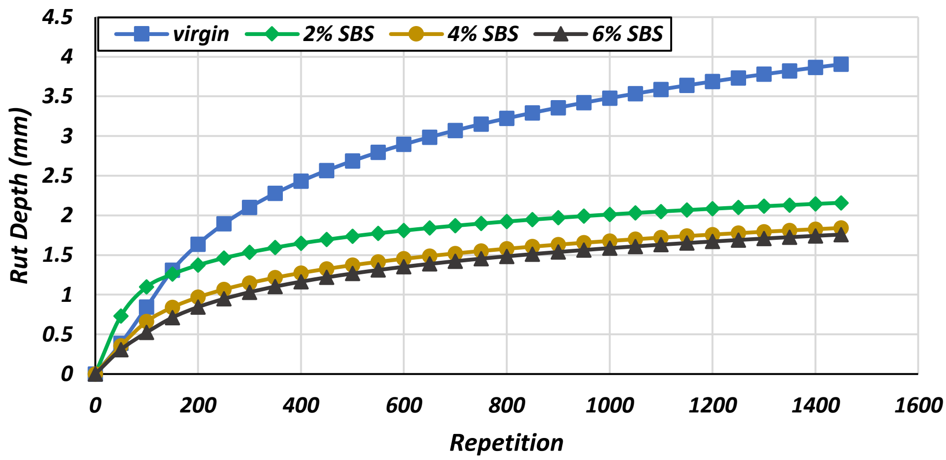

Figure 4-37. Rutting vs. Repetition for Control TAO Mixture with OPC Comprised Different Percentages of SBS (2, 4, And 6%).

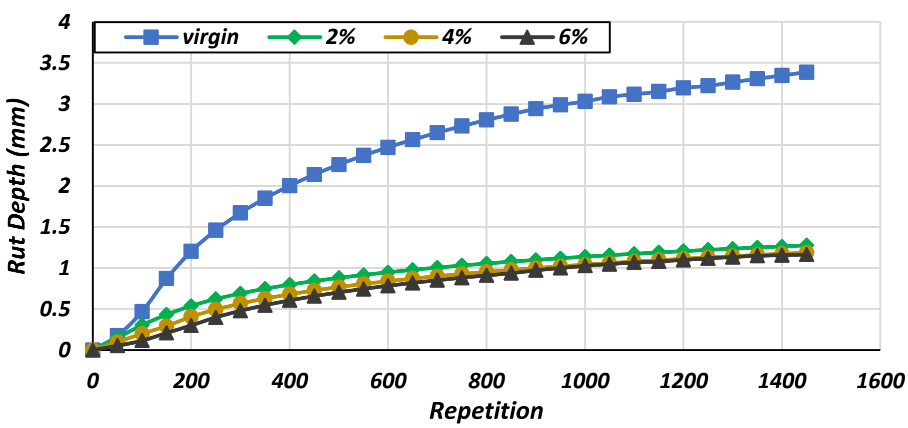

Figure 4-38. Rutting vs. Repetition for Control TAO Mixture with QL Comprised Different Percentages of SBS (2, 4, And 6%).

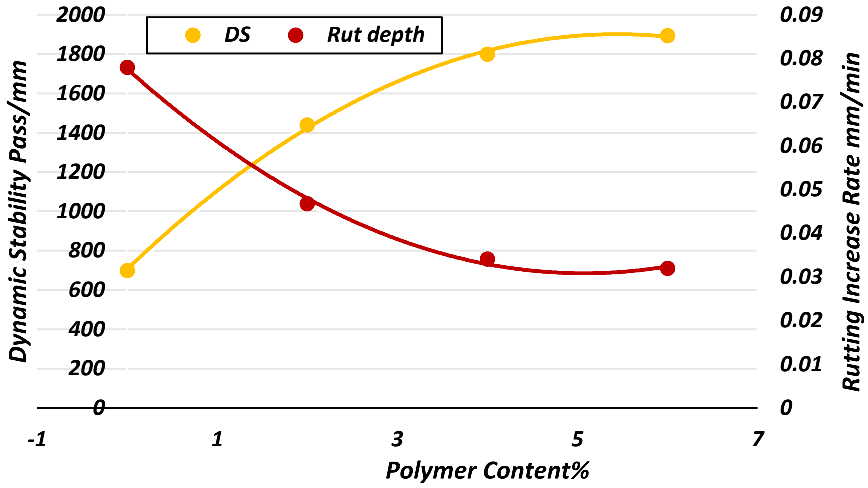

Figure 4-39. Relation between Dynamic Stability, Rutting Increase Rate and Polymer Content for Control TAO Mixture with CMF.

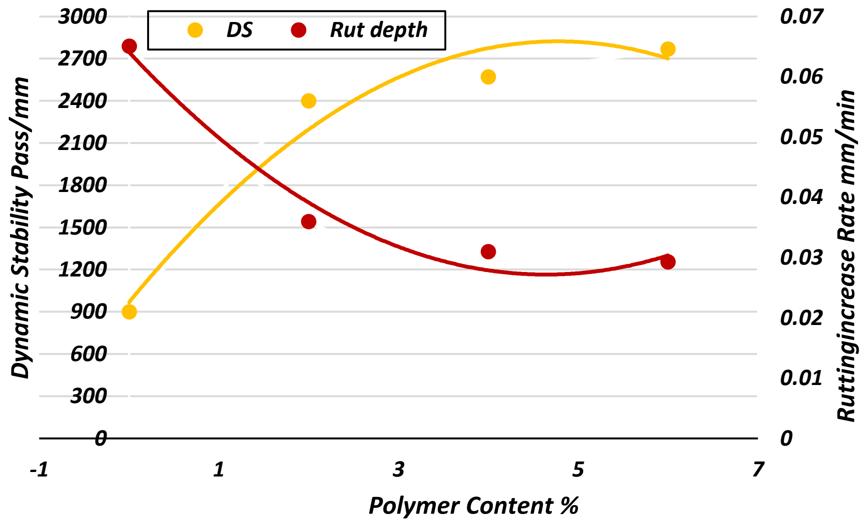

Figure 4-40. Relation between Dynamic Stability, Rutting Increase Rate and Polymer Content for Control TAO Mixture with OPC.

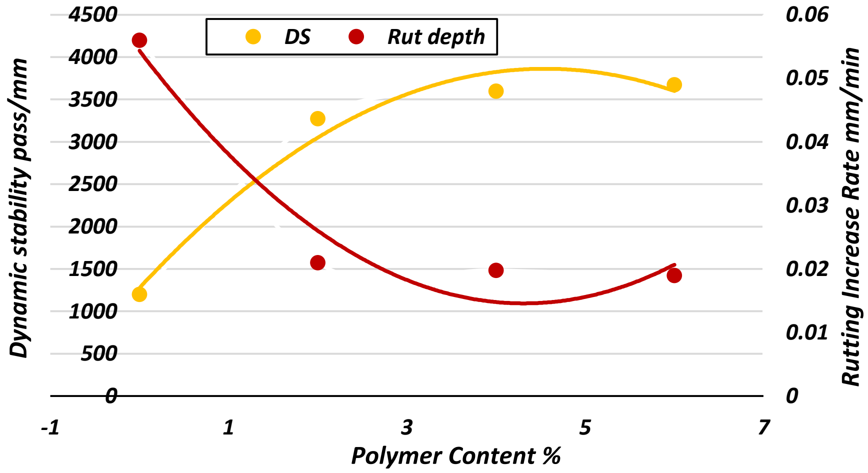

Figure 4-41. Relation between Dynamic Stability, Rutting Increase Rate and Polymer Content for Control TAO Mixture with QL.

Plate 4-2 WWT specimens of modified TAO mixtures using after test

4.3.3 Durability Properties

4.3.3.1 Tensile Strength Ratio

In order to evaluate the effect of SBS on the moisture damage resistance, Figure (4-42, 43, 44) shows the relation between the TSR and SBS content. The results show that the IDT for modified TAO mixtures with SBS at different contents are greater than IDT for control mixture in both cases (unconditioned and conditioned). This means, the mixtures that containing SBS have higher values of tensile strength at failure, which indicate greater cohesive strength of SBS modified mixtures. As shown in the mentioned figures, the TSR values increase with increasing SBS content. This increasing in TSR values refer, that the resistance of asphalt mixtures to moisture damage increase as well as the SBS content increase and exhibited more stripping resistance than control mixture. The network of SBS polymer and silica particles are the cause of these improvements, due to improving the binder stiffness.

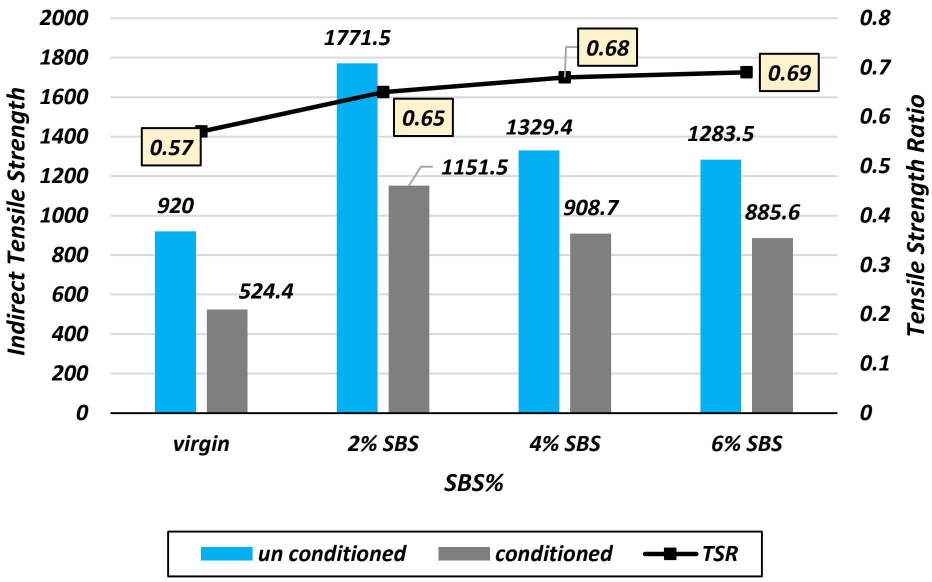

Figure 4-42. Indirect Tensile Strength and Tensile Strength Ratio Results for TAO Mixture with CMF.

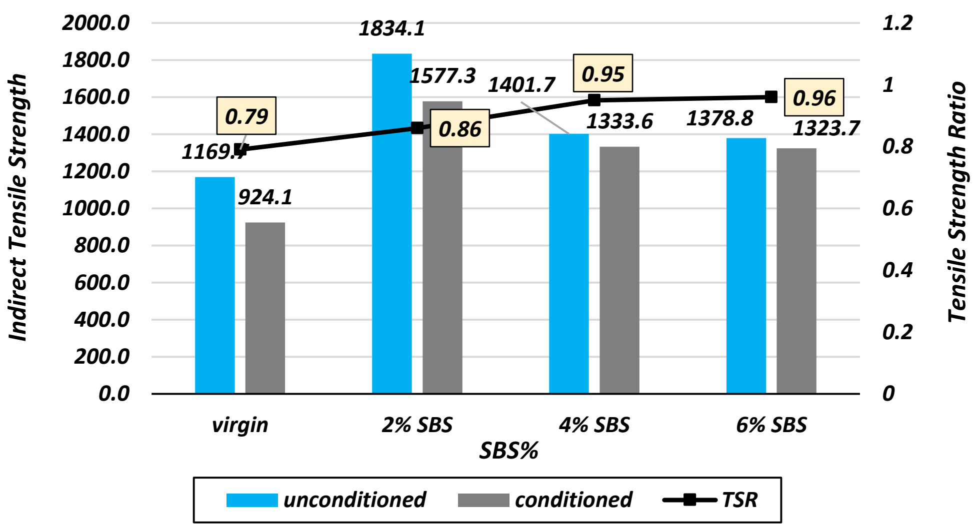

Figure 4-43. Indirect Tensile Strength and Tensile Strength Ratio Results for TAO Mixture with OPC.

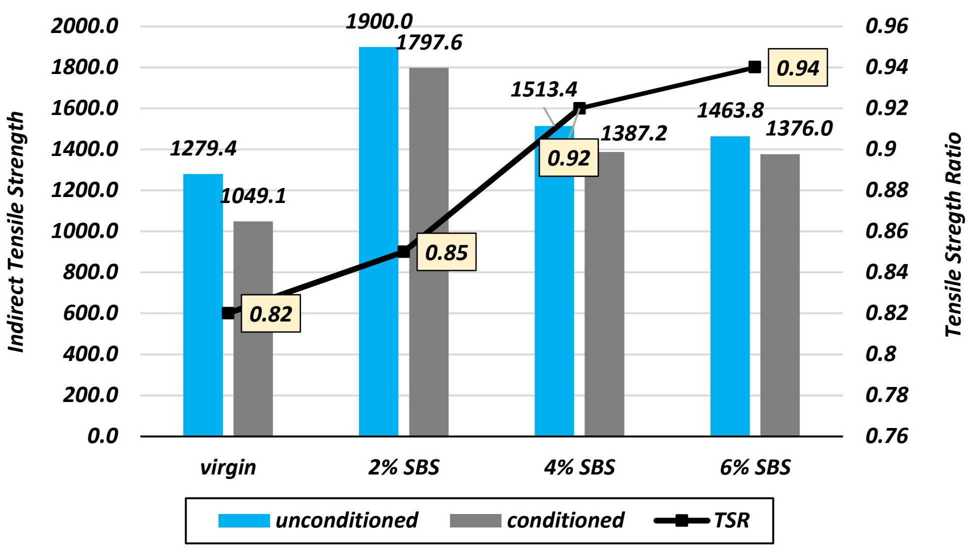

Figure 4-44. Indirect Tensile Strength and Tensile Strength Ratio Results for TAO Mixture with QL.

4.3.3.2 Cantabro Test

Figures (4-45, 46) explain the relation between the percentage of Cantabro loss and the polymer content for un aged and aged conditioned. The results show that the abrasion loss of the modified mixture with polymer SBS were lower than the mixture with neat binder. The reason for this may be returned to the addition of polymer SBS to the mixture which results in a thicker mastic film, more durable film around the aggregate particles that increases the cohesion within the mix. Also the increase of mastic stiffness due to SBS network and silica particles help essentially in this improvements. Consequently, the addition of polymer to the mixtures lead to greater improvement of the abrasion resistance. Plate (4-3) shows the significance of introducing the polymer to TAO mixture.

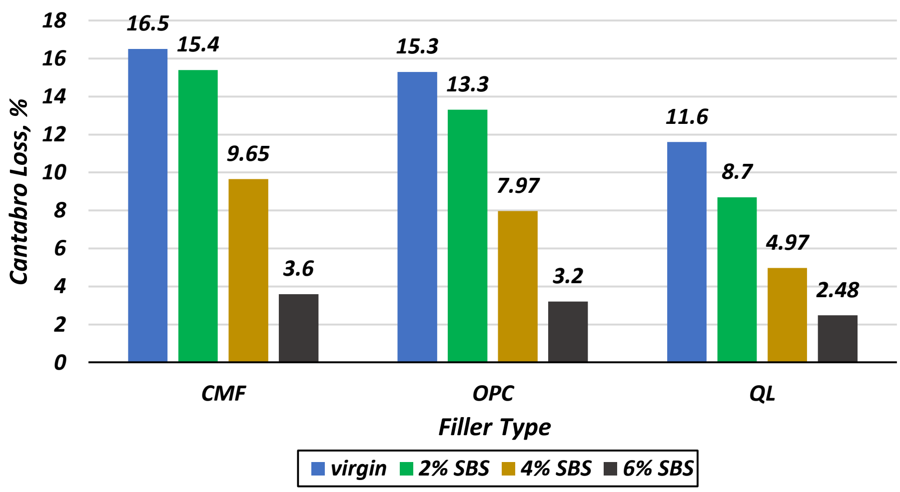

Figure 4-45. Cantabro Loss% for Un aged Control TAO Mixtures Modified with SBS (2, 4 And 6%).

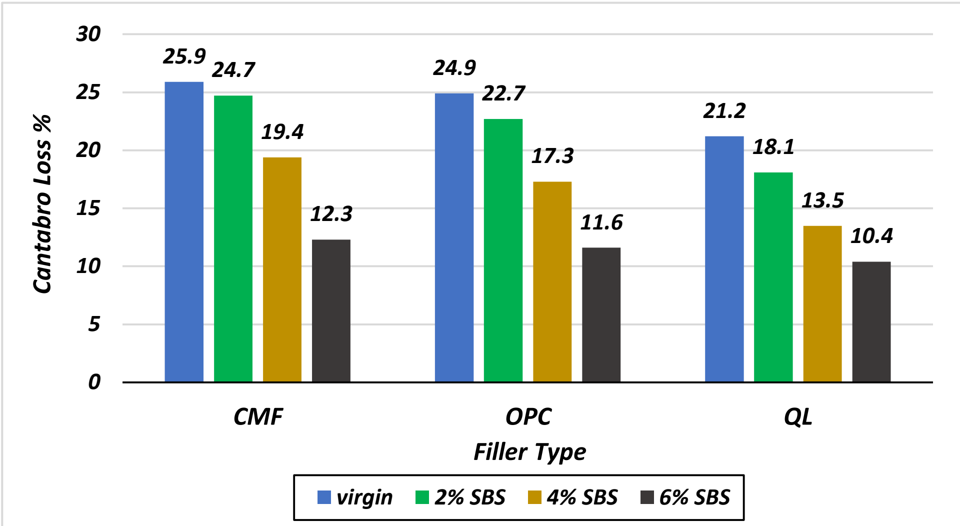

Figure 4-46 Cantabro Loss% for Aged Control TAO Mixtures Modified with SBS (2, 4 And 6%).

Plate 4-3 Cantabro Specimens after Test.

4.4 Summary

This chapter included the testing results for characterizing TAO using different materials. The main results are tabulated in Table (4-1). However, the following can be summarized:

1. The results indicated the importance role of filler type in enhancing the mechanical properties of mixtures such as Marshall Stability, Marshall Flow, indirect tensile strength, creep compliance, skid resistance, wheel track test, and durability properties such as water damage test and Cantabro test. Testing method find the ability of QL and OPC to improve TAO mixtures in terms of volumetric, mechanical, and durability properties.
2. Testing methods demonstrate the ability of using additives such as polymer modified SBS to modified binder, which lead to improve the mixtures in terms of functionality and durability properties. The modified TAO mixtures by QL and polymer SBS showed that the best characteristic in most mechanical, durability and volumetric tests.

Table 4-1 Overall view of result in this research

Mixture type			***Volumetric properties***				***Mechanical properties***								***Durability properties***		
	Filler type	***SBS %***	***VTM***	***VMA***	***VFB***	***BD***	***MS***	***MF***	***CC***	***IDT***	***SN***		***WWT***		***TSR %***	***Cantabro loss %***	
											Dry	***Wet***	***RD***	***DS***		***UN aged***	***Aged***
M1	***CMF***	**0**	3.9	17.3	80	2.34	1110	4	0.26	920	48	44	4.69	700	62	16.5	25.9
		2	3.28	15.5	88	2.367	2417	2.4	0.24	1771.5	---	---	2.81	1440	65	15.4	24.7
		4	3.4	15.6	84	2.362	2242.0	2.8	0.16	1316.9	---	---	2.04	1800	68	9.65	19.4
		6	3.7	15.9	83.6	2.358	2101.7	3	0.13	1303.6	---	---	1.92	1894	69	3.6	12.3
M2	***OPC***	**0**	3.7	16.9	76	2.345	1220.0	3.8	0.17	1169.7	46	43	3.9	900	82	15.3	24.9
		2	3.33	15.3	87	2.387	2097.0	2.9	0.16	1834.1	51.5	46	2.16	2400	86	13.3	22.7
		4	3.4	15.5	86.6	2.383	1960.7	3.07	0.15	1401.7	56	47	1.84	2571	95	7.97	17.3
		6	3.57	16	79.7	2.38	1885.2	3.1	0.12	1378.8	58	50	1.76	2769	96	3.2	11.6
M3	***QL***	**0**	3.5	16.5	71	2.363	1240.0	3.3	0.15	1279.4	47	42	3.39	1200	84	11.6	21.2
		2	3.38	15.7	78.7	2.384	1545.6	3.15	0.09	1900	---	---	1.28	3273	85	8.7	18.1
		4	3.45	15.8	77.9	2.381	1495.0	3.2	0.08	1513.4	---	---	1.19	3600	92	4.97	13.5
		6	3.78	16.4	75.9	2.378	1465.6	3.27	0.06	1463.8	---	---	1.16	3674	94	2.48	10.4

Chapter Five

STATISTICAL ANALYSIS MODEL

5.1 Introduction

A statistical model is a formalization of the relationships between variables in the form of mathematical equations. It describes how one or more random variables are related to one or more other variables. Statistical methods are used to improve the experimental methods, in which, instead of selecting one starting mix proportion and then adjusting by trial and error for achieving the optimum solution (Padmanaban, Kandasamy and Natesan, 2009). In this part of the study, the overall objective is to develop a predictive equations correlate the dependent variable with independent variable. However, because of the limitation space of this thesis three parameters only where selected from mechanical, volumetric and durability properties (namely, IDT, TSR and bulk density) represented as depended variables, while fillers as CMF, OPC, QL and percentage of SBS represented as independent variables for all modeling. The present study used Statistical Product and Service Solutions (SPSS) software (Version 24), which (SPSS) is a window based program that can be used to perform data entry and analysis and to create tables and graphs. It is capable of handling large amount of data and can perform all of the analyses covered in the text and more. More details about statistical analysis are demonstrated in Appendix (A).

5.2 Model Preparation

The Model prepared from the results obtained from experiments is one the core work in this study. Empirical modeling is done using analysis that performed on SPSS software. The variables involved in the empirical modeling are filler types and percentage of SBS. The collected results are 36 for each test of indirect tensile strength, tensile strength ratio and bulk density, divided randomly into 28 result to generate the model and the other 8 is used to validate the model. The first step to model preparations is the correlation between the variables by using SPSS Pearson's correlation. Many combinations of variables are used starting from only constant to quadratic form of both variables with the incorporation of multiple terms of both variables discussed above.

5.3 Identification of Variable, Coding for Empirical Modeling and the Correlation between Variables

Program testing needs to identify dependent and independent variables of the developed models to achieve the requirements to build the models. These variables and the code adopted for calculation are listed as follows in Table (5-1). Table (5-2) explained the bivariate Pearson Correlation between variables, this table shows

1. The independent variables have very low to absent of correlation between each other, which is good for the accuracy of the model.
2. The correlation between IDT and filler type are good when compared with polymer content
3. The filler type has the most significant correlation to TSR, then polymer content.
4. The correlation between bulk density and both filler type and polymer content are good but the correlation with filler type is more significant as explained in Table (5-2)

Table 5-1 Dependent and Independent Variables Considered in Regression Analysis.

Dependent variable				
Abbreviation	***Description***		***Unit***	***Coded values***
IDT	Indirect tensile strength		KPa	
TSR	Water sensitivity		%	
BD	Bulk density		gm/cm^3	
Independent variable				
F	Filler type	CMF		10
		OPC		20
		QL		30
P	Polymer content		%	

Table 5-2 Correlation between Variables.

		F	***P***	***IDT***	***TSR***	***BD***
F	***Pearson Correlation***	1	.000	.321	.761**	.534**
	Sig. (2-tailed)		1.000	.056	.000	.001
	N	36	36	36	36	36
P	***Pearson Correlation***	.000	1	.134	.420*	.474**
	Sig. (2-tailed)	1.000		.437	.011	.003
	N	36	36	36	36	36
IDT	***Pearson Correlation***	.321	.134	1	.350*	.771**
	Sig. (2-tailed)	.056	.437		.037	.000
	N	36	36	36	36	36
TSR	***Pearson Correlation***	.761**	.420*	.350*	1	.767**
	Sig. (2-tailed)	.000	.011	.037		.000
	N	36	36	36	36	36
BD	***Pearson Correlation***	.534**	.474**	.771**	.767**	1
	Sig. (2-tailed)	.001	.003	.000	.000	
	N	36	36	36	36	36

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

5.4 Design of Experimental Matrix

The input data (results) that analyzed in (SPSS) software are presented in Table (5-3) below:

Table 5-3 Matrix of Result

Filler type	***SBS%***	***IDT, KPa***	***TSR, %***	***Bulk density, gm/cm^3***
CMF	*0*	882.6	57	2.342
CMF	*0*	956.4	56	2.34
CMF	*0*	921	58	2.338
CMF	*2*	1714.3	65	2.368
CMF	*2*	1783	66	2.368
CMF	*2*	1817.2	64	2.365
CMF	*4*	1300	68	2.365
CMF	*4*	1305.6	68	2.36
CMF	*4*	1345.1	68	2.361
CMF	*6*	1264	69	2.357

CMF	*6*	1296	69.5	2.359
CMF	*6*	1290.5	68.5	2.358
OPC	*0*	1142.5	76	2.345
OPC	*0*	1170.3	81	2.344
OPC	*0*	1196.3	80	2.346
OPC	*2*	1842	86	2.388
OPC	*2*	1835	85	2.388
OPC	*2*	1852.3	87	2.385
OPC	*4*	1398	95	2.383
OPC	*4*	1410	95	2.383
OPC	*4*	1397	95	2.383
OPC	*6*	1380	96	2.38
OPC	*6*	1371	96	2.379
OPC	*6*	1385.4	96	2.381
QL	*0*	1294	82	2.363
QL	*0*	1261.3	82	2.363
QL	*0*	1283.9	82	2.363
QL	*2*	1920	85	2.384
QL	*2*	1896	85	2.384
QL	*2*	1884	85	2.384
QL	*4*	1510.4	92	2.382
QL	*4*	1507.3	92	2.38
QL	*4*	1522.5	92	2.381
QL	*6*	1463	93	2.378
QL	*6*	1453.8	95	2.379
QL	*6*	1474.6	94	2.377

5.5 Prediction Model

SPSS software was used to analysis and build predictive models. For the simplification the linear models were tried first, unfortunately all linear models were failed to represent the observations. For many trails it was found that all models were nonlinear.

5.5.1 Building the Indirect Tensile Strength Model

As mentioned previously, the IDT was selected to build a model from many mechanical properties. This selection is based on the believe of the author that it is the most important parameter, as it represents the cracking phenomenon for the paving materials. Modeling indirect tensile strength to filler type and polymer content was conducted, the analysis results of such modeling as shown in Tables (5-4, 5). Table (5-4) shows the parameter of the developed model and its limitation with Confidence Interval of 95%. Table (5-5) demonstrates that the MS_E is low and sum of residual is lower than the sum of regression, which is sustained the significant of the model. While, from the same table, the high value of the R-Square (0. 893) indicates a perfect prediction. Thus from this values a conclusion can draw that the developed model for IDT is good. Figure (5-1) shows the adequacy of the model and this figure indicates that an acceptable scatter can recognized between predicted and observed IDT values. Furthermore, almost all value are within the significant level boundaries.

Table 5-4 Nonlinear IDT Modeling

Developed model	$IDT= C_1*F^{C2} + C_3*P - C_4*P^2 + C_5*P^3 + C_6$			
Parameter Estimates				
Parameters	***Estimate***	***Std. Error***	***95% Confidence Interval***	
			Lower Bound	***Upper Bound***
C1	8.665	.000	8.665	8.665
C2	-247.702-	78.048	-409.563-	-85.841-
C3	946.235	.000	946.235	946.235
C4	349.501	41.760	262.896	436.105
C4	33.222	3.927	25.078	41.366
C6	1093.443	35.227	1020.387	1166.499

Table 5-5 ANOVA for IDT Modeling

Source	***Sum of Squares***	***df***	***Mean Squares***
Regression	60869410.120	6	10144901.690
Residual	268556.843	22	12207.129
Uncorrected Total	61137966.960	28	
Corrected Total	2521154.147	27	

Dependent variable: IDT

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .893.

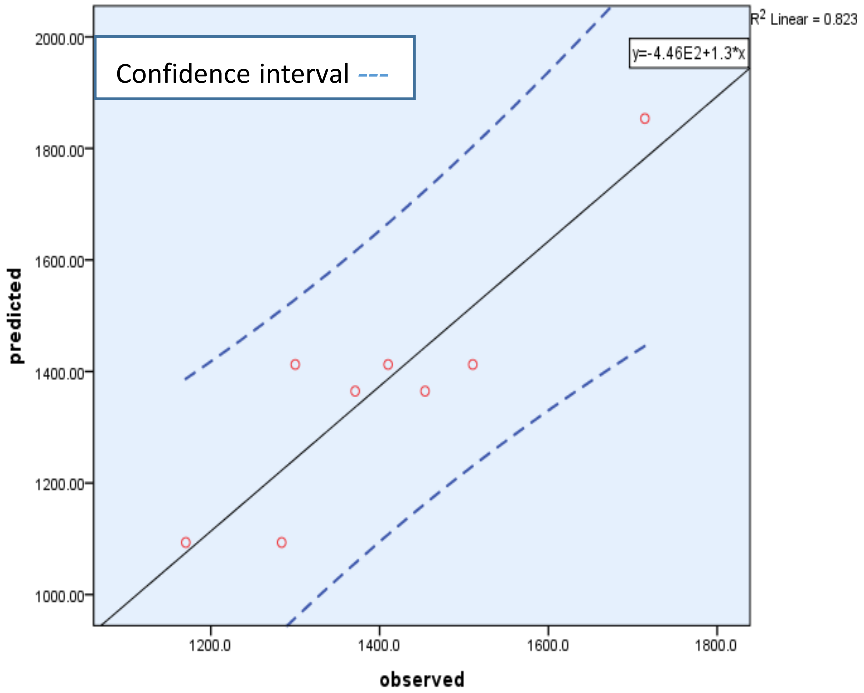

Figure 5-1 Comparisons between the Experimental and Predicted Values of the Indirect Tensile Strength.

5.5.2 Building the Tensile Strength Ratio Model

As mentioned previously the TSR was selected to build a model from other durability properties. This selection is based on the believe of the author that it is the most important parameter beside the ageing and abrasion which will initiate by coming research work. The analysis results of modeling TSR are shown in Tables (5-6, 7). Table (5-7) shows that the MS_E is low and the sum of residual is lower than the sum of regression which mean the significant of the model. From the same table, the high value of the R-Square is (0. 984) which indicates a perfect prediction, thus from this values a conclusion can draw that the developed model for TSR is good. Figure (5-2) illustrated the checking adequacy of the model and it indicates that acceptable scatter can recognize between predicted and observed TSR values. Furthermore, almost all value are within the significant level boundaries.

Table 5-6 Nonlinear TSR Modeling

Developed model	$TSR = C_1 + C_2*F - C_3*F^2 + C_4*P + C_5*P^2 - C_6*P^3$			
Parameter Estimates				
Parameters	***Estimate***	***Std. Error***	***95% Confidence Interval***	
			Lower Bound	***Upper Bound***
C1	7.902	2.641	2.426	13.378
C2	6.105	.299	5.485	6.725
C3	.123	.007	.108	.139
C4	1.815	1.299	-.879-	4.508
C4	.853	.585	-.360-	2.065
C6	.130	.065	-.005-	.265

Table 5-7 ANOVA for TSR Modeling

Source	***Sum of Squares***	***df***	***Mean Squares***
Regression	182043.027	6	30340.504
Residual	73.473	22	3.340
Uncorrected Total	182116.500	28	
Corrected Total	4512.929	27	

Dependent variable: TSR

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .984.

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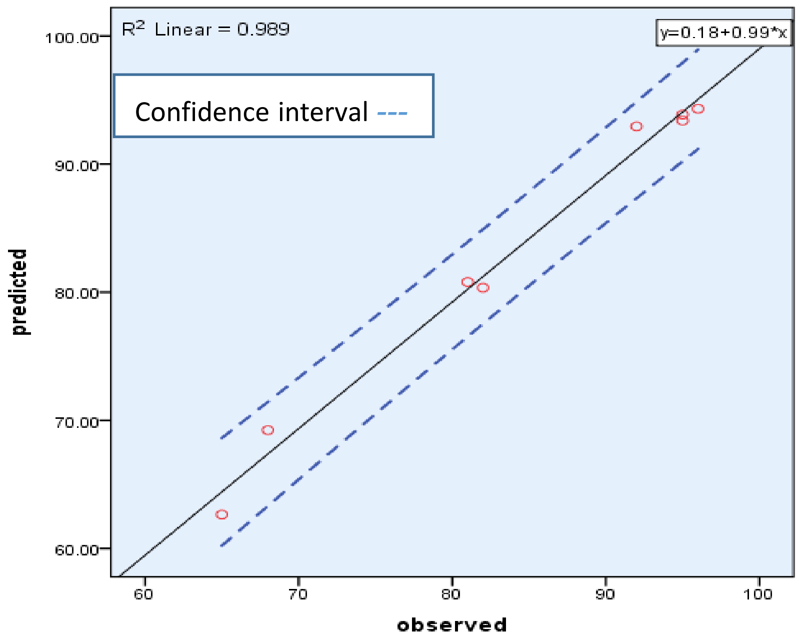

Figure 5-2 Comparisons between the Experimental and predicted values of the Tensile Strength Ratio.

5.5.3 Building the Bulk Density Model

As mentioned previously, the bulk density was selected to build a model from many others volumetric parameters. This selection is based on the believe that almost volumetric properties showed same trend with significant correlation. The analysis results of such modeling are as shown in Tables (5-8, 9). The analysis of the models includes the analysis of variance and goodness fitting between observed and predicted values. Figure (5-3) demonstrates the adequacy of the model and the following can be recognized form the analysis process:

- Table (5-8) shows the parameter of the developed model and its limitation with Confidence Interval of 95%
- Table (5-9) states that the MS_E is zero, which is good for the significance of the model
- Table (5-9) discloses that the sum of regression is higher than the sum of residue, which is sustained the significance of the model. While, from the same table, the high value of the R-Square (0.973) indicates a perfect prediction. Thus from these values, a conclusion can draw that the developed model for bulk density is good.
- Figure (5-3) indicates that an accaptable scatter between the pridicted and observed bulk density values. Furthermore, almost all values are within the boundaries of 95% Confidence Interval.

Table 5-8 Nonlinear BD Modeling

Developed model	$BD = C_1 + C_2{*}F + C_3{*}F^2 + C_4{*}P + C_5{*}P^2 + C_6{*}P^3 + C_7{*}(P/F) + C_8{*}P{*}F^3$			
	Parameter Estimates			
Parameters	***Estimate***	***Std. Error***	***95% Confidence Interval***	
			Lower Bound	***Upper Bound***
C1	2.328	.007	2.314	2.343
C2	.001	.001	-.001-	.003
C3	-2.333E-6	.000	-4.558E-5	4.092E-5
C4	.037	.003	.031	.043
C5	-.009-	.001	-.011-	-.007-
C6	.001	.000	.001	.001
C7	-.082-	.018	-.120-	-.045-
C8	-2.232E-7	.000	-3.244E-7	-1.221E-7

Table 5-9 ANOVA for BD Modeling

Source	Sum of Squares	df	Mean Squares
Regression	157.095	8	19.637
Residual	.000	20	.000
Uncorrected Total	157.095	28	
Corrected Total	.007	27	

Dependent variable: BD

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .973.

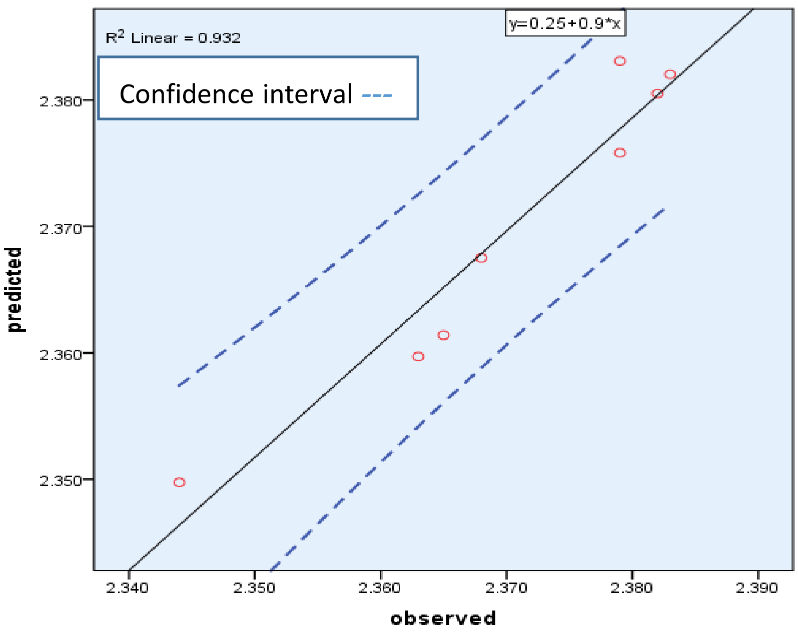

Figure 5-3 Comparisons between the Experimental and Predicted Values of the Bulk Density.

5.6 Summary

It is very valuable to conduct a statistical model which helps to understand the significant of the different parameters in characterizing the mechanical, volumetric and durability properties of the TAO mixtures. Building verified models help in predicting the performance characteristics for the TAO and save time and money. However, this chapter proved the ability to introduce an acceptable model to predict some TAO mixtures characteristics from mix component.

Chapter Six

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This research study focused on achieving possible investigations for characterizing the TAO using 9.5 mm NMAS with different filler types, further to the addition of modified SBS polymer with silica to improve the mechanical, durability and volumetric properties of the mixture.

6.2 Conclusions

According to the achieved research works, the main conclusions for this research are listed as below.

1. Traditional TAO mixtures (un modified) offer useful surface treatment technique for local use due to their mechanical, volumetric, durability and functional properties. For example, TAO mixtures showed high stability, high resistance to crack, good water damage resistance, good skid resistance and good resistance to permanent deformation, while the volumetric properties are within the acceptable rang of specification.
2. Mineral filler plays a critical role in the mechanical properties performance of TAO mixes. Among the three types of mineral fillers that used in this research, the utilizing of QL demonstrates significant positive effect on mechanical performance, whereas:
    - TAO with QL improving mix stability by approximate 2% and 12% with reference to that comprising of OPC or CMF respectively.
    - Introducing QL in TAO mixtures increase IDT by ٩% and ٣٩% with reference to that comprising of OPC or CMF respectively.
    - Introducing QL in TAO mixture enhance rutting resistance by ٣٣% and ٧١% with reference to that comprising of OPC or CMF respectively.

    - Similarly, other mechanical properties such as flow, creep compliance, and abrasion loss offer better performance when TAO mixture comprising QL.

3. durability properties are highly affected by filler type, whereas
    - Introducing QL in TAO mixtures increase the resistance to water damage by 4% and ٤٤% with reference to that comprising OPC or CMF, respectively.
    - Introducing QL in TAO mixtures reducing the abrasion loss by 15% and 18% for aged conditioned with reference to that comprising OPC or CMF, respectively.
4. Using PMB with stabilizer SBS polymer having inherently silica instead of neat asphalt in TAO mixtures leads to a significant improvements of binder properties, whereas penetration is decreased and this reflect on binder stiffness, Softening point of SBS modified asphalt are increased and high temperature viscosity is increased.
5. Modifying TAO mixtures with SBS appears to have significant improvement in the mechanical properties performance, whereas:
    - Compared with control TAO mix, TAO mixes with 2, 4, and 6% modified SBS show higher stability and lower flow. For example, the Marshall stability of TAO mixtures using CMF are increased by (118, 102, and 89%), and flow are decreased by (40%, 30, and 25%) respectively.
    - Compared with control TAO mix, TAO mixes with 2, 4, and 6% modified SBS show higher IDT. For example, the IDT of TAO mixtures using CMF are increased by (93, 43, and 40%).
    - Similarly, modified SBS improves the TAO performance in term of permeant deformation, creep compliance and skid resistance.
6. The volumetric properties of the mixture are also affected by modifying polymer SBS, whereas the bulk density is increased and the air void is decreased.
7. The durability properties of the TAO mixture are also affected by modifying polymer SBS, whereas:
    - Compared with control TAO mix, TAO mixes with 2, 4, and 6% modified SBS show higher resistance to moisture damage. For example, the TSR of TAO mixtures using CMF are increased by (14, 19, and 21%) respectively.
    - The abrasion loss of modified TAO mixture with 2, 4, and 6% SBS polymer were lower than the mixture with neat binder. For example, the Cantabro

loss of TAO mixtures using CMF are decreased by (5, 25, and 53%) respectively.

8. Among the three types of mixtures prepared with CMF, OPC and QL, using different modified SBS polymer i.e., 2%, 4% and 6% , the QL filler and 2% SBS had the highest stability, lowest flow and highest indirect tensile strength.
9. Using statistical modeling is achievable and offers a vital tool to describe the characteristics and performance of TAO mixture in terms of volumetric, mechanical and durability properties.

6.3 Recommendations.

Within the scope of this research work and the obtained data, several recommendations are presented as below:

1. TAO is a vital solution for surface treatment to increase the performance of the existing infrastructure network and the current study is highly recommended this type of surface treatment using available local raw materials
2. It is highly recommended to use QL as a mineral filler for TAO mixture, where the OPC could be a good alternative, but CMF is not recommended at all.
3. It is highly recommended to use modified SBS polymer instead of conventional SBS polymer for the preparation of TAO mixture. However, current asphalt plant has to modify to accommodate the preparation of modified binder introduction.

6.4 Further Work

Based on the laboratory experiments that obtained during this research, a number of possible future studies can be recommended, which are listed below:

1. Appling this mixture in site in order to compare the lab research sample characteristics with in-site samples, and explore TAO site performance.
2. SBS polymer have proven a good performance with TAO mixture. Trying to incorporate other types of polymers such as Ethylene vinyl acetate or cellulose fiber, individually or collectively, in such mixture is highly recommended to explore their effect on the properties of mixtures.
3. Sustainable filler material is highly recommended for future study to enforce the sustainability approach of asphalt paving industry.

4. Utilizing a suitable software to analysis the induced stresses for the thin mixes that demonstrate the scope effect of SBS polymer in increasing the resistance to various forms of traffic-induced stress.

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APPENDIX-A

STATISTICAL ANALYSIS

A.1 Correlation between Variables

Correlation is a statistical method that explains how strong the linking between two variables. For example, if we have information about the lengths and weights of certain people, we can know the relation between these two variables, by determining the correlation between them. Correlation coefficient is an index used to measure the correlation. The value of correlation coefficient ranges between -1 and 1. Some basic information about the correlation is essential to know before using SPSS for it calculating. Correlation types as following:

1. Negative and positive: When two variables move in the same direction, this is called a positive correlation, while the negative correlation occurs when a variable moves in a given direction and the other variable moves in the opposite direction of the first variable
2. Linear and nonlinear: The correlation is called a linear correlation when the first variable changes with the same ratio as the second variable, while the correlation is called a nonlinear correlation when the first variable changes by a different ratio than the second variable.
3. Simple and multiple: The correlation is called a simple correlation when only two variables are used for study whereas the correlation is called multiple when it takes into consideration several variables for correlation.

The correlation degree is classified as follow:

1. Perfect correlation when the first variable changes with the same ratio as the second variable.
2. Correlation with high degree when the correlation coefficient value is higher than 0.75.
3. Correlation with moderate degree when the value of correlation coefficient is between (0.5 - 0.75).
4. Correlation with low degree when the value of correlation coefficient is between (0.25-0.5).

5. There is no correlation when the correlation coefficient value rang is between (0-0.25).

A.2 Regression Analysis

Regression analysis is a statistical tool for investigating the historical relationship between an independent and a dependent variables to predict the future values of the dependent variables. The relationship is expressed through a statistical model equation that predicts a response (dependent) variable from a function of regression (independent) variables. It is used when a continuous dependent variable is to be predicted from a number of independent variables. Regression helps to estimate one variable or the independent variable from the other variables or the independent variables. In other words, this method can estimate the value of one variable, provided the values of the other variable given. The parameters are estimated so that a measure of fit is optimized.

- **Linear Regression Analysis**

The most commonly used form of regression is the linear regression and the most common type of linear regressions called ordinary least squares regression. Linear regression was the first type of regression analysis and to be used extensively in practical applications. Linear regression uses the values from an existing data set consisting of measurements of the values of two variables, X and Y, to develop a model that is useful for predicting the value of the dependent variable Y for given value of X. Linear regression is an approach for modeling the relationship between a dependent variable (Y) and one or more independent variables (X).

The regression equation is written as,

$$Y = a + bX + e \qquad \text{Equation } (7\text{-}1)$$

Where,

Y is the value of dependent variable, which needs to predict.

a or Alpha, a constant; equals the value of Y when the value of X = 0

b or Beta, the coefficient of X; the slope of the regression line; how much Y changes for each one -unit change in X.

X is the value of the independent variable, which is predicting the value of Y.

e is the error term; the error in predicting the value of Y, given the value of X.

- **Multiple Regression Analysis**

Multiple regressions are a technique that allows additional factors to enter the analysis separately, so that the effect of each can be estimated. It is valuable for quantifying the impact of various simultaneous influences upon a single dependent variable. Multiple regressions are an extension of simple (bi-aviate) regression. The goal of multiple regressions is to enable a researcher to assess the relationship between a dependent (predicted) variable and more independent (predictor) variables. The end result of multiple regressions is the development of a regression equation (line of best fit) between the dependent variable and several independent variables. It is used to predict the value of a dependent variable based on the value of two or more other variables.

When there are more than two variables available such as Y on X_1, X_2, X_3, X_4, in which Y is the dependent variable and the remaining variables are independent the equation can be written as in the given equation as below:

$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_{12}+ b_5X_{22}+ b_6X_{32} + b_7X_1X_2 + b_8 X_1X_3+ b_9X_2 X_3+$

Where:

b_0 is regression constant and b_1, b_2, b_3, b_4,... are regressions coefficient. The independent variables can be selected by the forward and stepwise regression methods.

- **Nonlinear regression analysis**

Nonlinear regression is a form of regression analysis in which dependent or criterion variables are modeled as a non-linear function of the model parameters and depends on one or more independent variables. The data are fitted by a method of successive approximations. Simple linear regression relates two variables (X and Y) with a straight line ($y = mx + b$), while nonlinear regression must generate a line (typically a curve) as if every value of Y was a random variable. The goal of the model is to make the sum of the squares as small as possible. The sum of squares is a measure that tracks how much observations vary from the mean of the data set. It is computed by first finding the difference between the mean and every point of data in the set. Then, each of those differences is squared. Lastly, all of the squared figures are added together. The smaller the sum of these squared figures, the better the function fits the data points in the set. Nonlinear regression uses logarithmic functions, trigonometric functions, exponential functions, and other fitting methods.

A.3 Some Definition about Statistical and Goodness of Fit

In order to more understanding performance of any model, it is required to understand some parameters of models, which are stated below:

- Coefficient of Determination (R^2): is a statistical measure of how close the data are to the fitted regression line. It is also known as the coefficient of determination, or the coefficient of multiple determination for multiple regression. The definition of R-squared is fairly straight-forward; it is the percentage of the response variable variation that is explained by a linear model. Or:

  R-squared = Explained variation / Total variation

  R-squared is always between 0 and 100%:

  0% indicates that the model explains none of the variability of the response data around its mean. 100% indicates that the model explains all the variability of the response data around its mean. In general, the higher the R-squared, the better the model fits your data.

- The residual (e): The difference between the observed value of the dependent variable (y) and the predicted value ($\hat{y}$) is called the residual (e). Each data point has one residual.

  Residual = Observed value - Predicted value

  $e = y - \hat{y}$ Equation (*7-1*)

- Analysis of variance (**ANOVA**): is a parametric statistical technique used to compare datasets. This technique was invented by R.A. Fisher, and is thus often referred to as Fisher's ANOVA, as well. It is used to compare means and the relative variance between them. However, analysis of variance (ANOVA) is best applied where more than 2 populations or samples are meant to be compared. The ANOVA test for significance of regression is usually summarized in a table, such as shown in Table (A-1)

Table 7-1 Analysis of Variance for Testing Significance of Regression

Source of Variation	***Sum of Squares***	***Mean Square***
Regression	SS_R	MS_R
Error or residual	SS_E	MS_E
Total	SS_T	

(SS_R) Regression sum of squares, or the model sum of squares

(SS_E) Error or residual sum of squares

(SS_T) Total of Sum squares

(MS_R) Mean Square of regression

(MS_E) Mean square of residual or error.

- Statistical significance: is the probability of finding a given deviation from the null hypothesis. This is commonly known as the “p value”. A small p-value basically means that your data are unlikely under some null hypothesis. A somewhat arbitrary convention is to reject the null hypothesis if $p < 0.05$.
- Confidence interval: describe the amount of uncertainty associated with a sample estimate of a population parameter. The confidence interval can take any number of probabilities, with the most common being 95% or 99%.

Also by SPSS can proved the terms of fit goodness of statistical model as: Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE), these calculate to compare the performance of estimation models.

It is important to evaluate forecast accuracy using genuine forecasts, the following terms used for this purpose:

- Root Mean Square Error (RMSE): is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are. In other words, it tells you how concentrated the data is around the line of best fit. Root mean square error is commonly used in climatology, forecasting, and regression analysis to verify experimental results.
- Mean Absolute Error (MAE): MAE measures the average magnitude of the errors in a set of predictions, without considering their direction. It is the average over the test sample of the absolute differences between prediction and actual observation where all individual differences have equal weight.

- Mean Absolute Percentage Error (MAPE): is a measure of prediction accuracy of a forecasting method in statistics, for example in trend estimation. It usually expresses accuracy as a percentage. Measures based on percentage errors have the disadvantage of being infinite or undefined if predicted value is zero or close to zero for any observation in the test set. However, if y_i is close to zero, $y_i^\wedge$ is also likely to be close to zero.

  The model is good when MAPE away close from zero (de Myttenaere *et al.*, 2016). Both the RMSE and the MAE are regularly employed in model evaluation studies (Chai and Draxler, 2014). A low RMSE value means that the error is characterized by a low dispersion. It can be assured of good model when the used model minimizes MS_E.

A.4 Mathematical Model

The some terms that mentioned above can be expressed mathematically as below:

$$SS_E = \sum_{i=1}^{n} e_i^2 = (y_i - y_i^\wedge)^2$$ Equation (*7-2*)

$$SS_T = SS_R + SS_E$$ Equation (*7-3*)

$$R^2 = 1 - \frac{SS_E}{SS_T}$$ Equation (*7-4*)

$$MS_R = \frac{SS_R}{k}$$ Equation (*7-5*)

$$MS_E = \frac{SS_E}{n-p}$$ Equation (*7-6*)

$$MAE = \frac{\sum_{i=1}^{n} |y_i - y_i^\wedge|}{n}$$ Equation (*7-7*)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - y_i^\wedge)^2}{n}}$$ Equation (*7-8*)

$$MAPE = \frac{1}{n} * \frac{\sum_{T=1}^{P} |y_i - y_i^\wedge|}{y_i}$$ Equation (*7-9*)

Where:

y_i : Observation value

$y_i^\wedge$: Predicted value

y^- : Mean of observed values

n: Number of samples, 1,2,….

k: Number of regressor variables

p: Number of parameters

الخلاصة

على مدى العقود الماضية, قامت إدارات النقل والطرق السريعة في اوربا والولايات المتحدة بتغيير سياستها من بناء طرق جديدة الى زيادة إمكانيات البنى التحتية القائمة عن طريق الصيانة وإعادة التأهيل باستخدام العديد من تقنيات الحفاظ على الأرصفة مثل slurry seal, chip seal, microsurfacing, fog seals و thin asphalt overlay (TAO). يمكن ان تُعرف هذه التقنيات بأنها مجموعة من الممارسات الفعالة من حيث التكلفة حيث تهدف الى إطالة عمر الرصيف وتحسين السلامة . تعتبر طبقة اعادة الاكساء الرقيقة (TAO) عموما على انه افضل تقنية بالنسبة لتقنيات معالجة وصيانة الأرصفة. تكون بالعادة طبقة TAO بسمك ٣٨,١ ملم او اقل ويكون الركام المستخدم في هذه الطبقة (١٢,٥ ملم او اقل كمقاس اسمي اعظم للركام). يوفر TAO حل اقتصادي بالنسبة للطرق التي تحتاج الى حماية وإعادة تأهيل وأيضا تعتبر التقنية الوحيدة التي تعمل في الوقت نفسه على تحسين مقاومة الرصف الهيكلية وبالتالي إطالة خدمة الرصيف. ولا بد من ذكر تم تنفيذ هذه التقنية من قبل عدة وكالات نقل و بنجاح متفاوت.

مع ذلك فأن توصيف أداء الخلطات TAO لايزال تحت التحري و الاستقصاء من قبل الباحثين ووكالات الطرق السريعة في جميع انحاء العالم ولهذا ركز هذا البحث على تحديد خصائص طبقة TAO المناسبة لشبكة الطرق المحلية التي توفر مقاومة مقبولة للتطاير والتشققات ومقاومة الانزلاق عن طريق اختيار الخلطة المثالية.

في هذه الدراسة ، شمل البرنامج التجريبي: تصميم خلطات TAO باستخدام تدرج واحد (٩,٥ملم) وثلاثة أنواع مختلفة من المواد المالئة (CMF, OPC, QL) وخمسة نسب من محتوى الاسفلت لتحديد المحتوى الأمثل ثم يتم إضافة البوليمر SBS لتحسين أداء الخلطة بثلاث نسب هي (٢, ٤, ٦%) من محتوى الاسفلت. تم اجراء فحوصات مختلفة حجمية وميكانيكية وفحوصات الديمومة لتحديد الاختلاف في خصائص خلطات TAO .

كشفت النتائج أن نوع الفلر له تأثير كبير على أداء الخلطات الإسفلتية TAO من حيث الخواص الميكانيكية والديمومة والحجمية. على سبيل المثال، أظهر الخليط الذي يحتوي على QL زيادة في الاستقرار، وقوة الشد غير المباشرة ، وصلابة الزحف ، والاستقرار الديناميكي بنسب (١٢ ، ٣٩ ، ٧٥ ، ٧١٪) على التوالي عند مقارنته بالمخلوط الذي يشتمل على CMF. من ناحية أخرى، أدى إضافة البوليمر المعدل SBS إلى الاسفلت بثلاث نسب مئوية إلى تحسن كبير في الخواص الميكانيكية وقوة التحمل مثل صلابة الزحف، مقاومة الانزلاق ومقاومة التدوير، وفقدان التآكل ومقاومة تلف المياه. أظهرت نسبة ٢٪ SBS كمثال زيادة في الاستقرار وقوة الشد غير المباشرة (١١٨، ٧,٨، ١٥٪)، (٩٣، ٣٥، ٣٨٪) على التوالي مقارنة مع النسبة الأخرى من SBS عند استخدام مواد مالئة نوع .(CMF) تجدر الإشارة إلى أن نمذجة بعض هذه الخصائص تم تحقيقها والتحقق منها لغرض التنبؤ. ومع ذلك ، كشف البرنامج التجريبي والتحليلي الشامل عن استنتاجين حيويين وهما القدرة على إنتاج خلائط الإسفلت الرقيقة عالية الأداء باستخدام المواد المحلية مع بعض الإضافات ، وحساسية أداء هذه المزيج لمحتواها النوعي.

جمهورية العراق
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دراسة خصائص طبقة اعادة الاكساء الاسفلتية الرقيقة للطرق السريعة

رسالة مقدمة الى قسم الهندسة المدنية, جامعة كربلاء وهي جزء من متطلبات الحصول على درجة الماجستير في الهندسة المدنية (هندسة البنى التحتية)

من قبل :
موسى زكي يحيى
بكلوريوس في علوم الهندسة المدنية لسنة ٢٠١١-٢٠١٢

بأشراف
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