REPUBLIC OF TURKEY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF CIVIL ENGINEERING

SKID RESISTANCE PERFORMANCE EVALUATION OF CHIP SEALS BASED ON DIFFERENT AGGREGATE TYPE, SIZE AND POLISHING LEVELS

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Master of Science, Department of Civil Engineering

March 2019, 82 pages

ABSTRACT

In this thesis, chip seals manufactured at laboratory conditions which skid resistance performances were evaluated in case of different aggregates features including their origin, chip sizes and different polishing levels with utilizing different standard test methods. For this purpose, five types of aggregates in different morphologic origins including natural aggregate and industrial by-products were used. Originally, limestone, basalt and river basin crashed stone were supplied as natural aggregates, while electric arc furnace slag and ferrochromium slag samples were as artificial one. Each aggregate property was characterized in terms of physically, mechanically and chemically. To provide polished aggregates at different levels, a standard procedure was identified based on Micro-Deval abrasion test method. Different polishing levels for aggregates were achieved for two different revolutions (10500 and 31500) following American Society for Testing and Materials (ASTM) D 6928. Aggregate particle sizes chosen for manufacturing chip seals were 8-10 mm and 10-12 mm. Aggregate's surface at each polishing level were monitored via scanning electron microscope. The mean-texture depths and skid resistance of each sample were found out according to relevant ASTM standards of outflow meters, dynamic friction tester and British pendulum tester. Mean profile depths and international friction index parameters (F(s), Sp) were calculated to make correlative analyses between each test method. In consequence, in terms of skid resistance performance of chip seals, it was clearly revealed that slags have superior features against natural aggregates at every polishing level and aggregate size. Accordingly, utilizing slags at chip seals may not only provide higher skid resistant surface, but also ensure environmental and economic benefits. Lastly, correlations between the test methods ranging from 0.55 to 0.76 were found.

Keywords: *Chip seals, polishing, pavement texture, skid resistance, dynamic friction tester, international friction index, British pendulum, aggregate, metalurgical slags*

SATHİ KAPLAMALARDA KAYMA DİRENCİ PERFORMANSININ FARKLI AGREGA TÜR, BOYUT VE CİLALANMA SEVİYESINE BAĞLI OLARAK İNCELENMESİ

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Yüksek Lisans, İnşaat Mühendisliği Bölümü

Mart 2019, 82 sayfa

ÖZET

Bu tez çalışmasında, farklı tür agregalarla farklı boyutlarda ve cilalanma seviyelerinde laboratuvar ortamında üretilen sathi kaplamaların kayma direnci performansları, farklı standart test metotları kullanılarak incelenmiştir. Bu amaçla, Türkiye'nin farklı bölgelerinden farklı morfolojik kökenlere sahip kireç taşı, bazalt ve dere malzemesi gibi doğal agregalar ve elektrik ark fırın çelik ve ferrokrom cürufu gibi endüstriyel yan ürünlerden oluşan 5 farklı agrega temin edilmiştir. Her bir agrega fiziksel, mekanik ve kimyasal özelikleri bakımından karakterize edilmiştir. Farklı seviyelerde cilalanmış agrega elde etmek için ASTM D 6928 bağlantılı olarak Micro-Deval aparatı iki farklı çevrim koşulunda (10500-31500) kullanılmıştır. 8-10 ve 10-12 mm olmak üzere iki farklı agrega boyutu, sathi kaplamaların üretilmesinde kullanılmıştır. Her cilalanma seviyesinde, agregaların yüzeyleri taramalı elektron mikroskobu ile görüntülenmiştir. Sathi kaplama numunelerinin ortalama doku derinliği ve kayma direnci değerleri akış ölçer, dinamik sürtünme ölçer ve İngiliz pandülü kullanılarak ilgili ASTM standartlarına göre belirlenmiştir. Ortalama profil derinliği ve uluslararası sürtünme indeksi parametreleri (F(s), Sp), test yöntemleri arasında bir ilgileşim analizi yapmak için hesaplanmıştır. Sonuç olarak, cüruflar ile üretilen sathi kaplamaların kayma direnci performansının doğal agregalar ile üretilenlerinkinden, tüm cilalanma seviyelerinde ve agrega boyutunda, daha iyi olduğu gözlenmiştir. Buna göre, sathi kaplamalarda cürufların kullanılması ile sadece kayma direnci yüksek yüzeyler elde edilemeyecek aynı zamanda çevresel ve ekonomik faydalar sağlanabilecektir. Son olarak, test yöntemleri arasında 0.55 ile 0.76 aralığında değişen farklı değere sahip ilgileşimler bulunmuştur.

<u>Anahtar Kelimeler:</u> *Sathi kaplamalar, cilalanma, kaplama dokusu, kayma direnci, dinamik sürtünme ölçer, uluslararası sürtünme indeksi, İngiliz pandülü, agrega, metalurjik cüruflar.*

ACKNOWLEDGEMENTS

First and foremost, I would like to express my gratefulness to Allah Almighty for his blessing and kindness that he gave me health and strength until the completion of this thesis.

With great honor, I would like to express my utmost and sincere gratitude to my supervisor, Assoc. Prof. Dr. Volkan Emre UZ for his selfless guidance, suggestions, encouragement and support to complete this thesis. I deem myself very lucky to have the chance of working with him. I do also appreciate very much his understanding and helpfulness with my academic development, for his valuable comments, insights and fast feedback. He always made wise suggestions and devoted his time whenever I needed.

I also would like to gratefully acknowledge financial support from the Scientific and Technological Research Council of Turkey-TUBITAK (Project No: 215M049), since this thesis was established on the extended part of studies in the scope of project idea.

The success of this thesis has been possible through the cooperation and assistance of a number of dedicated people. I would like to express my appreciation to every organizations and individual who supported me to complete this study. Specially, I am also greatly indebted to Res. Assistant İslam GÖKALP, Yağmur ÖZİNAL, MSc student Hüseyin GÜNDOĞAN and Assoc. Prof. Dr. Tayfun Yusuf YÜNSEL, Chemist Esin ATEŞÇİ, Res. Assistant Fatih ÇAVUŞLU for their kind support and offering help whenever needed. I would like to express my gratitude to Mehtap TEPE who is a research engineer at the department of Chief Engineering of Research and Development of 5th Regional Directorate of Highways and the whole staff of the department for assistance in supplying of material. Also, my appreciation also extends to the technicians of General Directorate of Highways in Ankara. I am also grateful to all thesis jury members for accepting to read and review this thesis and for their invaluable suggestions.

Last but not least, I would like to pay my appreciation to my beloved family and friends for their love and care, and also the encouragement all the time. I would like to express my special thanks to my dearest sainted father, Yusuf ERGİN, my dear alive mother, Elif ERGİN, who is, thank to Allah, alive, accompanied me whenever I needed, and always supported me during each steps I took throughout all my life. And I would like to express my eternal thanks to my dear wife, Nazlı ERGİN, and my dear son, Yiğit Yusuf ERGİN, for their patience, invaluable supporting, loving, caring, praying to me throughout this study.

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NOMENCLATURE

ASTM	American Society for Testing and Materials
CEN	European Committee for Standardization
WHO	World Health Organization
TSPA	Turkish Steel Producer Association
GDH	General Directorate of Highway
HTS	Highway Technical Specification
MTDs	Macro Texture Depths
BPN	British Pendulum Numbers
BPT	British Pendulum Tester
RNs	Revolution Numbers
OFM	Outflow Meter
OFT	Outflow Time
EAF	Electric Arc Furnace
SFC	Sideway Force Coefficients
DFT	Dynamic Friction Tester
IFI	International Friction Index
MSC	Magnesium Sulphate Value
SMA	Stone Mastic Asphalt
MD	Micro-Deval
XRD	X-Ray Diffractions
XRF	X-Ray Fluorescent
SEM	Scanning Electron Microscope
AIMS	Aggregate Imaging Systems
PSV	Polish Stone Value
RTM	Road Test Machine
LA	Los Angles
$MgSO_4$	Magnesium Sulphate
ASR	Aggregate Spreading Rate
ALD	Average Least Dimension
W_{24}	Water Absorption at 24 Hours Duration
Rpm	Revolutions per Minute
AD	Apparent Density

ODD	Oven Dry Density
SSDD	Saturated Surface Dry Density
δ	Slip Angle
^{o}C	Celsius Degree
h	hour
kW	kilo Watt
kN	kilo Newton
kph	kilometer per Hour
kg	kilogram
g	gram
l	liter
mm	millimeter
kg/m^3	kilogram per cubic meter

CHAPTER 1. INTRODUCTION

Traffic accidents are the main problem of highway transportation mode, with which the great majority of goods and passengers are carried, especially in Turkey. In Turkey, over 1.2 million traffic accidents occurred in year 2017. Among all those accidents, about 1 M accidents were with material loss and 0.2 M of them were with death or injury (TUIK, 2017). Due to traffic accidents, deaths/injuries of the people reach up to thousands. Consequently, financial loss is arisen as a results of loss of labor and properties. Many statistics, reports and researches (Hayakawa et al., 2000; Karlaftis and Golias, 2002; Lankarani et al., 2014) showed that road accidents are a complex issue and there are many reasons that affect traffic accident rate and severity. The reason may be based not only on faults of drivers or human in general, but also on road defects, environmental conditions and vehicles features. Human faults has the greatest rate; however, road defects have also a significant role within the factors those cause traffic accidents (Akçay, 2011; Uz and Gökalp, 2017b). Due to traffic loadings, environmental conditions, inadequate maintenance-rehabilitation and road surface distresses, pavement surfaces are deteriorated throughout service life (Sarsam and Al Shareef, 2015).

Slip type accidents, one of road faults factors that this study focused on, are the most common road faults and caused traffic accidents. Friction force formed while tire spin throughout the road surface is specified as skid resistance. This resistance is known as one of the priority effects that influence pavement safety, particularly at wet weather conditions (Rezaei et al., 2011; Tighe et al., 2000). Rising of the traffic crashes is occurred due to lack of skid resistance, especially in wet weather condition. (Fwa and Ong, 2008; Mayora and Piña, 2009; Meyer, 1991; Ong and Fwa, 2007). Reduction in skid resistance may be affected by numerous factors including type of pavements, properties and amount of aggregates and bitumen (Asi, 2007; Do and Cerezo, 2015; Fwa et al., 2003; Kogbara et al., 2016).

Earlier studies (Andriejauskasa et al., 2014; Artamendi et al., 2013b; Mayora and Piña, 2009; Sandberg and Descornet, 1980) indicated that pavement surface texture certainly affects the skid resistance performance of the pavement during its service life. Rehabilitation of skid resistance can provide a decrease in traffic crashes, by means of micro and macro levels (Ahmedzade and Sengoz, 2009; Chang and Wang, 2006; Xiao et al., 2000). Road safety and quality is widely affected by a road-related feature that is known as texture (Davis, 2001; Freitas et al., 2008). Deflections of the road surface from a true plane is qualified as pavement surface texture. Micro texture, macro texture, mega texture and unevenness are the four main categories for the pavement surface in terms of texture wavelength and amplitude (Association; Bitelli et al., 2012; Hall et al., 2009). Macro and micro textures both influence pavement surface skid resistance. Micro texture ensures direct tire-pavement contact, which is an aggregate mineralogy function and coaction with traffic and climate agents. On the other hand, macro-texture ensures the hysteresis component of the friction and allows for quick drainage of water on the pavement surface. In general, the resistance against skidding on a road surface is dominantly affected by the micro texture of pavement. However, adequate drainage improves the contact between the tire and the surface and therefore this reduce the probability of hydroplaning, and this shows the importance of macro-texture (Cafiso and Taormina, 2007; Do and Cerezo, 2015; Hegmon and Mozoguchi, 1900; Huang, 2010; Luce et al., 2007; Tighe et al., 2000; Uz and Gökalp, 2017b). To evaluate surface texture features, there are numerous methods that developed based on different operating principles by researchers and/or agencies. One of them may be utilized portably and statistic, on the other hand, some of them may be dynamically and vehicle connected based. Sand patch method and outflow meter (OFM) give mean texture depths (MTDs) and circular texture meter (CTM) and laser based vehicle mounted equipment methods give a result as mean profile depths (MPDs) (Andriejauskasa et al., 2014; Fisco and Sezen, 2013; Gökalp and Uz, 2017a; Nataadmadja et al., 2015; Sezen and Fisco, 2013; Wallman and Åström, 2001b). In the scope of this thesis, OFM was utilized owing to their portability, cheapness and simplicity. Beside, utilizing a correlational equality referred in (ASTM, 2012b; ASTM, 2012d) to calculate MPDs values from CTM by the values of MTDs gathered with Outflow meter Test Method. Outflow meter test method can be explained as flowing time measurement of a certain volume of water drainage from a specialized cylinder to the road surface (Doty, 1975; Kim and Lee, 2005; Meyer, 1991). Pavement types including flexible and rigid ones is also indicated important task. For prophylactic operation of present pavements and/or covering low volume roads, surface coating (type of flexible pavement) is thoroughly utilized. In pavement engineering, skid resistance has an important role on safety of pavements and it is being protected and recovered by surface coating (Cafiso and Taormina, 2007; Saykin et al., 2012b). Chip seal evaluated in the scope this study is a type of surface coating used for different engineering purposes including surface course and/or extending the service life with restoring texture of existing pavements. Chip seal consists of laying bituminous, mostly, binder and spreading aggregates on a pavement surface. Against to other conservation and reclamation, chip seals are common surface coatings type in terms of its low cost, operative, environment and being easy to apply (Adams and Richard Kim, 2014; Cenek and Jamieson, 2005; Gransberg et al., 2005b; Praticò et al., 2015; Uz and Gökalp, 2017b; Wilson and Black, 2008; WSDOT, 2016; Zoghi et al., 2010). Turkey, Australia, the United Kingdom, New Zealand, Canada, South Africa are some of the countries which have been using chip seals on their pavement design widely. For instances, they consist of 95%, 75-78% of the total road network of New Zealand and Turkey, respectively (Gransberg et al., 2005a; Karasahin et al., 2011; Terzi et al., 2013; Transit New Zealand (TNZ) et al., 2005; Uz and Gökalp, 2017b; Wilson and Black, 2008).

Pavement skid resistance is known as a hard and complex work. For the purpose of achieving the most proper value for skid resistance at any sort of road surface, many apparatus and/or technique that gives dissimilar value for the same road surface have been improved for years (Artamendi et al., 2013a; Fwa et al., 2003; Kogbara et al., 2016; Mayora and Piña, 2009; Ong and Fwa, 2007). The coefficient of friction, which gives an idea about skid resistance of the pavement surface between tires and road surfaces, can be found directly. Skid resistance measurement methods and/or devices may be categorized into three main group according to their implementing rule. These are Stationary or Slow-Moving measurement, Longitudinal Friction Coefficient measurement and Sideway Force Coefficient measurement and Sliders methods (Andriejauskasa et al., 2014; Do and Roe, 2008; Sandberg and Descornet, 1980). In this thesis, laboratorial based methods were followed. For this reason, methods included the last measurement principle were utilized. The last operating principle that comprises methods used for stationary condition and preferable in laboratory. With these concerns in mind, British Pendulum Tester (BPT) and Dynamic Friction Tester (DFT), which use rubber sliders, but have different operating principles were utilized. The other concern is to make an evaluation skid resistance performance at different speeds. Since, DFT can give friction coefficients up to 80 kph speeds, while BPT generates a skid resistance performance in term of British pendulum number (BPNs) at speed 10-20 kph (Kogbara et al., 2018; Kogbara et al., 2016; Saito et al., 1996). For the classification of friction properties of pavement surfaces, some reference scale has also been developed (Güneş and Topal, 2017). One is well-known as International Friction Index (IFI) that being developed by PIARC-World Association, and this value for each samples were also calculated in the present study.

Aggregate has a widely application range in almost every area of the infrastructure as it is an all-purpose material. It can be obtained from nature or by unnatural methods and makes up large portion of construction works, especially pavement construction (Uz and Gökalp, 2017b). Due to the increasing number of human population, the need for construction, infrastructure and their maintenance is increasing and this increases the consumption of natural resources in general and natural aggregates in particular (Gökalp et al., 2018). Consequently, for a sustainable transport, decreasing the utilization of natural material and finding an alternate material for pavement structure from refuse materials has been an interesting area to investigate. The objective is to substitute natural aggregates with alternative materials without sacrificing structure performance.

Utilizing waste materials by means of industrial by-products such as meteorological slags and construction and demolition waste aggregates supply a possible helpful usage in the construction area (Arribas et al., 2015; Aschuri and Yamin, 2011; Buzatu et al., 2015; Fronek, 2012b). Until now, many research has been done by scientists about the potential uses of slags. For instances, Bessa et al. (2014), Yonar et al. (2015), Gökalp et al. (2018), Chaurand et al. (2007); Motz and Geiseler (2001); Proctor et al. (2000); Xirouchakis and Manolakou (2011), Kehagia (2009), Sorlini et al. (2012), Wu et al. (2007), Krayushkina et al. (2012), Lind et al. (2001); Yilmaz and Sütaş (2008), Khan and Wahhab (1998) and Ziari and Khabiri (2007) investigated not only physical, mechanical, chemical characteristics of metallurgical slags and their influence on the environment, but also potential areas of usage and their performances in those area. Results of those studies showed that slags' technical features meet with the relevant specifications and the harmful effect to the environment is not observed, since they were identified as inert or non-hazardous materials. With the production capacity in excess of 50 million tons steel, Turkey is the 8th biggest country in steel production and as a result of this production approximately 7 million tons of slag (10-15 % of total steel production) could come out. (Gökalp et al., 2018)As mentioned before that slag is valuable materials. Despite this knowledge, the use of slags is not used practically in Turkey because of various legal reasons and environmental concerns. This is may be one of main reason for stoking such valuable materials in waste storage fields. The need to reduce both the environmental and technical concerns in the light of science, more studies must be done in Turkey to detect the potential utilization of slags in pavement layers In the scope of this thesis, ferrochromium slags and electric arc furnace steel slags (EAFs) in chip seals were appraised accordingly.

Skid resistance performances of chip seals manufactured at laboratory with dissimilar sizes, kinds of aggregate and in case of different polishing levels was evaluated with utilizing various test methods in this thesis. For this purpose, five type of aggregates in different morphologic origins including three natural (river basin crashed stone, limestone and basalt), and two industrial waste products (electric arc furnace steel and ferrochromium slag) samples were supplied from different countries located in different zones of Turkey. Each aggregate was characterized in terms of physical, mechanical and chemical features based on related EN standard test methods. Aggregate samples used for chip seal production are considered in two-particle size. These were 8-10, and 10-12 in mm both for unpolished and polished chip seal samples. Micro-Deval abrasion test was utilized, according to ASTM D 6928 (ASTM, 2012f), in case of two different revolutions (10500 and 31500) to provide polished aggregates at different levels. Aggregate's surface at each polishing level were monitored via scanning electron microscope. Chip seal samples, thirty in total, were prepared on steel plates with certain dimension with a standard method. Following a standard production, macro-texture depths by means of MTDs were found out according to relevant ASTM standards of OFM (ASTM, 2012e). DFT and BPT methods were utilized according to (ASTM, 2009; ASTM, 2012a). Moreover, international friction index parameters (F(s), Sp) were calculated to make correlative analyses between each test methods based on the MPDs and friction coefficient gathered by DFT at different speeds (ASTM, 2012b). Adhering to all analysis and results, the influence of aggregate size, kind and polishing level to skid resistance on chip seal samples were evaluated.

CHAPTER 2. LITERATURE REVIEW

2.1 Traffic Accidents and Their Reasons

A report related to traffic safety published by World Health Organization, traffic accident statistics demonstrates the total amount of road traffic deaths in all over the world occur 1.25 million (m) annually. Data indicate in all over the world predicted 3% of Gross Domestic Product (GDP) is lost to road traffic deaths and injuries. Moreover, in low- and middle-income countries, road traffic deaths and injuries are predicted to induce economic losses of up 5% of GDP (WHO, 2018), which clarified expense of worldwide traffic accidents is predicted over US$ 500 billion (Aeron-Thomas et al., 2000). In the road network of Turkey, about 1.2 m traffic accidents occurred in total during year 2017. Among these, about 1.0 m accidents were returned with only material loss while 0.2 m of them were resulting with death or injury (TUIK, 2017).

Many studies (Ahammed and Tighe, 2009; Andreescu and Frost, 1998; Edwards, 1999; Hayakawa et al., 2000; Híjar et al., 2000; Karlaftis and Golias, 2002; Lankarani et al., 2014; Mayora and Piña, 2009; Tighe et al., 2000; TUIK, 2017; Xiao et al., 2000) indicated that numerous agents such as traffic operations, driver actions, faults from pavement geometrics, safety measures, speed limits, vehicle functions and pavement related engineering are all agents those effect road accidents. Therefore, traffic safety is subjected to and interacted together with extensive and complicated dimensions which the and as a result needs assorted information and experiences (Pakgohar et al., 2011). Factors influence the traffic safety are categorized as driver behavior (Drivers tiredness, alcohol state, lack of seat belt usage, etc.) road geometric features (alignments, curves and type of crossing) and vehicles factors (speed, mobility, vehicle safety). As a result of integrated influences such as environmental, behavioral and technological agents traffic accidents occurs (Abdel-Aty and Radwan, 2000; Akçay, 2011; Edwards, 1999; Hayakawa et al., 2000). However, the factors mentioned above can be given under three headings: (1) driver, (2) road-environment and (3) vehicle agents (Uz and Gökalp, 2017b), and they are included approximately 90%, 25% and 10% of crashes, respectively (Austroads, 2002; Híjar et al., 2000). Herein, it can be concluded that a traffic accident is a combination of several factors.

According to statistical data, environmental factor and vehicle factor has 70.5% and 31.5% portion of all accidents, respectively (Pakgohar et al., 2011).

Due to poor maintenance and restoration operation, vehicle usages and environmental circumstances pavement surfaces may get out of order (Sarsam and Al Shareef, 2015). One of the main factors influencing traffic safety is the friction between the vehicles' tires and the road surface (Wallman and Åström, 2001b). Slip type accidents, one of road-environment factors that this study focused on, are the most common road fault caused crashes. Skidding is caused by inadequate friction between the vehicles' tires and the road surface. Inadequate friction of road surfaces might cause a quite a hazard environments for highway safety (Tighe et al., 2000). Certainly, for traffic safety causes, pavement friction and surface conditions are the most widespread indices.

Friction force formed while tire spin throughout the road surface is specified as skid resistance. This resistance is known as one of the priority effects that influence pavement safety, particularly wet surface skidding crashes possibility (Rezaei et al., 2011; Tighe et al., 2000). Pavement skid resistance is a complex task and affected by many factors e.g. road surface properties, tire properties and climatic and environmental conditions (Kogbara et al., 2018; Kogbara et al., 2016). Previous reports and studies have discussed that surface texture is one of the most effective factors influencing performance of the skid resistance of a pavement and rehabilitation of the properties of the road surface may ensure a decline in traffic accidents (Ahmedzade and Sengoz, 2009; Chang and Wang, 2006; Xiao et al., 2000). Also making improvement on road surface features and highway safety of traffic may provide a reasonable decrease on deaths and injuries rate of traffic crashes (Sengoz et al., 2012) (Chang and Wang, 2006).

Furthermore, a considerable reduction in traffic accident can be obtained by restoring pavement skid resistance performance. For instance, 60% reduction in traffic accidents can be achieved with restoring pavement skid resistance from 35% to 48%. As one of the important surface properties that influence traffic accidents, skid resistance is underlined in this thesis. Thus, the importance of skid resistance will be figured out. Its significance is clearly seen from previous studies (Abdel-Aty and Radwan, 2000; Al-Masaeid, 1997; Andreescu and Frost, 1998; Ansari et al., 2000; Edwards, 1999; Hayakawa et al., 2000; Híjar et al., 2000; Karlaftis and Golias, 2002; Lankarani et al., 2014; Mayora and Piña, 2009; Saplioglu et al., 2013; Vlahogianni et al., 2012; Xiao et al., 2000) traffic accident rate raises while skid resistance decreases.

2.2 Pavement Surface Textures and Texture Depth Measurement Methods

2.2.1 Pavement Surface Textures

In pavement operating system, estimation of the lifetime and performance of pavement type is significant for highway engineers. Highway traffic safety and functional quality of the pavement are widely affected by surface texture. Surface wear and voids, aggregate size and gradation, aggregate mineralogy and road construction techniques are all the features those have an influence on surface texture (Bitelli et al., 2012; Gökalp and Uz, 2017b)According to amplitude and wavelength, road surface texture is classified into four type as they can be seen visually in the Figure 2.1, which is defined as "the minimum distance between periodical repeated parts of the curves" as micro texture, macro texture, mega texture and unevenness (Bitelli et al., 2012; PIARC, 1987b; Wambold and Henry, 1994).

In addition, friction, wearing, noise, drainage etc. are considerable features of the surface texture. Moreover, the interaction phenomena depend on the exercise conditions such as speed most significant properties of road pavement, affected, dimension, mass and suspension of vehicle, road characteristics, and environmental conditions etc. and depending on wavelength of roughness or unevenness. A proposal for identification of relationship between fields of texture types and interaction phenomena was presented by the World Road Association (PIARC, 1987b). One of the main surface texture types mentioned above is micro texture and it is identified as surface texture of each singular aggregate particle, while macro texture is defined as the sizes of the aggregate particles separately and gaps among them. Other surface texture type, mega texture, is known as large-scale deterioration and failure on the pavement surface. Also, there is a continuity in disorders of the pavement surface from micro texture to macro texture (Bitelli et al., 2012; Henry, 2000; Kogbara et al., 2016; Kokkalis et al., 2002).

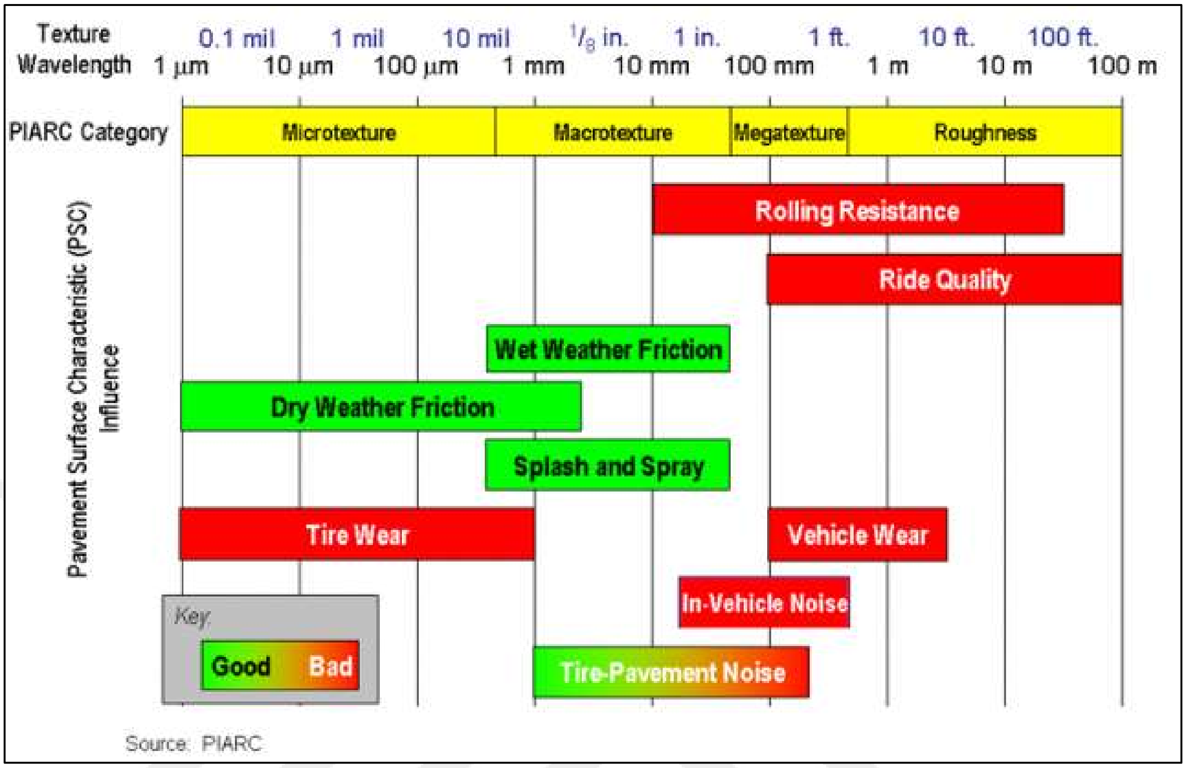
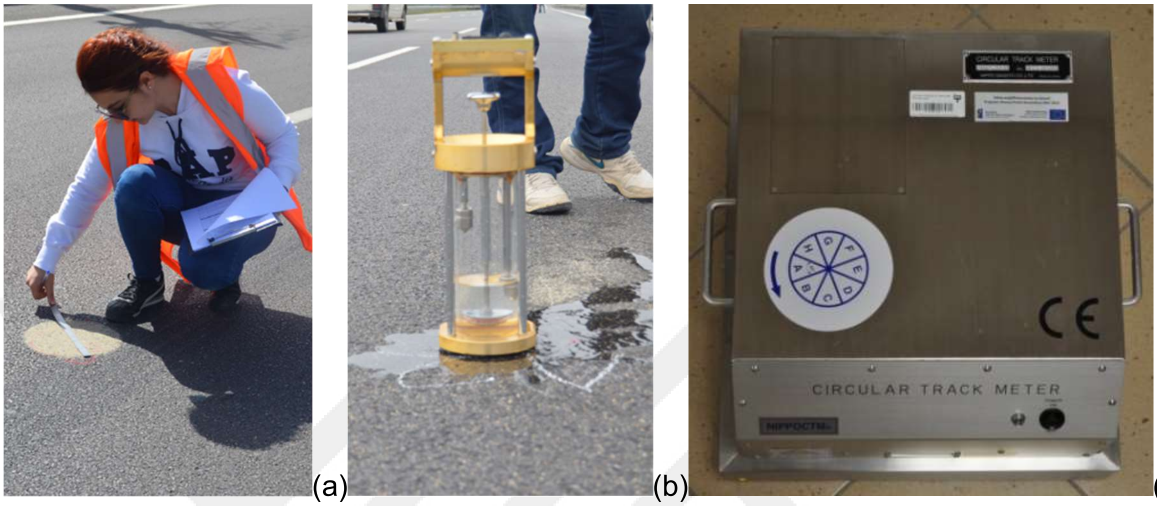


Figure 2.1 Pavement texture and surface characteristics influences

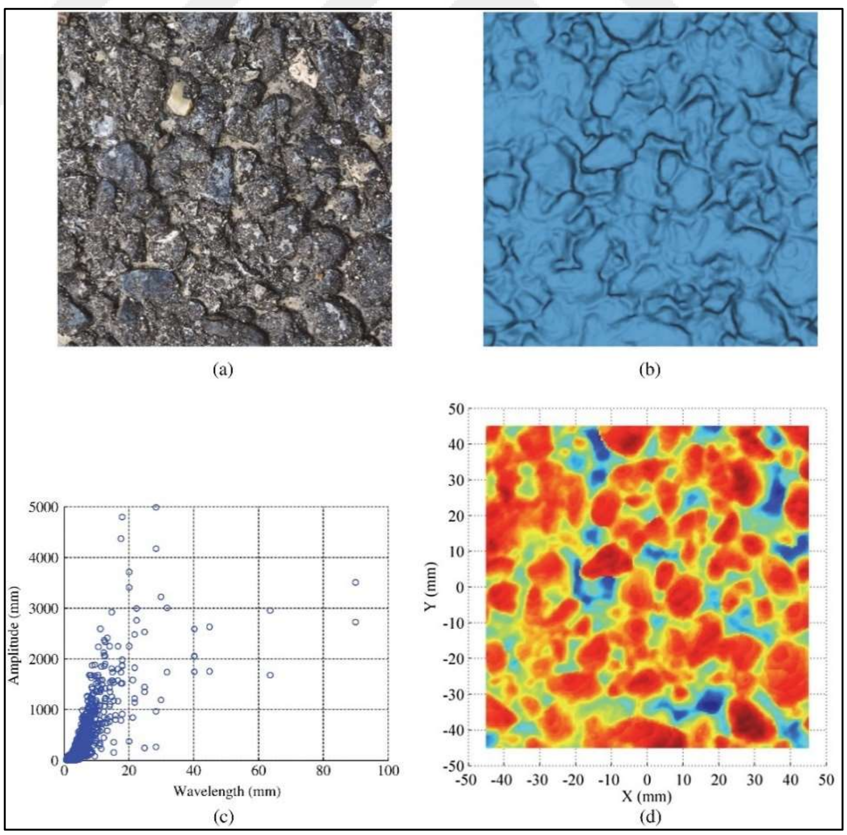
In terms of surface friction, micro and macro textures are essential for resistance to skidding as seen in Figure 2.1. Conversely, mega texture and roughness have wide influence on rolling resistance, vehicle wear features and driving quality. Also, tire-pavement and in-vehicle noises mostly rely on mega and macro textures.

2.2.2 Texture Depth Measurement Methods

There are many test methods which can be operated to evaluate macro texture of pavement surface. Sand patch and outflow meter tests, known as volumetric test methods, gives mean texture depth (MTD) of the pavement surface, while laser based methods such as circular texture meter, laser profiler and laser texture scanner gives results in terms of mean profile depth (MPD). Furthermore, in order to evaluate sensor measure texture depth (SMTD), visualization techniques such as image processing, X-ray tomography and photogrammetry methods can be operated. Since all these test methods supply different outputs according to their diverse operation procedure, correlations among them must be improved with applying comparative studies. A figure (Figure 2.2) is given to present such methods visually (ASTM, 2012d; Freitas et al., 2008; Miao et al., 2014; Prowell and Hanson, 2005; Rado and Kane, 2014).



(a) (b) (c)



(d)

Figure 2.2 Some images for pavement texture evaluation method (a and b: volumetric test method, c: circular track meter and d: image processing)

One of the volumetric test methods known as Sand patch test, which standard is specified ASTM E 965 and EN 13036-1, is the most extensive and well known test method to measure macro texture (ASTM, 2012c; CEN, 2010; Gransberg and James, 2005a; Gransberg and James, 2005b; Pidwerbesky et al., 2006). Volumetric test methods are well utilized and low cost, but the application process of these methods needs more time and road lane closing is appeal deficit (Goodman, 2009; Gökalp et al., 2016a). Also, in wet and windy weather conditions, the test method is not capable of being utilized and the due to traffic, environment and weather conditions it is inconvenient to obtain acceptable level of reproducibility on the application area (Gransberg, 2007; Kelvin, 2005; Khasawneh et al., 2015; Mahboob Kanafi et al., 2015; Praticò et al., 2015). Moreover, the test method has a deficiency to discriminate between free and active gaps. On the other hand, owing to its portability, simplicity and low cost, the test method is frequently being utilized for measuring surface texture (Sarsam and Ali, 2015)

Outflow meter test, which is specified in ASTM E 2380, is also utilized to detect the macro texture of the pavement surface. The test method is measuring elapsed time while a certain volume of water escape between the surface of the pavement and test apparatus in order to get drainage characteristics of the pavement. Outflow test method is extremely sensitive to local variations and its repeatability was reported as poor and strongly up to the operator (Aktaş et al., 2011; Ech et al., 2009; Praticò and Vaiana, 2013)Volumetric based methods are utilized for evaluating surface textures of a known region of pavement and a few variants influence the precision of the methods. The outputs of two tests indicate that accuracy of the results obtained from outflow meter test is higher than the those of sand patch test method. Moreover, sand patch test method has a weak repeatability, particularly among users (Hegmon and Mozoguchi, 1970). The differences in surface texture measuring can be significantly excessive as performed between two operators on the same place, while this difference was shown lesser as applied with single operator (Sugg, 1979). Besides, sand patch utilization was recommended for pavements with MTD bigger than 0.79 mm, whereas pavements with MTD less than 1.26 mm was advised for outflow meter test method by Aktaş et al. (2011). Another study done by Uz and Gökalp (2017a), 6 mm mean texture depth was specified as a limit for application of sand patch and outflow meter test methods. MTD bigger than 6 mm cannot be measured with outflow meter due to quick discharge.

Here, it can be implied that there are certain limitations as considering for utilization these methods. Thus, many techniques have been developed to overcome the limitations of the volumetric method (Gendy and Shalaby, 2007). Laser and/or sensor based and image processing and/or photogrammetric based systems are some of developed techniques that known as fast but expensive to operate and they are not suitable for using mobile unlike volumetric test methods (Goodman, 2009; Gökalp and Uz, 2017b). Professionals, who are interested in this task notice that there is a need to develop an alternative in spite of the volumetric test method to evaluate surface texture. Thus, many innovative approaches have been made in the light of researches and new devices and methods have been developed considering operator and traffic safety and efficiency. Following paragraph summarizes some related studies. Then, Table 2.1 is formed for some studies based on utilizing the new methods and traditional methods, and relationships between the methods for all study summarized here and/or not presented in the scope of this thesis.

In a study done by Fisco and Sezen (2013), multiple macro-texture measurement methods including sand patch, various laser based systems, and X-ray computed tomography scanning were utilized on twenty-six laboratory samples of Stone mastic asphalt, hot mix asphalt and chip seals. In this study where comparative evaluations were made, best-fit lines were drawn and root squares (R^2), which show their relationship with each other were determined for each test pairs and calculations indicate a strong relationship. In the study of Martino and Weissmann (2008), there can be seen a decent correlation between circular track meter and outflow meter tests. The study put forth that outflow meter test had been utilized effectively on seal coat surface texture due to its low cost and mobility. But, within this study, the researchers pointed out a threshold for utilizing outflow meter test method. Surfaces with mean profile depth of ≤ 0.46 mm or an equivalent time of ≥ 14.5 seconds were not recommended for outflow meter. Three-dimension laser and sand patch test methods were operated to evaluate asphalt concrete pavements surface including of stone mastic asphalt and hot mix asphalt texture in İzmir, Turkey at 31 different locations.

Furthermore, (Sengoz et al., 2012) presented a good correlation between 3-D laser based test methods and sand patch test outputs. Also, two volumetric test methods, outflow meter and sand patch were applied on slurry seal and chip seals surfaces which manufactured at laboratory by Uz and Gökalp (2017a). In contrast to other studies, this study yielded surfaces with a wide range of depths, strong relationship was found between the two test methods. However, a limitation is defined on the surfaces to be tested by outflow meter. The limited surface depth of 6 mm was designated. As a result of a study (Sarsam and Ali, 2015), in terms of macro texture depth measurement, both outputs which supplied from sand patch test and photogrammetric seem to be have similar results. Another study was conducted on asphalt pavement to determine texture depth and a good conformity was obtained between sand patch test method and laser-binocular vision results (Cui et al., 2015). A different study, done to measure surface texture, informed that a strong correlation between sand circle method and circular track meter has been showed up. Considering the presented studies, it can be seen that there were many works with respect to implementation of different test methods for the same aim. This meant that usually those methods are described based on traditional test method. Also, it is obvious that these traditional tests are still feasible and handy and for a comparison they are practically the first methods to test a model.

Table 2.1 Relationships between surface texture measurement methods

Reference	Utilized Methods	R^2 Values
Uz and Gökalp (2017a)	Sand patch method, Outflow meter	0.97-0.86
Sengoz et al. (2012)	Sand patch method, 3-D laser based test methods	0.97
Sarsam and Ali (2015)	Sand patch method and photogrammetric method	0.98-0.99
Praticò and Vaiana (2015)	Sand patch method and Laser profiler	0.94
Henault and Bliven (2011)	Sand patch method, Laser profiler and Circular Track Meter	0.65-0.87
Prowell and Hanson (2005)	Circular track meter, Sand patch method	0.95
Wang et al. (2011)	Sand patch method and Laser profiler	0.96
Fisco and Sezen (2013)	Outflow meter, Circular track meter	0.90
Martino and Weissmann (2008)	Outflow meter, Circular track meter	0.75
Goodman (2009)	Sand patch method and Image processing	0.71-0.96
Abbas et al. (2007)	Image processing and Circular track meter	0.56-0.89
Flintsch et al. (2003)	Sand patch method and Laser profiler	0.85
Gendy and Shalaby (2007)	Photometric Stereo Systems and Image processing	0.82-0.92

2.3 Skid Resistance and Measurement Methods

In this part of this thesis, the concept of skid resistance will be introduced and then measurement methods will be discussed.

2.3.1 Skid Resistance

Frictional forces between tire and pavement surface is known as skid resistance which is one of the significant surface features for road safety and it is the primary subject in this thesis. Inefficient friction between the pavement surface and the tires creates skidding which is the well-known event among the factors those effect safety of a road. Skidding is a feature of irregular road surface and as the tire load exposes the pavement surface, skidding effect friction forces (Kogbara et al., 2016; Kumar, 2014). Environmental and road traffic conditions those cause bleeding, raveling and polishing brings out a decrease in skid resistance and this resistance performance depends on numerous agents such as characteristics of bitumen and aggregates, type and age of pavement, highway thermal conditions. (Asi, 2007; Do and Cerezo, 2015; Fwa et al., 2003; Kogbara et al., 2016; Saplioglu et al., 2013). Through the lifetime of highway, micro and macro textures of the surface effect pavement skid resistance value (Hicks et al., 1997; Hicks et al., 1999; Huang et al., 2009). A study done by Noyce et al. (2005) demonstrate the influence of micro and macro texture on the friction of road surfaces in a diagram given in Figure 2.3.

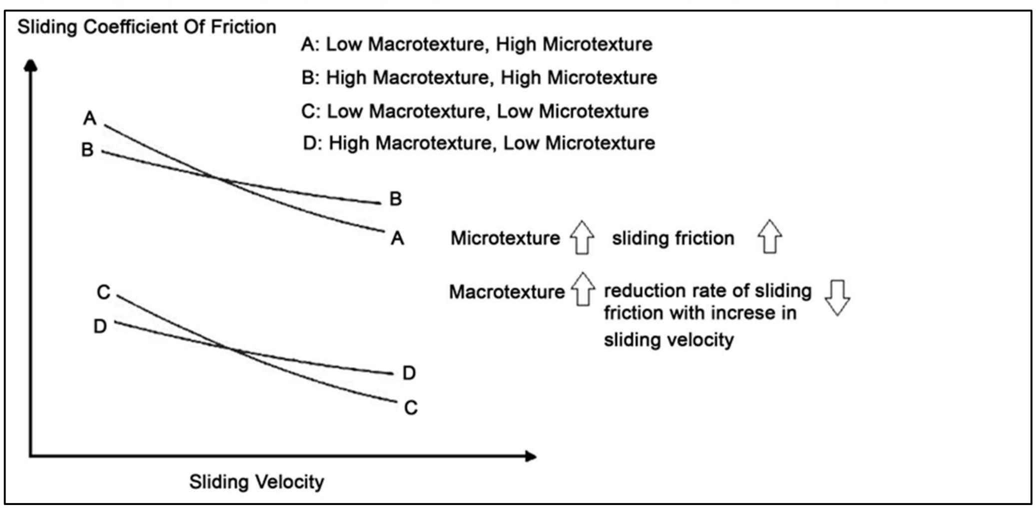


Figure 2.3 Micro and macro texture influence on pavement surface friction (Noyce et al. (2005))

Reduction in skid resistance induce a rise in traffic crashes. Formation of water film on pavement surface in wet-weather conditions cause a reduction of friction resistance on the road surface and therefore accidents (Fwa and Ong, 2008; Mayora and Piña, 2009; Meyer, 1991; Ong and Fwa, 2007). To show contact situations during wet and dry surface of pavement, Figure 2.4 is presented for the interaction tire rubber with pavement surface in case of dry and wet interface (Anonymous, 2018).

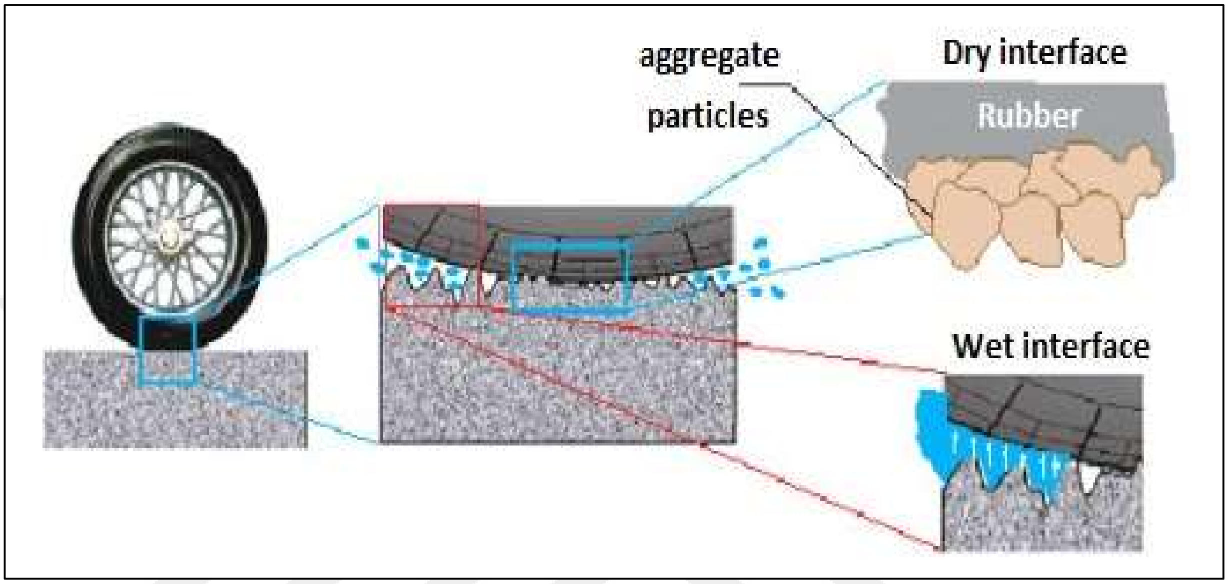


Figure 2.4 Skid resistance between tire and road surface for dry and wet condition

As mentioned above that the friction between the vehicles' tires and the road surface is influencing traffic safety (Wallman and Åström, 2001a). Therefore, over many years there have been many researches about intercourse between traffic accident and skid resistance (Andreescu and Frost, 1998; Ansari et al., 2000; Chang and Wang, 2006; Hayakawa et al., 2000; Híjar et al., 2000; Lankarani et al., 2014; Lindenmann, 2006; Mayora and Piña, 2009; Saplioglu et al., 2013). The outputs verified that for achieving particular decreases on traffic accidents adequate friction of pavement surface is required. Figure 2.5 is given here to make a graphical presentation for a wet pavement condition, which is presented in the study done by Mataei et al. (2016). This graph shows that friction coefficient decreases as accident rate of pavement in wet weather condition increases.

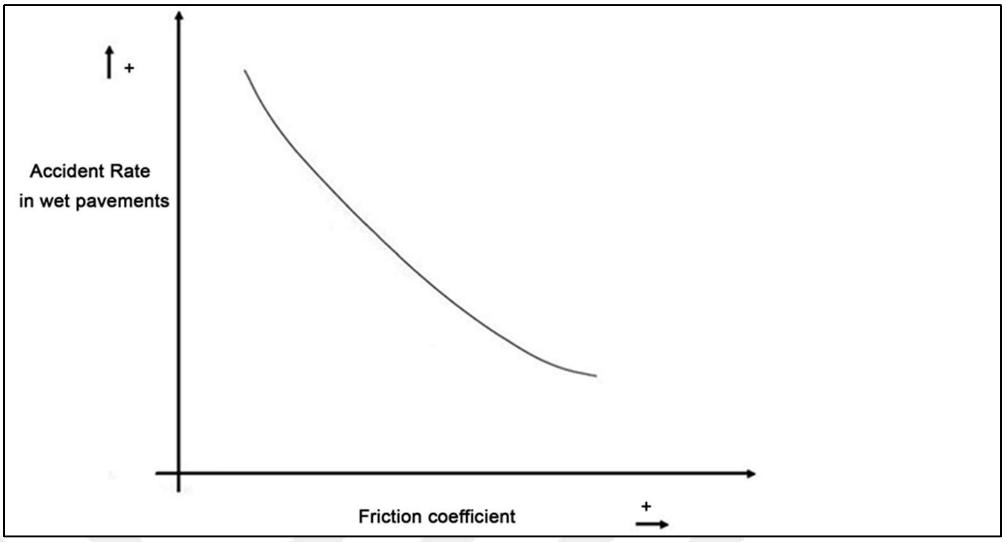


Figure 2.5 Accident rate versus skid resistance relationship in wet condition (Mataei et al. (2016))

Moreover, many factors like driving speed, water and ice presence on pavement surface, features of road surface, tire shape, tread depth, pressure and load are all have an influence on skid resistance. As a result of this information, four categories those effect skid resistance of road pavement can be listed as driving factors, vehicle factors, road surface characteristics factors and environmental factors (Andriejauskasa et al., 2014; Kogbara et al., 2018; Kogbara et al., 2016). Therefore, it can be concluded that the measurements of skid resistance of pavement surface are quite sophisticated as mentioned in the studies listed above. Furthermore, many devices and test methods, which give various values, have been improved in order to achieve the most proper outputs on the same road surface. In the following section, skid resistance measurement methods will be discussed.

2.3.2 Skid Resistance Measurement Methods

Pavement surface skid resistance which is influenced from tire, wheel load, water film thickness, dissimilar measurement speed, etc. can be interpreted with numerous of different test apparatus and test operations. It should be considered each of the tests applied to measure skid resistance of the pavement surface may calculate different parameters due to their particular properties.

Therefore, the results gathered by them may not be compared directly with each other, however in some cases researchers can make a comparison between those measurement tests (Gökalp and Uz, 2017a; Mataei et al., 2016; Wambold and Henry, 1994). Skid resistance measurement can be classified into two groups as (1) Portable and laboratory tests and (2) Field tests methods, according to their place of use. These measurement methods are shown in the following schema given in Figure 2.6. The figure is reformed from the studies published by Mataei et al. (2016) and Wallman and Åström (2001b).

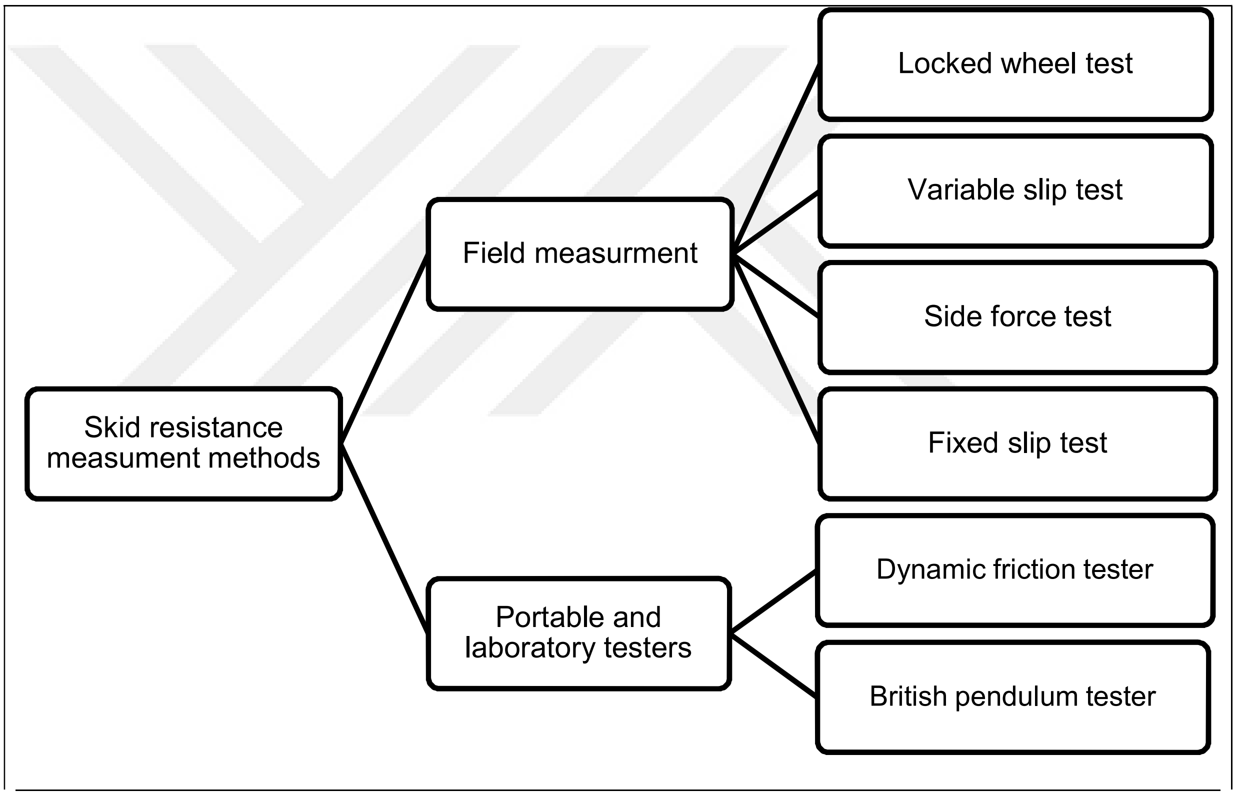


Figure 2.6 Skid resistance measurement methods (Mataei et al. (2016) and Wallman and Åström (2001b))

As seen from Figure 2.6, there are four skid resistance measurements methods for field application, which are locked wheel test, variable slip test, side force test and fixed slip test. On the other hand, there could be seen dynamic friction tester and British pendulum tester as portable and laboratory tester. To discuss the skid resistance measurement methods characteristics, Table 2.2 were reconstructed based on the study done by Wallman and Åström (2001b), Gökalp and Uz (2017a), Mataei et al. (2016) in this thesis.

Table 2.2 Skid resistance measurement methods characteristics

Test method	Standard	Measurement index	Strengths	Weaknesses
Locked-wheel	ASTM E 274	The Coefficient of friction (μ) is computed by measuring the resistive drag force and the wheel load applied to the pavement. Friction is reported as friction number (FN) or skid number (SN)	*It contains user friendly Systems with relatively simple and non-time consuming performance	*Continuous measurement of skid resistance is not possible due to its intermittent performance. *Its test equipment has high primary and operating costs. *Determination of speed dependency of skid resistance can only be performed by repeated measurements
Side-force	ASTM E 670	The Mu Number, (MuN) or the sideways force coefficient, (SFC) is computed by measuring the average of the side force perpendicular to the plane of rotation	*Skid condition is like the fixed slip device, relatively well controlled. *It can be used on straight sections and Curve -T sections or Roundabouts. *It performs continuous measurement throughout a test pavement section.	*It is very sensitive to road potholes, cracks, etc. and these defects can destroy tires quickly. *Mu-Meter is not a universal test rig and is often used for airports in the U.S.
Fixed slip	Various	Coefficient of Friction, (μ) is computed by measuring the resistive drag force and the wheel load applied to the pavement. the Friction is reported as FN	*It presents continuous measurement. *High resolution friction data can be collected.	*The slip speed of this device especially on snow covered surfaces does not always coincide with the critical slip speed value. *This device needs large amounts of water for continuous measurement.
Variable slip	ASTM E1859	This test produces the indices below: Longitudinal slip friction number, Peak slip friction number, Critical slip ratio, Slip ratio, Slip to skid friction number, Estimated friction Number, Rado Shape factor	*It can present continuous measurement The Rado shape factor can be provided for detailed evaluation	*This test equipment is large and complex. *Maintenance costs of equipment are high. *Data processing and analysis is complicated. *Needs large amounts of water for continuous measurement.
British pendulum tester	ASTM E303	The British pendulum tester provides British Pendulum Number (BPN) based on the return height of pendulum, after a low speed sliding contact with the pavement surface	*The British Pendulum skid tester is probably the most widespread skid resistance measurement equipment in the world. *Can be used for both field and laboratory evaluation. *This device is highly portable and easy to handle *The IFI statistics have good correlate with BPN.	*It only measures a frictional property of surface at a low speed. *It exhibited unreliable behavior when tested on surfaces with coarse texture. *BPN has a large variability and operator procedures and wind can have impact on it. *This test needs traffic control and lane closure. *It cannot be used for network evaluation because of its spot measurement
Dynamic friction test (DFT)	ASTM E1911	DFT numbers or friction coefficients Peak friction, Associated peak slip speed, International Friction Index (IFI) designated by F(60) and SP, It presents the graph of the friction coefficient for different rotational speeds	*This test is highly repeatable and reproducible and is unaffected by operators' procedure or wind. *Results of this method produce friction coefficients that are representative of high speed values.	*This test needs traffic control and lane closure. *It does not always simulate pavement–tire characteristics. *It cannot be used for network evaluation because of its spot measurement.

When the Table 2.2 is examined in detail, it can be inferred following results: Each type of measurement methods and/or devices,

1. gives different friction coefficients parameters,
2. works with different principle,
3. have certain strength and weakness characteristics, and
4. are identified based on internationally acceptable standards.

It is worth to say that this thesis is established on laboratory based produced chip seal samples. Thus, field measurement based methods were not described.

British pendulum tester is commonly utilized for skid resistance performance of pavement measurement tool in earlier studies performed all the world (Fwa et al., 2004; Kelvin et al., 2005; Kogbara et al., 2016; Shrimer, 2001). The tester has been used due to their simplicity, cheapness and portability. This test method is specified by ASTM E 303 (ASTM, 2012a) and it can be used in both field and laboratory condition at a pavement surface material low-speed friction. Due to its all-purpose usage in many test situations, British pendulum tester is accepted to be an effective pavement surface material micro texture measurement method in remote form by many researchers (Fwa et al., 2004).

Evaluation of the friction between pavement surface and tire for wheeled vehicles is of vitally important for the automotive industry. Because, friction is the main mechanism for producing forces on the vehicle, it is significantly important to have a reliable and accurate characterization of the intensity of the friction force generated at the surface/tire interface. For measuring a dynamic friction force between a road surface and a vehicle tire, there has been used a pendulum type measuring apparatus as indicated above. But, this pendulum type measuring apparatus has been applicable to the measurement of friction only when the speed fairly low range, which is 10-20 kph. But, the friction coefficient of the road surface differs significantly according to real speeds of an automobile on roadway. In general, at higher speeds, smaller friction coefficients are measured. Therefore, in order to measure the friction coefficient accurately it is needed that the high speed under the same condition as the real speed. To achieve that dynamic friction tester is developed (Brumund and Leonards, 1973; Rado and Kane, 2014). Dynamic Friction Tester is introduced in this thesis including its principle, structure and method. Friction of a range of surfaces can be evaluated directly from DFT and these measurement procedures and given outputs are set by the standard ASTM E 1911 (ASTM, 2009). The results gathered by this device is strongly correlated with the other mentioned devices, methods (Fwa et al., 2004; Gökalp and Uz, 2017a; Mataei et al., 2016; Nataadmadja et al., 2015; Saito et al., 1996; Wambold and Henry, 1994). Specifically, based on determination of coefficient of friction between rubber pads and road surfaces as is the case for the DFT and the BPT as used in this study (Saito et al., 1996). Some reference scale has also been developed for pavement surfaces friction features (Güneş and Topal, 2017). One is well-known that International Friction Index (IFI) that being developed by PIARC-World Association, and this value for each samples were also calculated in the present study (PIARC, 1987a). Former studies have reported the test methods used in this thesis which are portable, simple and utilized frequently for stationary or laboratory testing apparatus in particular (Gökalp and Uz, 2017a; Gökalp et al., 2016a; Uz and Gökalp, 2017b; Uz et al., 2014).

2.4 Chip Seals

Surface coating has a widespread usage on weak capacity roads and as an inhibitor handling of present pavements. Skid resistance, which is known as one of the main safety factors in pavement surfaces, is being protected and improved by surface coating application (Cafiso and Taormina, 2007; Saykin et al., 2012a; WSDOT, 2016). Structural capacity of surface coating varies with some agents such as traffic, construction applications, weather conditions and material features and quantity of usage (Krugler et al., 2012).

Chip seal is composed of aggregate layer and over the bituminous binder layer. This type of surfacing method is an economical type, and used for to maintain and lengthen the time of usage of present road (Gransberg, 2007; Gundersen, 2008; Gürer et al., 2012; WSDOT, 2016; Zoghi et al., 2010). Turkey, Australia, the United Kingdom, New Zealand, Canada, South Africa are some of the countries which have been using chip seals in their low-volume road network for many years as a maintenance work and a wearing course owing to its cost-effective property. For instances, they consist of 95%, 75-78% of the total road network of New Zealand and Turkey, respectively (Gransberg et al., 2005a; Karasahin et al., 2011; Terzi et al., 2013; Transit New Zealand (TNZ) et al., 2005; Uz and Gökalp, 2017b; Wilson and Black, 2008). Chip seal performance is affected by numerous factors. Following explained factors have to be taken into consideration for more durable pavements throughout not only design, but also construction period. Environmental conditions, temperature, binder type, aggregate gradation and type, rolling and bitumen spreading are the factors those referred above (Ball, 2005; Gransberg et al., 2005a; Gransberg, 2007; Gransberg and James, 2005b; Gundersen, 2008; Gürer et al., 2012; Karasahin et al., 2014; Kucharek et al., 2011; WSDOT, 2016; Zoghi et al., 2010). Construction-related factors are also affecting the chip seal performance. These factors are reported as uniformity in binder application rate, construction equipment and material diversity, delay time between the construction materials application to field, weather situation before, during and after construction and road traffic volume (Gürer et al., 2012). Chip seal can be utilized as preventive road layer for overload traffic and makes a suitable surface for vehicles. The aim of the utilization of chip seals are indicated as followings: keeping water from penetrating surfaces, filling small surface cracks observed on surface of pavement, decreasing possible distresses, improving skid resistance of polished surfaces (Cenek and Jamieson, 2005; Karasahin et al., 2014)

The initial cost of this type of coating is lower than the other types of applications by means of materials, equipment and labor. It is usually overlaid on pavements to make the pavement more adequate structural capacity. Thus, it is more suitable surfacing for both low-volume and high-volume roads. According to applied road sections, different types of chip seals may be considered. The types of chip seals may consist of single-layer seals, double-layer seals, void fill seals, texturizing seals, sandwich seals and racked-in seals. The difference between varieties of such seals are mainly depending on construction methods and the number of layers (Gransberg et al., 2005a; Gundersen, 2008; Kodippily et al., 2011; TNZ, 2005; Wilson and Black, 2008).

Overall, it can be pointed out that better performing chip seal type surfacing is one that achieve the objective and provide a safe, comfortable and aesthetic surface for public (Cenek and Jamieson, 2005; Gransberg, 2007; Kucharek et al., 2010; Zoghi et al., 2010). On the other hand, of course, there are some advantages (low cost, a thin restorative surface layer, ease to construct due to less labor and equipment, materials and energy requirements) and disadvantages as mainly having short service-life, some construction constraints due to lack of design procedures and criteria (Anonymus, 2016; Jianwen, 2006; Kai-bing, 2013; Lee and Orhan, 1984; Lee, 1977; TNZ, 2005).

2.5 Steel Slags and Evaluation in Pavement

In the scope of this thesis, steel slags were also utilized due to their superior features in terms of high polishing resistance characteristic. For this reason, this section is established to introduce the term of steel slags, characteristics of them and their utilization area, especially, in pavement construction. In the light of earlier studies and reports, it is attempted to explain these two tasks in detail.

2.5.1 Steel Slags

Obviously, it is accepted that aggregate is a value important and versatile material utilized in almost all aspect of the construction infrastructure. Aggregate may be supplied either natural as raw materials or artificial e.g. mine waste, recycled materials, demolition materials as secondary materials. However, mostly it is gathered in the form of natural rocks and it makes up approximately high amount of by means of volume and mass to be used in pavement construction (Ayan et al., 2016; Gökalp et al., 2018; Theyse, 2002)Construction infrastructures may be either building, and hydraulic structures or highway facilities. Since this thesis is focused on chip seal, which is one type of highway facilities, it can be said for transportation industry that huge amount of aggregates in required quality is a necessity. With a great part of transportation industry based works is consisted of aggregates, it leads to increased demand for limited natural resources (Marinković et al., 2010). Besides, the population of the world continues to grow, more roads will need to be constructed to meet their transportation needs. Dependently, rehabilitation and maintenance of the existed infrastructure increases. To meet these needs, utilization of natural resources, which is going to be scarce will gradually continue. Depending on this compelling circumstances, the concentration of researchers is leaded to find a possible alternative material. Alternative materials to be used as aggregate, must have similar or superior technical properties. But, environmental and economic concerns have also to be taken into account (Bodor et al., 2013; Marinković et al., 2010; Ossa et al., 2016). For this aim, scientists explored numerous secondary materials for being utilized as aggregate sources (Asi, 2007; Asi et al., 2007; Aziz et al., 2014; Fronek, 2012a; Yildirim and Prezzi, 2011). Among the secondary type materials, industrial by-products, steel slags for this thesis, is one of the best choice as by product aggregates for construction works, particularly road construction (Oluwasola et al., 2014).

2.5.2 Utilization of Steel Slags in Road Pavement

World crude steel production for the 64 countries reporting to the World Steel Association was 148.6 million tons (Mt) in November 2018. Specifically, Turkey’s crude steel production for November 2018 was 3.1 Mt (WSA, 2018). On the other hand, a report on the production capacity of steel Turkey published by Turkish Steel Producer Association (TSPA, 2016) showed that production of steel is approximately 35 million tons. Electric-arc furnace mills are accounted for 77% of the total capacity.

Metallurgical industries produce considerable amount of by-products. Examples can include iron, steel, nickel, lead, zinc, and etc. production industries. Each generates many different types of by-products (Fox, 1999; Kresta, 2014). Among them, iron and steel industries are essential for the development of a numerous of industries in the global economy (Fronek, 2012a; Gómez-Nubla et al., 2018; Polprasert and Liyanage, 1996; Reuter et al., 2004). Slag is known a by-product generated (about 15 % of the total production) during the manufacturing metals, particularly steel. The slag is utilized in various applications, particularly in civil works because of its superior characteristics (Gökalp et al., 2016a; Gökalp et al., 2018; Krishnan and Balasubramanian, 2014; Safiuddin et al., 2010; Uz and Gökalp, 2017b). Slag is generally considered as an alternative aggregate instead of the natural one for different purposes including road construction aggregate, railroad ballast, and filling materials, concrete aggregate (Asi et al., 2007; Aziz et al., 2014; Fronek, 2012a; Motz and Geiseler, 2001; Oluwasola et al., 2014; Proctor et al., 2000; Yildirim and Prezzi, 2011).

Fwa et al. (2013) investigated in-situ and laboratory performance of a porous pavement containing steel slag substitute to natural aggregates. Pavement performance in terms of skid resistance, visibility, and tyre-pavement noise were evaluated by researchers. It has conclusively been shown that pavement constructed with steel slags provide better drainage, skid resistance and decrease tyre-pavement noise as compared with the others.

In their study, Wu et al. (2007) also explored the availability of usage of steel slag in wearing course mixtures. The features of slags were determined with X-Ray diffraction, Scanning Electron Microscope, and mercury intrusion porosimetry. To compare the features of slags with the natural aggregates, basalt was used the prepared mixture. The findings of current study are consisted with those of Sorlini et al. (2012) who reported the compatibility of features of slags with material specifications. Additionally, rutting and fatigue cracking resistance in case of high temperature, and low-temperature cracking resistant and skid resistance performance were found better than the mixture prepared with basalt aggregate.

Ziari and Khabiri (2007) assessed numerous mechanical performance of asphalt concrete with slag. Marshall, high-temperature stability and creep stiffness test conducted on asphalt concrete. The results of this study did demonstrate that use of slag in asphalt concrete is available. There are similarities between the attitudes expressed in this study and those described by Krayushkina et al. (2012) and Kehagia (2009). Reusability of EAF steel slags in bituminous hot mix asphalts was undertaken by Sorlini et al. (2012). Feasibility of analysis slags was done by numerous tests to determine physical, mechanical, and chemical properties of them, individually and also of bituminous mixtures with EAF slags up to 40%

content. This study pointed out that mentioned properties adapted to the related specification limits.

Gökalp et al. (2016b) and Yilmaz and Sütaş (2008) suggested that metallurgical slags from steels and ferrochromium origins could be used in construction of different pavement layers including subbase, base, wear layer, and surface coatings due to their superior physical and mechanical properties according to Turkish Highway Technical Specification.

Analysis of steel slags involved in surface coating was carried out in a laboratory study by Khan and Wahhab (1998) to improve the physical and mechanical features of slurry seals. The results demonstrated that a certain improvement are provided in slurry seal samples with slags terms of abrasion and crashing resistance.

The studies presented thus far provide evidence that utilizing of slags is feasible as alternative aggregate instead of naturally produced ones. Utilization slags ensures reduction of deposits and the preservation of raw materials by diminishing the amount of landfill, and emission gas produced by equipment during supplying and manufacturing natural aggregate. The use of slags will also lead to a reduction in production costs of aggregates. Therefore, the cost required for construction of road pavement will decrease. Overall, there seems to be some evidence to indicate that slags are valuable both economically and environmentally, and superior material than natural aggregates in terms of their properties.

2.5.3 Aggregate Polishing Methods and Processes

It can be seen that variety methods of polishing such as Los Angeles, Micro-Deval, Road Test Machine, Aachen Polishing Machine, Polish Stone Value, Wehner/Schulze machine and Auckland Pavement Polishing were executed in early studies to specify aggregate performance in accordance with resistance of abrasion. Aggregate polishing techniques are summarized in this part of the study.

Micro-Deval Test was used by a plenty of surveyors to polish aggregate. Exemplarily, Crouch and Goodwin (1995) improved an indirect process to evaluate resistance of polishing utilizing Micro-Deval. The test device was operated for nine hours to polish aggregate samples and as the next step evaluating of uncompact cavities was done, where smother aggregates is referred with fewer cavities.

Mahmoud and Masad (2007) developed an empirical method to evaluate resistance of aggregates against to abrasion, polishing and breakage. In this method, SEM apparatus was used to determine the variation in aggregate samples micro texture as a polishing duration time function before and after performing of Micro-Deval test and degrading time of aggregate micro texture was accepted as aggregate polishing resistance.

Similar to the previous method, aggregates polishing rate was investigated by system of aggregate imagination before and after Micro-Deval test in approach of Xue et al. (2010). As a result of this procedure, it was observed that aggregate morphology had a significant effect on the abrasion resistance of the aggregates.

(Ortiz and Mahmoud, 2014) performed both Micro-Deval test and aggregate imagining system (AIMS) to measure polishing rate of variety of aggregates types such as dolomite, quartz, sandstone, limestone, gravel, diabase, blast furnace slags and steel slags with respect to different polishing time. For the Micro-Deval test, 750 grams of aggregate retained between 12.5 mm and 9.5 mm sieves were prepared and ten different polishing times (15, 30, 45, 60, 75, 90, 105, 180, 210, 270 minutes) were determined to polish the samples. As a result of the study, researchers observed an increment in texture indexes of chert gravel and steel slag while other aggregate types had a remarkable reduction in their texture indexes as polishing process continues and each aggregate type had final texture level in a specific duration of polishing. Therefore, it can be seen that aggregate mineralogy has an important role on polishing resistance.

In one of the other studies, an empirical model was evolved to estimate of the asphalt pavement skid resistance. Rezaei and Masad (2013) used Micro-Deval test to polish aggregates samples such as gravel, sandstone dolomite and limestone. Two different times, 105 and 180 minutes, were decided to operate Micro-Deval test in accordance with the standard named ASTM D 6928. After polishing process, textures of polished samples were imagined by AIMS. Researchers noted that aggregate gradation and texture have a significant effect on skid resistance.

A study done by Cafiso and Taormina (2007) focused on asphalt pavements wearing course in terms of aggregate texture. Limestone and basalt from different origins were used to operate a kind of polishing test named accelerated polishing test with different time periods (0, 3, 6, 9 hours). Researchers also used British pendulum test method to analyze aggregate texture. According to the results of the study, it was found that the limestone resistance was lower than the basalt and as the polishing time increase, skid resistance performance of the aggregate decreases.

Another study about aggregate polishing process is done by Wang et al. (2013) with using diabase and granite. These aggregate types used to produce asphalt samples and aim of the study was the measurement of the shear resistance properties of asphalt samples under different polishing conditions such as different combination of polishing factors (quartz powder as sand, fine/course corundum and water) and various polishing durations (16.67, 33.33, 100, 200, 300 and 600 minutes). Aachen Polishing Machine with real tires was used to polish the samples and then skid resistance capacity was determined by using Wehner/Schulze machine. The results of the study showed that different polishing conditions have a significant effect on skid resistance performance of asphalt samples.

(Do et al., 2009) were also studied on polishing techniques according to EN 1097-8 standard test method in order to identify the skid resistance characteristics of a pavement (prepared with limestone and rhyolite) surface under traffic loadings. Polishing process was run with Wehner/Schulze machine and at every specified rotation, surfaces of the samples were measured with a laser sensor to detect behaviors of surface textures. The first rotation time was considered to be 1000 and 1000 turn increments were made up to 15000 turns. Also at 30000, 50000, 90000, and 180000 rotation time, these process was repeated. At the end of the study, results indicated that polishing process exposed two treatments: globally materials being disposed to suspend and regeneration of roughness owing to hardness variation between aggregate minerals.

Wehner/Schulze machine was used by Kane et al. (2013) in order to identify skid resistance capacity of the road surfaces produced with the aggregates such as limestone, granite and greywacke under different traffic loading which was simulated with tire rotation up to 180000 turns. The study also focused on the relation between the aggregates mineralogical composition with using an optical microscopy in a petrographic analysis. After the tests measurement were done, the resulting friction coefficients and the new hardness parameter introduced in the study were correlated and as a result of the study the new hardness parameter was accepted to be a well-indicator of the aggregate capacity in order to keep good levels of friction.

A study done by Woodward et al. (2004) focused on aggregate skid resistance performance found with both laboratory estimation and the real conditions. Granite, basalt and gabbro were used to produce asphalt samples for modified polish stone value (PSV) test. The accelerated polishing machine with modified arm allowing angles 0°, 3°, 6° and 10° used to determine PSV. The researchers concluded that PSV was tending to decrease up to 6° and increment was observed after the angle of 10°.

Friel and Woodward (2013) studied on the skid resistance behaviors of the various road type such asphalt concrete, stone mastic asphalt, high friction surfacing system and proprietary thin surfacing systems in order to estimate changes of skid resistance performance under polishing process. In the study, because of having full-scale tires, road test machine (RTM) was preferred to polish the samples. Hereby, it was thought that different materials would had been ranked according to different measurement characteristics. Long-term traffic loading (5 to 10 years) was simulated with passes of tire mounted to RTM up to 100,000 passes and a specified number of stops were done during polishing passes. For the purpose of measuring wet skidding resistance of the road samples, British pendulum tester was used. The results taken from the study pointed that there was an important variation in skid resistance between different aggregate types and gradations.

In a recent study done by (Bessa et al., 2014), Lon Angeles abrasion test was utilized in 500 rpm to abrade the steel slag, gneiss, granite and phonolite samples which had range in 12.5-19.5 mm and 9.5-12.5 mm. After abrasion process done, polishing and degradation resistance of the aggregates were analyzed with aggregate imaging system (AIMS). It was observed from the study, steel slag had a better polishing and abrasion resistance among all aggregate samples used for test methods.

CHAPTER 3. MATERIALS AND METHODS

3.1 Aggregates

In laboratory work of this study, totally five coarse aggregate types including natural aggregates which are river basin crashed stone, limestone and basalt; and waste products which are ferrochromium and electric arc furnace slags were used. All samples were obtained from a different in Turkey in order to get a wide range of results. Waste products were obtained from the metal manufacturing companies and from waste storages while the natural aggregates were obtained from quarries belonging to private enterprises. Acquisition area of the aggregates, material lithology and representative identity abbreviations are shown in Table 3.1.

Table 3.1 Aggregate distributions

Order	Sample ID	District	Origin
1	LS	Ceyhan / Adana	Limestone
2	BS	Develi / Kayseri	Basalt
3	BLD	Aksu / Kahramanmaraş	River Basin Crashed Stone
4	EAF	Iskenderun / Hatay	Electric Arc Furnace Steel Slag
5	FER	Elazığ	Ferrochromium Slag

The reasons for choosing such aggregates may be briefly explained as follows: Limestone has the most extensive usage in Turkey especially in pavement construction on account of geological formation in that region. Other preferable natural aggregates such as river basin crashed stone and basalt also have wide application area due to their unsurpassed mechanical and physical properties. In crude steel production, Turkey has a large portion in the sector with 33 million tons per year and those production is done by oxygen-blown converter (over than 11 mt) and electric arc furnace (over than 22 mt) (WSA, 2018). Ferrochromium production in Turkey is about 100 thousand tons, annually. Moreover, 10-15% of the steel production emerges almost 5 million tons of slag, which is the end product of oxidation of different additives within the steel. Due to their better mechanical and physical characteristics, slag can be preferred more than natural aggregates (Geiseler, 1996; Krayushkina et al., 2012; Mihok et al., 2006)

As one of the primary materials at any construction work either in pavement construction or concrete structures, aggregates features should be detected to achieve more reliable design.

3.1.1 Properties of aggregates

It is crucial to determine the properties of aggregates in terms of mechanical and physical view as planned to be used for pavement construction. In this study, some features of aggregate samples were determined performing series of tests including Micro-Deval test for abrasion and polishing resistance, Los-Angeles test for fragmentation resistance, $MgSO_4$ solution for freezing and thawing, dry unit weight and water absorption tests according related TS EN standards. It is important to determine chemical components of each material by means of both elemental and mineral compositions. In this study, X-Ray Diffraction (XRD) analyses and X-Ray Fluorescence (XRF) analysis were performed to detect mineral composition and chemical elemental composition of aggregates. Also, surface of aggregates has been monitored and images were taken from the surfaces in order to get information and make a comparative assessment about changes in micro texture of aggregates with variation of polishing level. The tests used in this thesis are summarized as follows.

3.1.1.1 Micro-Deval test

Micro-Deval test is utilized to measure abrasion loss of coarse aggregate in the presence of water and steel balls according to European standard encoded with EN-1097-1 (CEN, 2011a). A sample is prepared by separating into individual size fractions of the required masses. Typical prepared sample sizes are 500g for fine aggregate and 1,500g for coarse aggregate. The test procedure can be explained as following:

The sample is immersed in water (2,0 ± 0.05 liters) at 20 ± 5 °C for at least 1 hour in the Micro-Deval container. An abrasive charge of magnetic stainless steel balls (10 ± 0.5 mm diameter) by the weight of 5000 ±5 gr. is added to the prepared test sample with the water. The cover is fixed and the Micro-Deval container is placed on the test machine. The Micro-Deval test machine is set to rotate the containers at 100 ± 5 rpm for a 10500 revolutions. At completion, the sample is carefully washed over a specified sieve and percentage loss is determined by comparing the oven-dried mass of the retained sample to the original total sample weight. The 75µm (No. 200) sieve is used for fine aggregates, and a 1.18mm (No. 16) sieve is used for coarse fractions. The following equation is utilized for calculating MDC:

$$MDC = \frac{500-m}{5} \quad (1)$$

where m is the mass of aggregate retained on the 1.6 mm sieve.

Figure 3.1 Micro-Deval test apparatus and implementation

3.1.1.2 Los Angeles test

Los Angeles abrasion test is used to measure the degradation of a coarse aggregates in a rotating drum via steel spheres, with internal dimension 711 mm in diameter and 508 mm in length, for specific number of revolutions. Aggregate abrasion and toughness are indicated by this common test method. In this study EN-1097-2 (CEN, 2010b) standard is followed to identify fragmentation resistance of each material. The aggregate degrades by abrasion and impact with other aggregate particles and the steel spheres as the drum rotates. The number of revolutions is 500 at a speed of 30 to 33 revolution per minute After the application of the test, the percentage loss between the retained and the original samples weight owing to abrasion is calculated. The percentage abrasion due to rubbing steel spheres is detected and is known as Los Angeles abrasion value. The Los Angeles coefficient (LAC) is calculated with following equality.

$$LAC = \frac{5000-m}{50} \quad (2)$$

where m is the mass retained on a 1.6 mm sieve.

Figure 3.2 Los Angeles machine and implementations

3.1.1.3 Thermal weathering resistance test

This test method simulates the volumetric changes in the coating surface caused by changing seasonal temperatures in long-term weather conditions. Aggregates that are not resistant to varying ambient temperatures may cause disruption of the road surface, cracks, pits and loss of bearing capacity of the layers. As one of the specified test method in Turkish Highway Technical Specification, the thermal weathering resistance of aggregates can be determined with magnesium sulphate (Mg2SO4) solution based test method. During the drying of saturated aggregates, volume change is simulated by hydration and crystallization of magnesium sulphate in aggregate pores.

A mass of 500 gr of aggregate particles between 10.00 and 14.00 mm is immersed in a Mg2SO4 solution for 17 ± 0.5 hours as specified in EN 1367-2 (CEN, 2011b). For a period of 2 ± 0.25 hours the aggregate is left to drain and then dried at 110°C ± 5°C for 24 ± 1 hours. After repeating this circle five times, Mg2SO4 solution is removed by washing aggregate with water. As the next step, drying procedure is applied on the aggregate at 110°C ± 5°C and 10 mm sieve is utilized to sieve aggregate manually. The weight loss in the wearing process is recorded and expressed as a percentage of the original sample mass. As rounded to the nearest integer, the mean value of two tests is defined as the magnesium sulfate value (MSC). The following equation is used for calculating MSC.

$$MSC=\frac{500-m}{5} \quad (3)$$

where m is the mass of aggregate retained on the 10 mm sieve.

Figure 3.3 Thermal weathering resistance test

3.1.1.4 Polishing resistance test

Polishing resistance of the samples are measured with two following testing procedure. Primarily, accelerated polishing machine is used to polish test samples and then British pendulum test is being processed to detect level of polishing. To produce a test sample, 7.2-10 mm sized aggregates (more or less 36 to 46 particles) are placed in a standard mold. The points that needs to be considered here is that the flat surfaces of the aggregates must be touched to the mold base and must be laid in a single layer. Gaps formed due to the physical properties of the aggregates are filled with fine sand that the amount of three quarters of the gap depth. Afterwards, epoxy resin is poured on the aggregate surface with the help of spatula so as not to overflow the mold. Last step of preparing test specimens for polishing machine is unmolding the samples, cleaning the surfaces of the samples from sand particles. The accelerated polishing machine has a metal wheel that rotates 320 revolutions per minute with a diameter 406 mm and holds the 14 test samples and stone control samples around its rim (Figure 3.4). A rubber-coated wheel that polish the specimens has a 725 N static contact force with molds. The wheel is fed three hours at a 27 ± 7 g/min rate with an enough amount of water and corn emery that has particles passing through the 0.600 mm sieve with a gradation of 98% – 100%. At next three hours, the test is repeated with fitting rubber-tire wheel utilizing flour emery and water with the rate of 3 ± 1 g / min and of approximately 6 ± 1 g / min, respectively. After 6 hours, the polishing process finishes and the samples are prepared for British pendulum tester to specify friction. Complying with a standard of European that numbered EN-1097-8 (CEN, 2010c) to calculate the polish stone value (PSV) is the last step of the testing procedure. The following equation is utilized for the detection of PSV:

$$PSV = S + 52.5 - C \quad (4)$$

where, S is the skid resistance mean value for the four aggregate test samples, C is the skid resistance mean value for the four PSV control stone samples, that must range from 49.5 to 55.5 PSV units.

Figure 3.4 Polising resistance test aparatus and samples

3.1.1.5 Dry-unit weight and water absorption test

In order to sample and lower the quantity of the aggregates, EN 932-1 (CEN, 1997) and EN 932-2 (CEN, 1999) standards are followed, respectively. A scale with 0.1 g weighing capacity and a wire basket hanging on it and waterproof tank are main fittings for specification of the coarse aggregate density. At first, an enough quantity of dry coarse aggregate is placed in wire basket and conditioned in waterproof tank at 22°C ± 3°C for 24 ± 0.5 h.

Table 3.2 The minimum mass of test portions.

Sieve Size (mm)		Mass (kg)
Passing	Retained	
31.5	16	1.5
16	8	1.0
8	4	0.5

After the required time is completed, both wire basket with aggregate (W2) and tare of basket (W3) are weighted separately, in sequence. Then the aggregate removed from basket is dried up to no water particles left on the surface and weighted (W1). At last, constant mass of aggregate (W4) is measured just after drying it in a furnace at 110°C ± 5°C. The following formulas are given for the calculation of surface dry density (SSDD), the water absorption after immersion for 24 h, (WA24), the relative density (RD), oven dry density (ODD):

$$SSDD = \rho w \times W1 / (W1 - (W2 - W3)) \quad (5)$$

$$WA_{24} = 100 \times ((W1 - W4) / (W4)) \quad (6)$$

$$RD = \rho w \times W4 / (W4 - (W2 - W3)) \quad (7)$$

$$ODD = \rho w \times W4 / (W1 - (W2 - W3)) \quad (8)$$

3.1.1.6 X-Ray fluorescent test

Owing to allowing the spectral data to be checked against with respect to elements relative concentrations from pattern to pattern, semi quantitative XRF test is utilized to specify aggregate chemical compositions. Without using calibration curves created with specific reference samples, a special software package suitable for X-Ray fluorescent test analysis is used in semi quantitative XRF. About 200 g aggregates passing from No. 200 sieve (with opening 0.074 mm) were made ready as powder form. In order to get lumps with a diameter 32 mm, 180 kN pressure is applied on slags powders while 150 kN pressure is applied other four types of aggregate powders for 30 seconds. After placing lumps into the covered box and put the box into the X-Ray fluorescent test machine, the software program is run and the data are acquired. Also, in order to get chemical properties of each material, material's mineral compositions are detected.

3.1.1.7 X-Ray diffraction test

In this test method, test samples are prepared like XRF test method. But unlike the previous method, dissimilar X-ray diffraction test procedures are applied on each of the aggregate samples. The range of 5-70° (2ϴ) Cu Kα radiation with one second count time and 0.02° increments is used to measure XRD samples. In addition, the software program is run to get diffraction data and to exude standard XRD lines' relative densities. The following figures show continuum of XRF and XRD test methods.

Figure 3.5 Photos from XRF and XRD analysis procedures

3.1.1.8 Scanning electron microscope (SEM) test

Scanning electron microscope test is a strong magnification apparatus that handled with focused beams of electron to get proper data from materials. Supplying compositional, morphological and topographical data from materials make scanning electron microscope test a priceless all-purpose test method for scientific and industrial fields. Also, surface fractions can be analyzed with this test method in order to get information about qualitative chemical analysis and microstructure, to specify crystalline structures and to survey surface contaminations. In summary, scanning electron microscope is a necessary apparatus in many science fields such as material and metallurgy, geology, biology, forensic and medical science (Goldstein et al., 2012).

Components like X-ray detectors, computer, field and thermionic emission guns, pattern storage section, secondary electron, electrostatic and electromagnetic lenses, backscatter detector and vacuum chamber are the constituents of scanning electron microscope. Also, a field isolated from electrical and magnetic forces, flicker-free area, cooling and vacuum systems and a stationary power supply are the requirement of the scanning electron microscope apparatus (Postek, 1997).

Five types of aggregates used in this thesis are examined with a mini scanning electron microscope which can magnify up to 100.000x with range of 5-30 voltage in a short time like seconds and supply superior quality images to observe surface characterization. The implementation of this test and diagrammatic guideline about working of SEM device (Figure 3.6) are as follows:

- Transmission of electron beams generated by the electron gun from the column onto a set of winding-wrapped electromagnetic lenses
- Calibration of windings to focus the incident electron beams onto test specimens
- Focusing of computer controlled incident electron beams through the area in which samples are placed to scan sample surfaces
- Occurrence of an interaction due to the acceleration rate of incident electrons between the incident electrons and the sample surface
- Obtaining data from scatter patterns by interaction about the composition, texture, shape and size of the samples

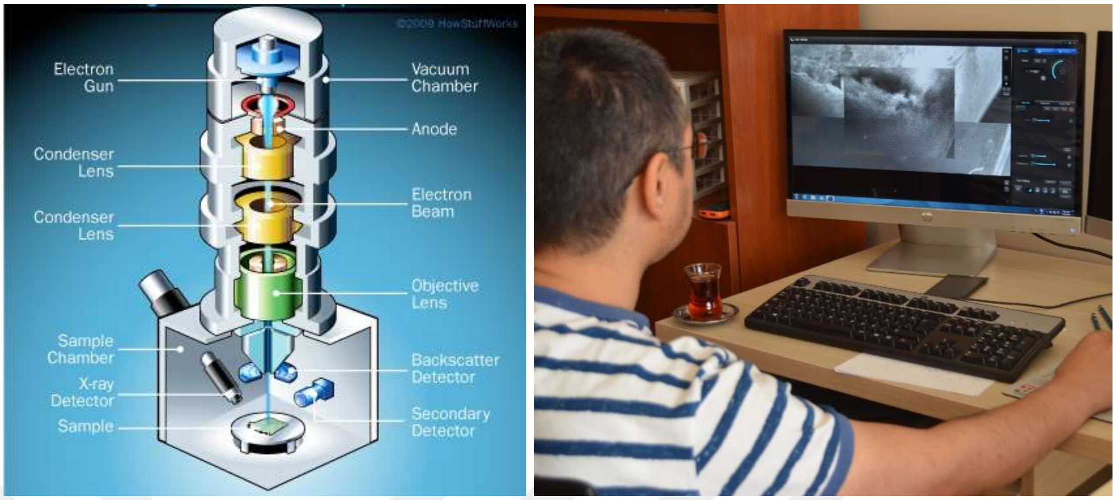


Figure 3.6 Schematic diagram for working principle of SEM and monitoring

3.2 Aggregate Polishing Process

In this thesis, Micro-Deval test was used to polish the aggregate samples, which have maximum nominal grain sizes, according to ASTM D 6928 (ASTM, 2012g). The aggregates samples those are defined as A, B, C and retained between 19.0 mm -4.75 mm sieves are recommended for producing test specimens. The sieve sizes those samples passing and retaining with specified masses for each case are shown in Table 3.3.

Table 3.3 Mass of the aggregates and sieve size utilized in ASTM D6928

Sieve Size (mm)	Passing	19.0	16.0	12.5	9.5	6.3
	Retained	16.0	12.5	9.5	6.3	4.75
Case of ASTM D 6928	A (g)	375	375	750		
&	B (g)			750	375	375
Mass of Samples	C (g)				750	750

In this study, Case B was followed to obtain polished aggregates. The mass of the test sample used for each case can be seen Table 3.3, in total, 1500 ± 5 g. For case of B specified mass of sample supplied as 750 g from 12.5-9.5 mm sieve sizes, and 375 g from 9.5-6.3 and 6.3-4.75 sieve sizes. To perform the test on samples following steps were taken; Firstly, it is required to remove the friable particles from samples and this is done with washing. Wet sample are dried in oven at 110 ± 5°C to constant mass. Dried aggregate, 2.0 ± 0.05 L of water at a temperature 20 ± 5°C is added in the MD drum and conditioned for at least 1 hour. 5000 ± 5g steel balls having a diameter of 10 ± 0.5 mm and specified mass are poured into the drum with aggregate and water. The drum is then tightly capped and allow to be rotated for 10500 ± 100 at 100 ± 5 rpm. After completion of the test, the aggregates are dried and sifted through the 1.18 mm sieve. Following equation is used to calculate MDC.

$$MDC = (1500-m)/15 \quad (9)$$

where m is the mass of aggregate remained on the 1.18 mm sieve.

With a view to get the 8-10 and 10-12 mm grain sizes aggregates with different polishing levels, ASTM standard test method has been applied in the case of B grading size which ranges 4.75 to 12.50 mm. Case of standard revolution number and polishing levels are given in Table 3.4. It is worth to make remind that 8-10 and 10-12 mm aggregates were sieved within flakiness sieves to gather cubical samples. Figure 3.7 shows a visual summary for polishing process

Table 3.4 Polishing levels and case of standard revolution number

Wear Level	Wear-Free	1st	2nd
Revolution Numbers	0	10500	31500
Case of Standard RN	None	Standard	Triple

Figure 3.7 Polishing process steps with MD apparatus

3.3 Chip Seal Design and Manufacturing

It must be considered that utilizing aggregates at standard spreading rates, size and shape is significant in order to prevent any fallacious test results. Sieving was carried out to get the single size of aggregates at different dimensions and also to get cubic particles in shape according to ASTM D 4791 (ASTM, 2012c). Average Least Dimension (ALD) theory which indicates the anticipated chip seal thickness when the aggregate settles on the smooth side was used to specify aggregate spreading rates (Transit New Zealand (TNZ) et al., 2005). The following equation specified by TNZ was utilized to calculate aggregate spreading rate (ASR) in unit of ml/m^2. The aggregate distribution rates for the specified samples production annular plate, which has 1 cm thickness, 10 cm inner and 19 cm outer diameter with 0.075 m^2 area (Figure 3.8) for each size of aggregates are shown in the Table 3.5.

$$ASR=950/ALD \tag{10}$$

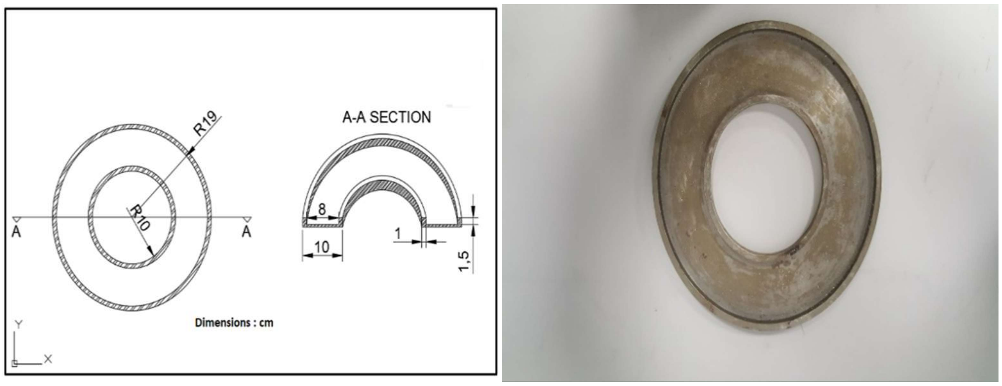


Figure 3.8 Photos from production process of the chip seal samples

Table 3.5 Aggregates spreading rate and flakiness sieves sizes

Chip Sizes (mm)	ALD (mm)	Flakiness Sieves (mm)	ASR (ml)		
			Calculated*	Used	
				Natural Aggregates	Slags
8–10	9	5.0	710.53	720	800
10–12	11.3	6.3	888.16	900	1000

While manufacturing the chip seal samples, series of procedures listed below were followed. Besides, manufacturing process are given visually in Figure 3.9

- Evaluating the quantity of aggregates in terms of volume,
- Grassing the plate’s surface and coating it with aluminum foil paper,
- Spreading the aggregate uniformly on the coated plate,
- Spreading limestone powder with certain gradation that is passing 0.600-mm and retaining on the 0.300-mm sieves to fill the void between oriented aggregates for avoiding flowing the resin to the surface of plate and to ensure certain macro texture
- Preparing the resin for adhesive purpose,
- Pouring the resin on the plate, and spread with a spatula for smooth surface,
- Cooling the resin for 24 hours and putting the sample out of the plate,
- Removing the sample from the plate and if the resin has flowed over the sample so as to close the micro and macro texture, the surface is drilled.

Figure 3.9 Photos from production process of the chip seal samples

3.4 Macro Texture Measurements

3.4.1 Outflow meter test method

ASTM E 2380 (ASTM, 2012e) identifies outflow meter test method. This test method uses a volumetric approach of measuring pavement mean texture depth (MTD). The principle is clear that the greater the texture, the less time will be taken up by it. The test is performed a special device that holds water in a certain volume. With implementation the test, the researchers have an idea of how long a known volume of water escapes through voids on the pavements surface being tested in case of gravitational pull.

The device is in the form of a vertical cylinder, which allows the body to hold water. A rubber ring is disposed centrally on the base and upper opening of the device body. The spring-loaded plunger controls the water discharge from the device. Float switches with an electronic timer of 0.01 accuracy via cable are mounted vertically on top and bottom. This feature of the device contributes to more accurate and reliable results (ASTM, 2012f). The procedure for estimating the texture depth of the sample by this method is as follows.

The device is placed on the pre-cleaned road surface with a piston that prevents water from escaping from the discharge opening. In order to prevent pre-operation of the timer, some amount of water is added to the device and the switch is raised to the upper level of the device. The timer connected to the switches is reset before the piston is released. After the piston is released, the water flows through the device base and the pavement voids passes through the upper switch, allowing the timer to operate. The timer stops counting when the water level drops down from the switch located at the base of the device. The time elapsed when the water level in the device drops from the upper switch to the switch level in the base is shown in the timer and it is called outflow time. Finally, mean texture depth (MTD) is determined with following equation.

$$MTD=\left(\frac{3.114}{OFT}\right)+0.636 \tag{11}$$

where, OFT is average outflow time.

In order to get preferable data and results, at least four tests are applied on the samples and arithmetic average of the outputs is being accepted as average time. Photos from test application is given in Figure 3.10.

Figure 3.10 Test operation with Hydrotimer

3.5 Skid Resistance Measurements

In the scope of this thesis, two kind of skid resistance tester method were used. The reason is to get data for evaluating skid resistance of the chip seal samples produced in laboratory in case of both high speed and low speed. The other unique reason is to make a comparison between the two and related analytical methods.

3.5.1 Dynamic friction tester method

The Dynamic Friction Tester (DFT) is a portable device that measure frictional properties of the surfaces and so dynamic coefficient of friction both in the laboratory and in the field. Three rubber slider pads fitted to the lower part of a disk that spin horizontally and has a diameter 284 mm are the main parts of the tester for measuring friction properties of samples. Once the operator set and software controlled circumferential speed is reached by the spinning disc, the control system initiates water delivery and lowers the spinning disc to the test surface. The rubber sliders thus will be pressed to the surface by the weight of the device and the torque generated by the friction between the rubber sliders and the test surface as spinning disc is slowed down is measured. The calculated force then is divided by the weight of the disk and motor assembly to calculate coefficient of friction. When used with pavement macro texture measurement, such as mean profile depth, dynamic friction tester results can be utilized to calculate the International Friction Index(IFI). The speed range is generally from 90 km/h down to 5 km/h. The tester can be connected to a personal computer and the data can be displayed on the screen and saved on disks. The friction at 20, 40, 60, and 80 km/h is recorded as a graph of the friction-speed relationship. The test was performed according to ASTM E 1911 (ASTM, 2009) and the outputs are reported as friction coefficient (μu). Optionally, the operator can display a friction-speed relationship graph in the desired speed ranges or in a specific speed (ASTM, 2009; Saito et al., 1996). A picture (Rado and Kane, 2014) is given to show DFT in the following figure.

Figure 3.11 Dynamic friction tester

3.5.2 International friction index

One of the main factors influencing traffic safety is the friction between the vehicles' tires and the road surface (Wallman and Åström, 2001a). Environmental factors, driving factors, vehicle factors, road surface geometry and characteristics factors can be listed as the factors that have an effect on skid resistance (Andriejauskasa et al., 2014). As it can be understood these factors, there are several methods developed to measure friction characteristic of pavement. Some of them are directly based on measure the coefficient of friction between tires and road surfaces. Another one based on determination of coefficient of friction between rubber pads and road surfaces as is the case for the DFT and the BPT (Saito et al., 1996). Moreover, for the classification of pavement surfaces friction properties some reference scale has been developed (Güneş and Topal, 2017). One is well-known that International Friction Index (IFI) that being developed by PIARC-World Association. The data obtained from the friction resistance and texture measurements are applied worldwide for the purpose of determining the pavement surface characteristic (PIARC, 1987b). Friction resistance parameters is supplied by DFT and the texture characteristics supplied by both volumetric and laser based methods. The IFI consists of a Speed Constant (Sp) and Friction Number (Fs) and is notified as IFI (Fs, Sp) according to ASTM E 1960 (ASTM, 2012b) Evaluating Coefficient of Friction F(s) at any speed S is probable as the IFI is acquired. These two parameter is calculated with the following equalities.

$$Sp = 14.2 + 89.7 \times MPD \tag{13}$$

$$Fs = 0.081 + 0.732 \times DFT_S \times Exp^{((S-60)/Sp)} \tag{14}$$

3.5.3 British pendulum tester method

The British pendulum tester, an impact type device, is used to measure the loss of energy lost by the rubber slider fixed to a rotating arm during contact with the sample surface. This test method is developed by the British Transport Research Laboratory (TRL). The tester can be used both in the laboratory and the field due to its portability. Because of the swing speed of the rotating arm is about 10 km/h, the tester measures the surface micro texture rather than the macro texture. The data obtained as a test output is called as British Pendulum Tester The test procedure followed in this study is ASTM E 303 standard test method (ASTM, 2012a).

Before starting the test, the operator must sweep the loose particles on the samples in order to prevent a clean surface and misreading. Also to obtain a surface in the balance, the leveling screws is being turned until the bubble is centered in the water gauge and the sample is placed on the tester. As the next step, calibration of the tester must be done by the operator. This procedure is important to get correct readings. To do that, the operator fixes the friction ring until the pendulum swing carries the pointer of the tester to zero.

To properly adjust the slip length on the sample surface of the rubber slider, the pendulum arm is slightly lowered until the rubber slider first touches one side of the sample and then on the other side of the vertical. The slip length can be explained as the distance between the two points where rubber slider edge touches the surface. By means of the lifting arm, the rubber slider is lifted from the test surface, thereby preventing excessive wear of the rubber slider when moving the pendulum arm along the contact arc. When the apparatus is set correctly, the sliding length, measured with the Perspex setting gauge provided, should be between 125 mm and 127 mm for a site test, and 76 mm for a laboratory test.

Figure 3.12 Contact length adjustment

To perform the test, the sample must be wet firstly. Then the operator releases the pendulum arm and provide pendulum arm to swing through its arc. It is important to catch the pendulum arm before it touches the sample surface on its return path. This procedure is repeated four times and the results are reported (ASTM, 2012a).

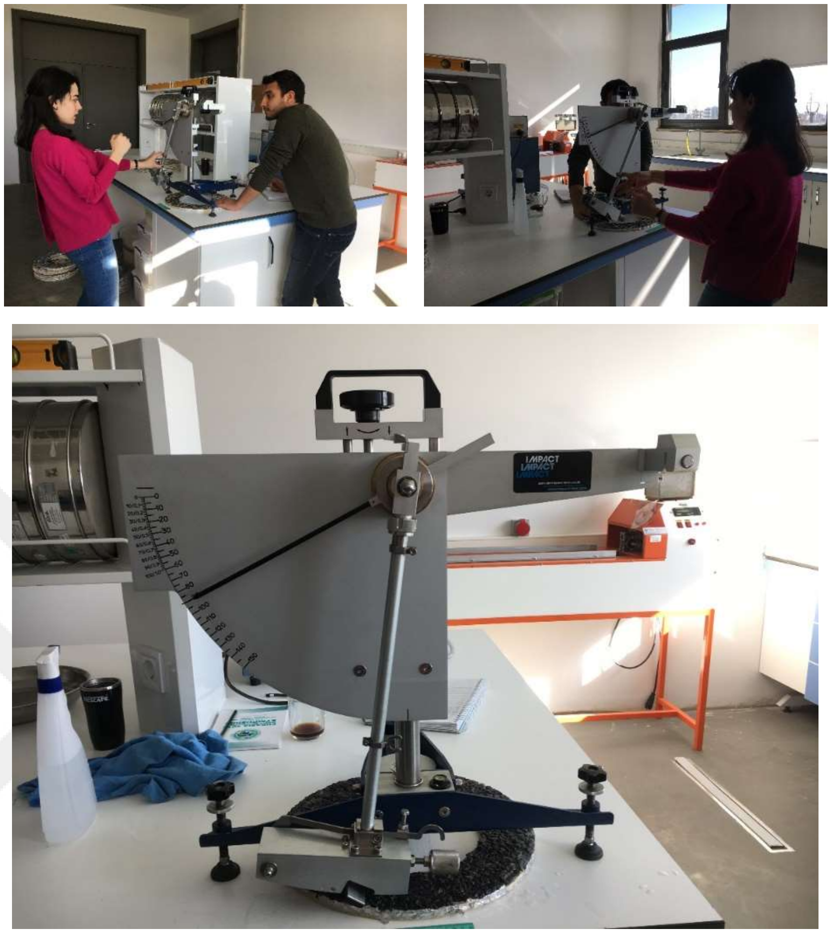


Figure 3.13 Application the test on sample

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Properties of Aggregates

4.1.1 Physical and mechanical properties

According to variation of aggregate geological formations, their mechanical and physical features also changes. Particularly, with the changes in the lithological features of a material, abrasion, polishing resistance, weathering and fragmentation performances of the material also vary. Mechanical and physical properties of the aggregates used in this thesis are given in Table 4.1.

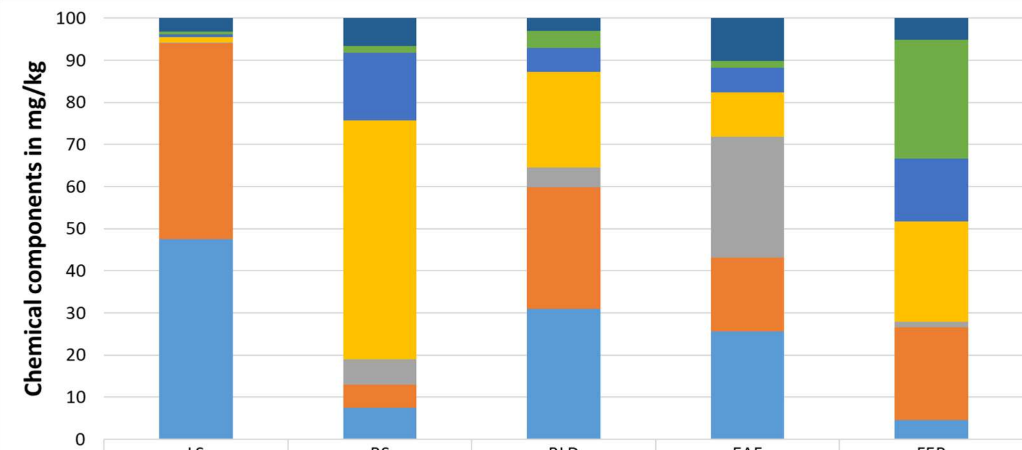
Table 4.1 Mechanical and physical properties aggregates

Order	Tests	Standards	Units	Results				
				LS	BS	BLD	EAF	FER
1	Abrasion resistance	EN 1097-1	%	11.7	9.4	11.3	9.5	7.6
2	Fragmentation resistance	EN 1097-2	%	24.4	25.9	17.5	22.9	16.5
3	Weathering resistance	EN 1367-2	%	8.1	9.4	6.2	2.3	6.1
4	Polishing resistance	EN 1097-8	PSV	41.6	52.4	57.9	76.1	61.7
5	Dry unit weight	EN 1097-6	g/cm3	2.69	2.67	2.73	3.40	2.93
6	Water absorption	EN 1097-6	%	0.28	1.44	0.90	1.79	1.10

Mechanical and physical properties of the aggregates vary with the changes in their place of supply and origins. As seen in Table 4.1 ferrochromium slags have the best resistance performance (7.6%) while LS has the worst value (11.7%). For each material used, thermal weathering varies. Moreover, slags have higher polishing resistance and water absorption percentage and dry unit weight than the natural aggregates. However, these properties can be said to be undesirable depending on the application areas of the materials. Depending on the limitations given in Turkish Highway Technical Specifications, a relevance was monitored as the test outputs compared.

4.1.2 Chemical properties

Chemical composition of the materials in terms of both the mineral and element contents were identified by X-Ray based analyzes. By XRF analysis, chemical compound for each material was detected as specified at EN-15309 test standard. Also, XRD analysis was used to determine mineral composition of the materials as in test standard mentioned above. X-Ray based analyses results are shown in figures 4.1 and 4.2, respectively.



	LS	BS	BLD	EAF	FER
Others	3.16	6.62	3.07	10.18	5.11
MgO	0.76	1.6	4.01	1.65	28.3
Al2O3	0.64	16	5.62	5.77	14.9
SiO2	1.18	56.8	22.7	10.6	23.8
Fe2O3	0.26	6	4.7	28.7	1.35
CO2	46.5	5.48	28.9	17.5	22
CaO	47.5	7.5	31	25.6	4.54

Figure 4.1 XRF results for chemical elemental composition

As seen in Figure 4.1, LS mainly consists of calcium oxide and carbon dioxide, whereas silicon oxide is the main component of BS, as expected. The other natural one, river basin crashed stone is mainly constituted calcium oxide, carbon dioxide and silicon oxide. Besides calcium oxide, carbon dioxide and silicon oxide components, ferric oxide was found as another chemical components EAF slags. At last, carbon dioxide and silicon oxide, magnesia and alumina have been revealed in Ferrochrome slags. Accordingly, XRF analysis results indicated that as the materials' geological formations and manufacturing change, the compositions of the materials also vary.

On the other hand, to make a brief discussion on the results of XRD analyses from Figure 4.2 that show mineral composition of aggregates, it is worth to highlight that mineral components of aggregates vary depending on their geological formation in nature and the manufacturing processes in industrial plant, which is similar to XRF analyses. Mineral composition gathered by XRD analysis also seem to be consistent with these XRF results. The main minerals that exhibited for the materials were displayed in the given figures. To sum up in the light of literature review, all samples have chemical contents that reflect their formation.

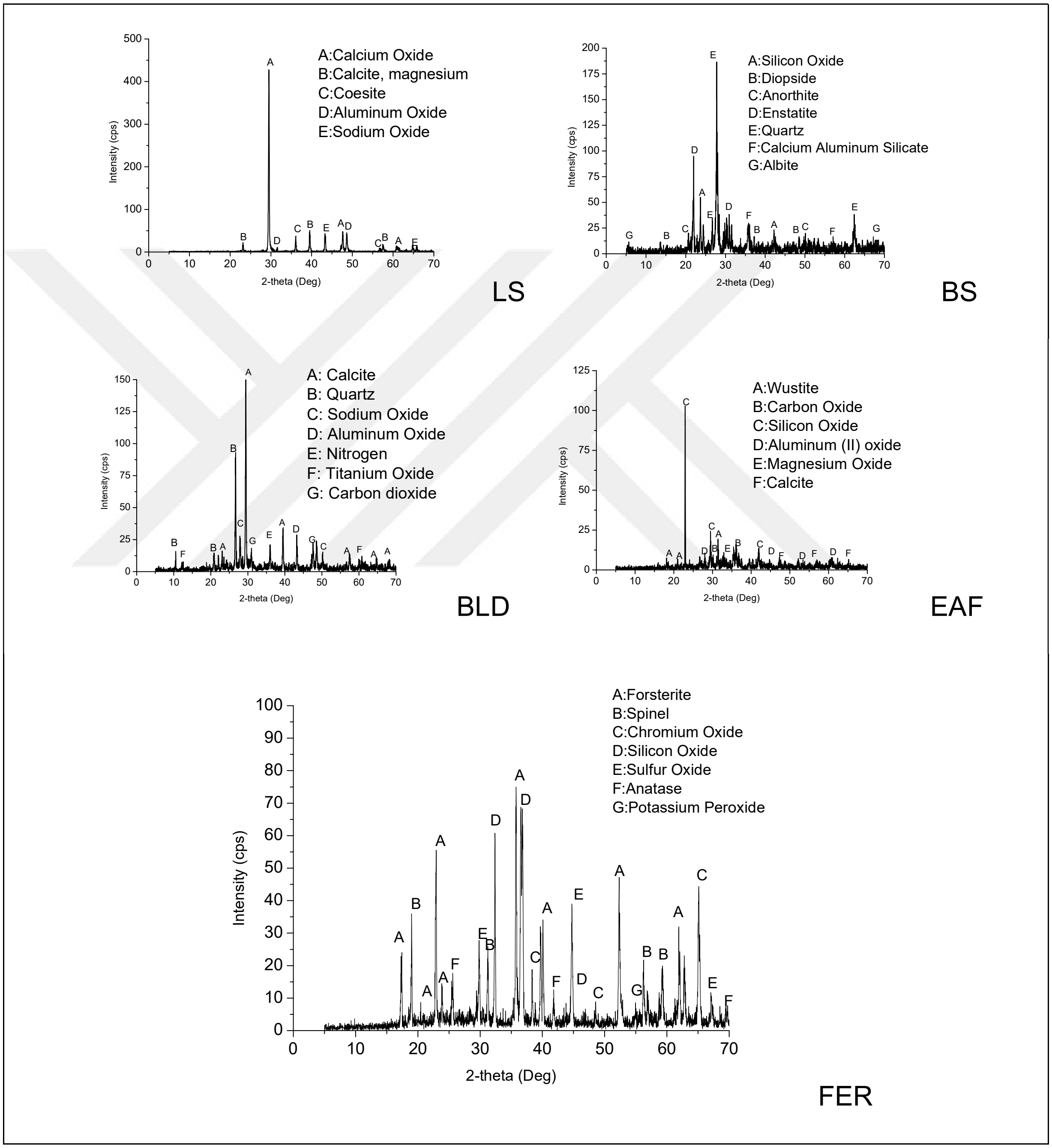


Figure 4.2 XRD results for mineral composition

4.2 SEM Analysis of Aggregates

In this study, randomly selected 8 and 10 mm cubical aggregates' surfaces at 3 polishing levels which were mentioned above have been monitored via SEM at a constant magnification (60X) for imagining process. Images were taken more than one time during examination because of focusing problem due to aggregate surface topography. Scanning electron microscope images according to aggregate type and polishing levels are shown in Figure 4.3

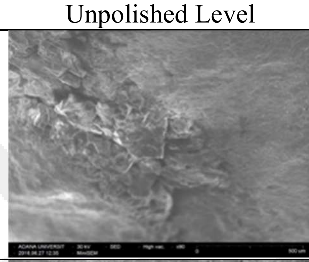
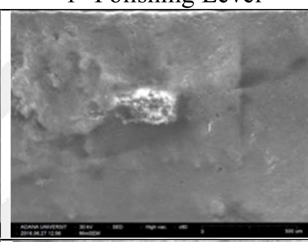
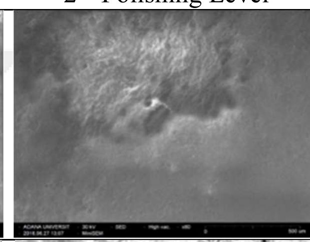
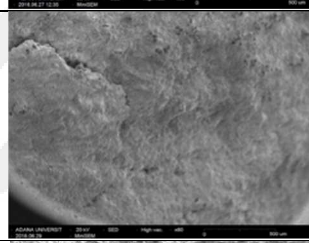
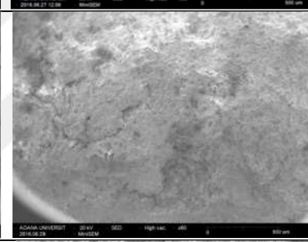
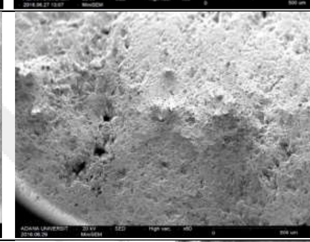
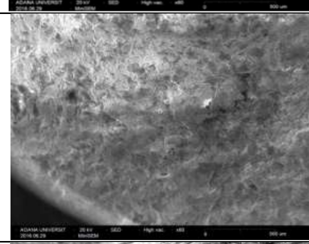
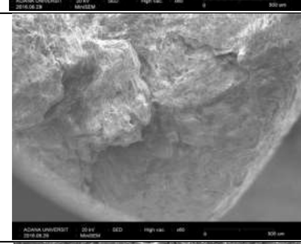
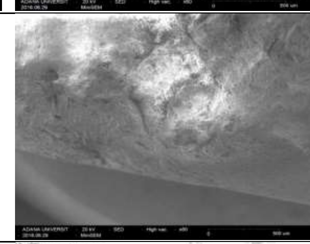
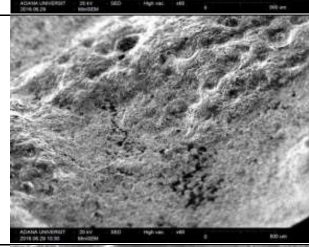
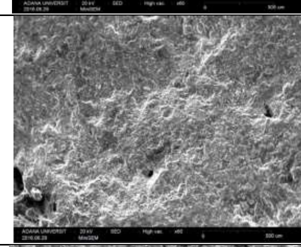
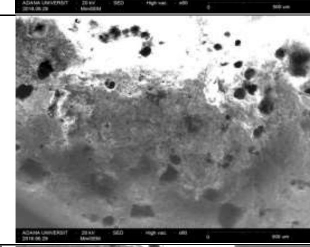
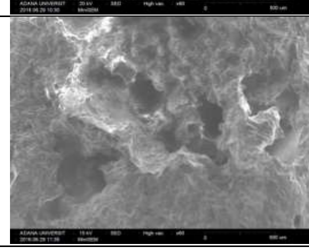
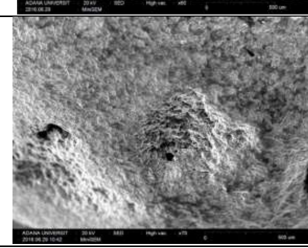
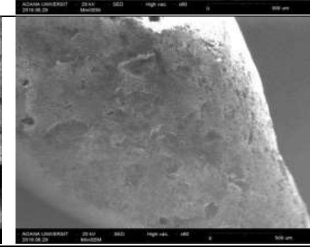
Order	Materials	Unpolished Level	1st Polishing Level	2nd Polishing Level
1	Limestone			
2	Basalt			
3	River Basin Crashed Stone			
4	Electric Arc Furnace Slag			
5	Ferrochromium Slag			

Figure 4.3 SEM images at different polishing levels

To make a brief discussion, we can say that at the beginning for all aggregate types at unpolished level micro texture of the surfaces of each type vary from each other and as polishing levels increases the loss of micro texture of the aggregates' surfaces also increases. As comparing with natural aggregates, slags denote their porous structures even at 2nd level of polishing.

4.3 Macro-Texture Depth Evolution

In this thesis, outflow meter test method is used to detect chip seal macro texture depths, which is a kind of standard volumetric test methods an according to ASTM E 2380. To evaluate international friction number (IFI), it was required to supply mean MPD values, however, MTDs derived outflow meter test methods can be used to estimate MPDs. As known that aggregates which have 8-10 mm and 10-12 mm particles sizes at three polishing levels were utilized to manufacture chip seals at different depths of macro texture. In the following two sections MTDs gathered by OFM test for all samples are given in Table 4.2.

Table 4.2 MTDs for chip seal samples

Grain Sizes (mm)	Polishing Level	MTDs LS	BS	BLD	EAF	FER
10-12	Unpolished	2.09	1.78	1.76	2.14	1,63
	1st Polishing	1.91	1.59	1.63	2.01	1,61
	2nd Polishing	1.74	1.58	1.52	1.71	1,50
Average (mm)		1.91	1.65	1.64	1.95	1.58
Standard Deviations		0.14	0.09	0.10	0.18	0.06
8-10	Unpolished	1.74	1.69	1.60	1.71	1,50
	1st Polishing	1.59	1.42	1.39	1.62	1,39
	2nd Polishing	1.34	1.43	1.29	1.47	1,40
Average (mm)		1.56	1.51	1.43	1.60	1.43
Standard Deviations		0.16	0.12	0.13	0.10	0.05

Depending on the Table 4.2, MTDs of samples would be seen as the higher for samples with bigger chip size, as expected. The measured data of the studied samples produced with the unpolished aggregates were assessed as greater than those produced with polished aggregates. The original aggregates' surface roughness is better than the polished ones depending on loss of micro texture after abrasion. Since, EAF steel slag has more porous structure or rougher surfaces, MTDs for that measured higher than natural aggregates for both chip sizes.

4.4 Skid Resistance Evaluation

In this section of thesis, British pendulum tester (BPT) and dynamic friction tester (DFT) results are initially presented. Then, International friction index (IFI) values were determined based on the friction coefficient obtained by DFT results and estimated MPDs values. Finally, a comparative analysis was performed between the DFT results for different measurement speeds.

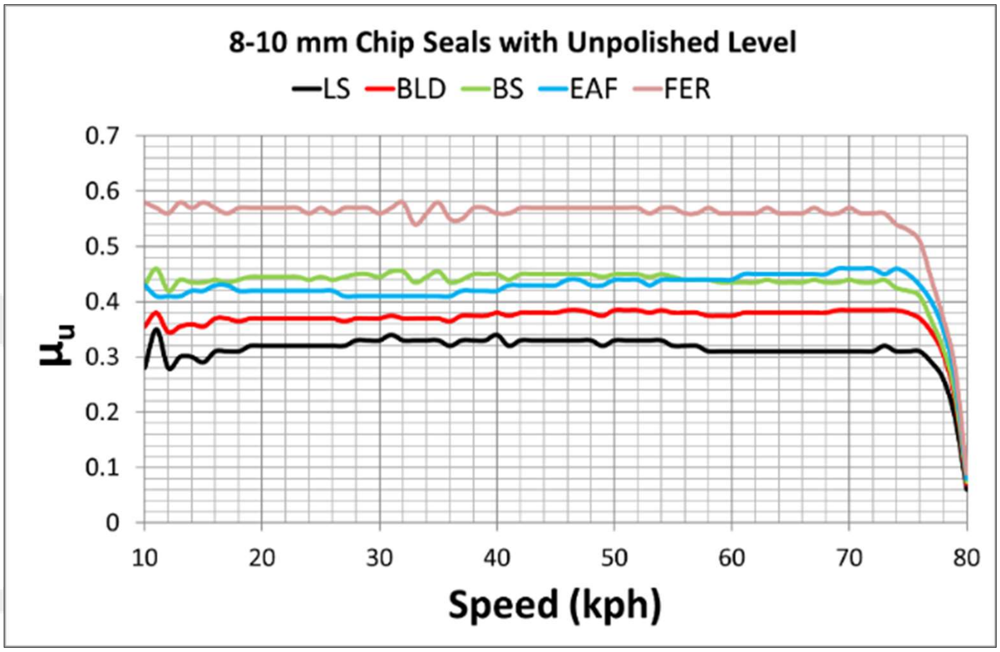
4.4.1 Dynamic friction tester results

The results of skid resistances of chip seals were determined with DFT is reported for 10, 20, 40 and 60 kph. To show those results based on aggregate type, size and polishing level and to make a graphical representation for those data for mentioned speed, following figures were presented.

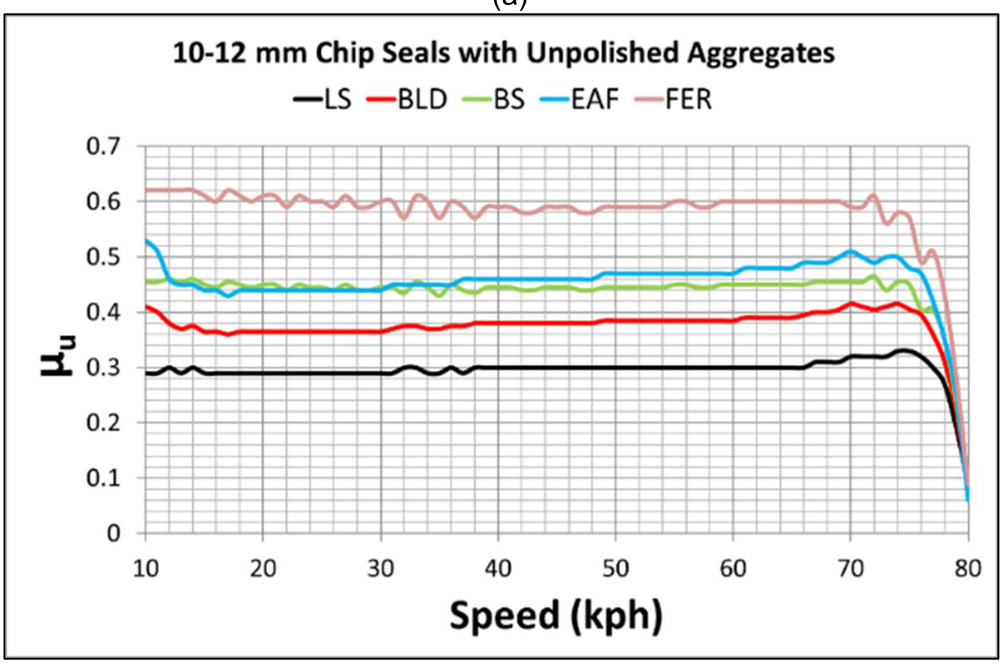
The following remarks can be highlighted for 8-10 mm and 10-12 mm chip seals produced at laboratory with different aggregates including natural and slag ones and polishing levels based on the numerated from "a" and "b" with for chip seals.

- In general, the tendency of development of skid resistance was in direction of decreasing with increasing polishing levels respect to RNs.
- For all polishing level, the highest skid resistance performances were observed in slags whereas the lowest was monitored in limestone. In particular, in order of Ferrochromium slags, EAF slags, basalts, river basin crashed stone and limestone can be indicated from highest to lowest in terms of aggregates skid resistance performances.
- Exceptionally, chip seal sample with 10-12 mm basalt at all polishing level for certain speed (10 up to 40 kph) and the ones with 8-10 mm basalt at unpolished level for certain speed (10-60 kph) showed better skid resistance than EAF slag.

- At each polishing level, 10-12 mm chip seal samples have higher skid resistance performance comparing with 8-10 mm ones.

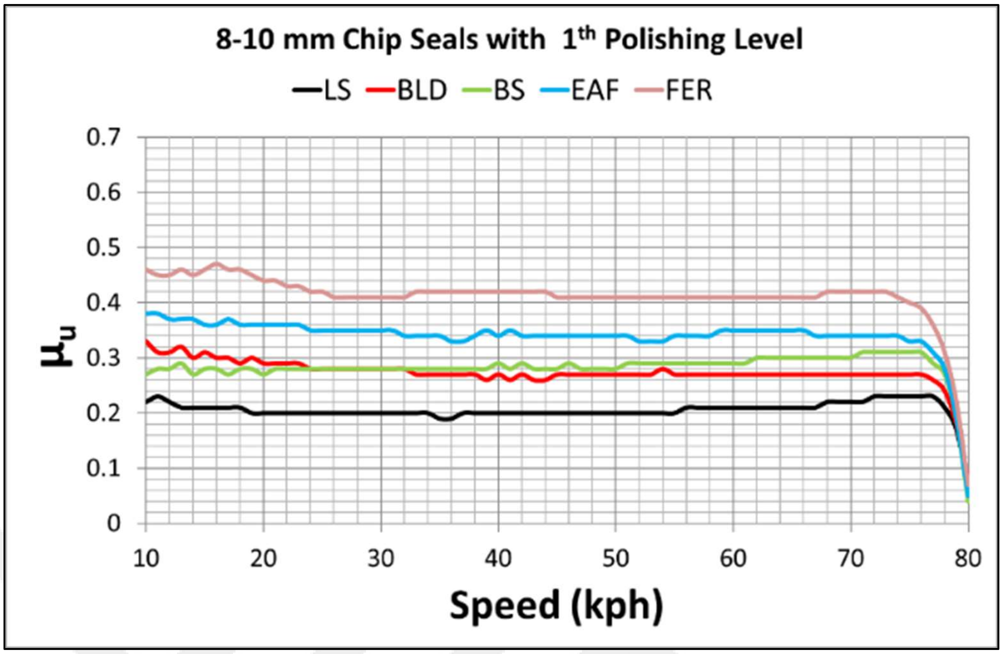


(a)

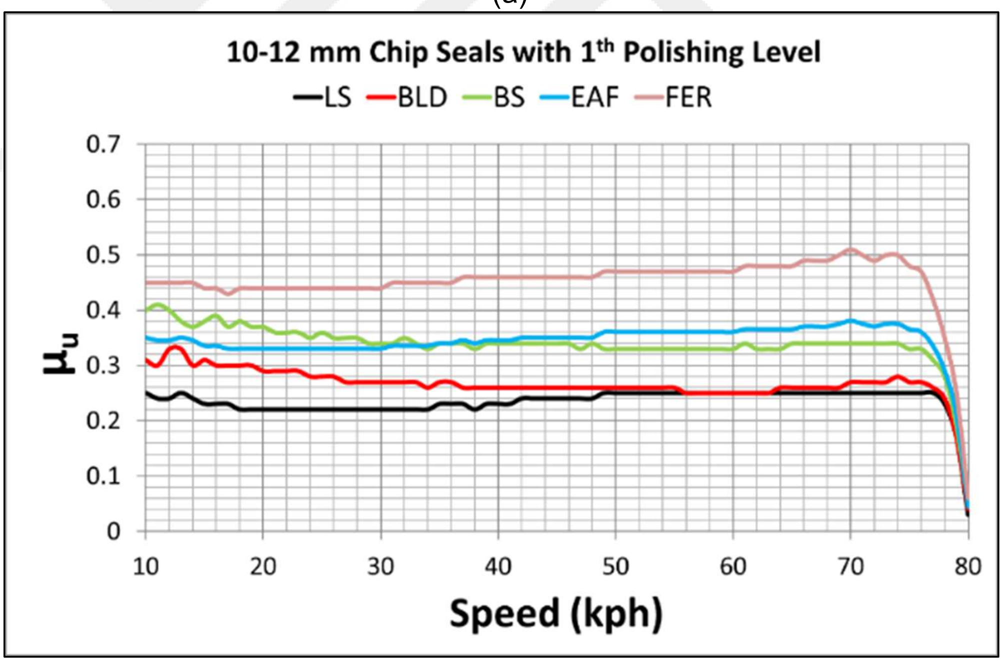


(b)

Figure 4.4 DFT for 8-10 mm (a) and 10-12 mm (b) for chip seals at unpolished level

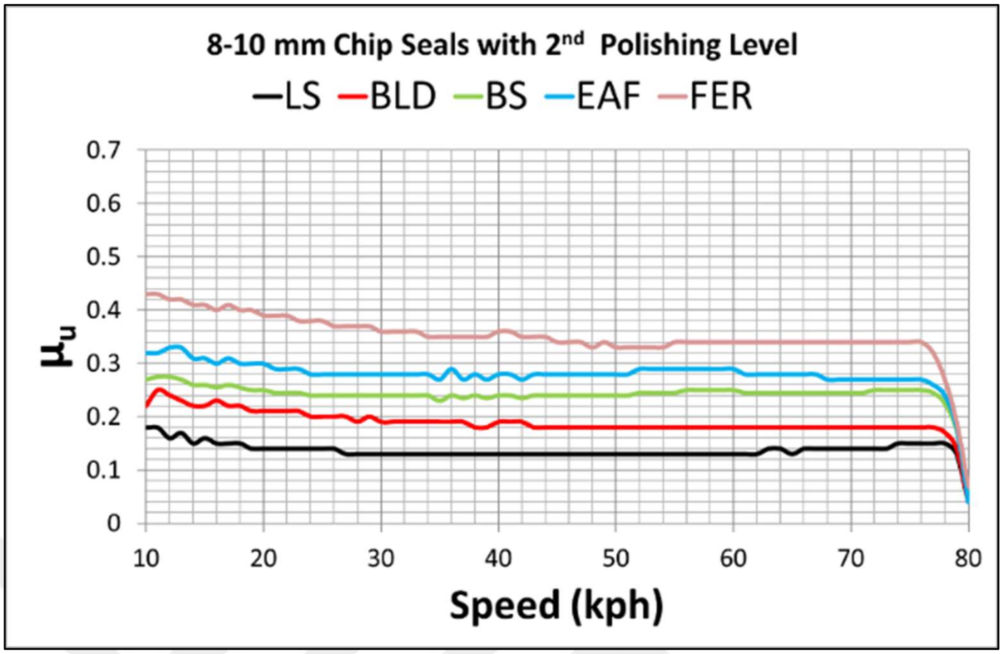


(a)

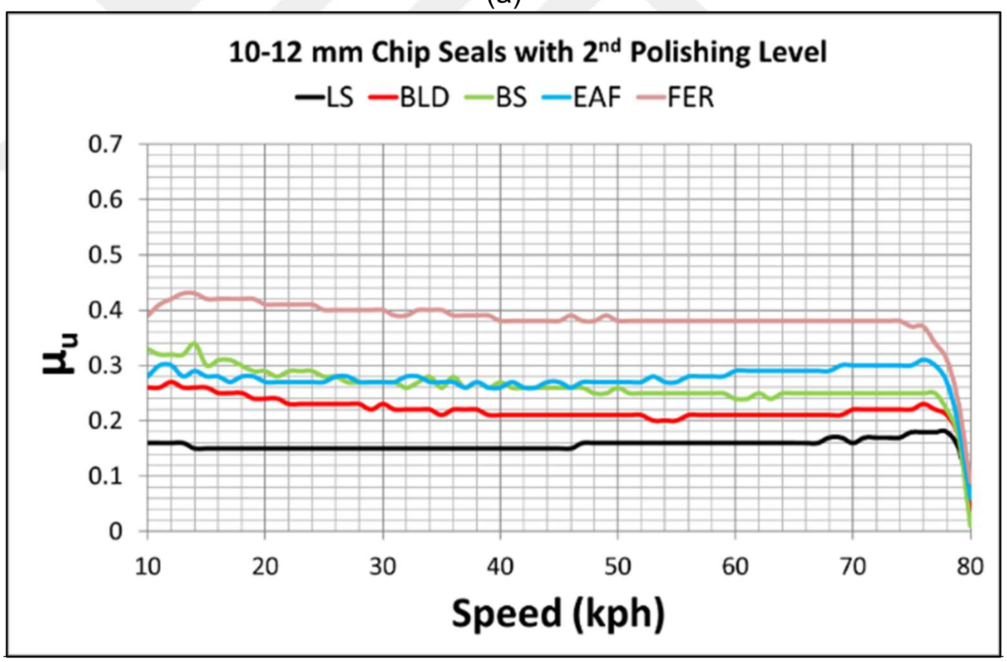


(b)

Figure 4.5 DFT for 8-10 mm (a) and 10-12 mm (b) for chip seals at 1st polishing level



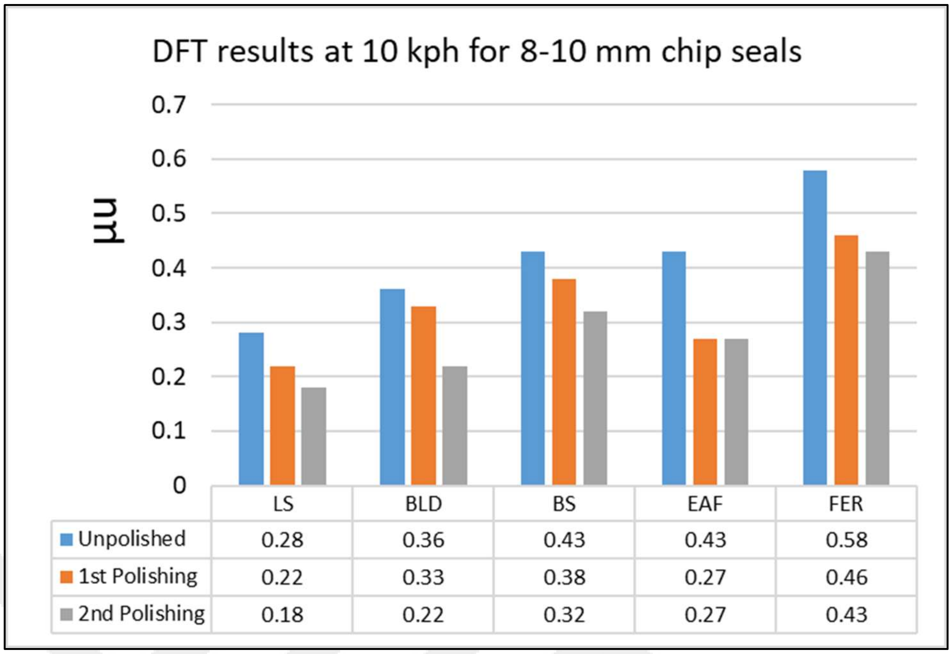
(a)



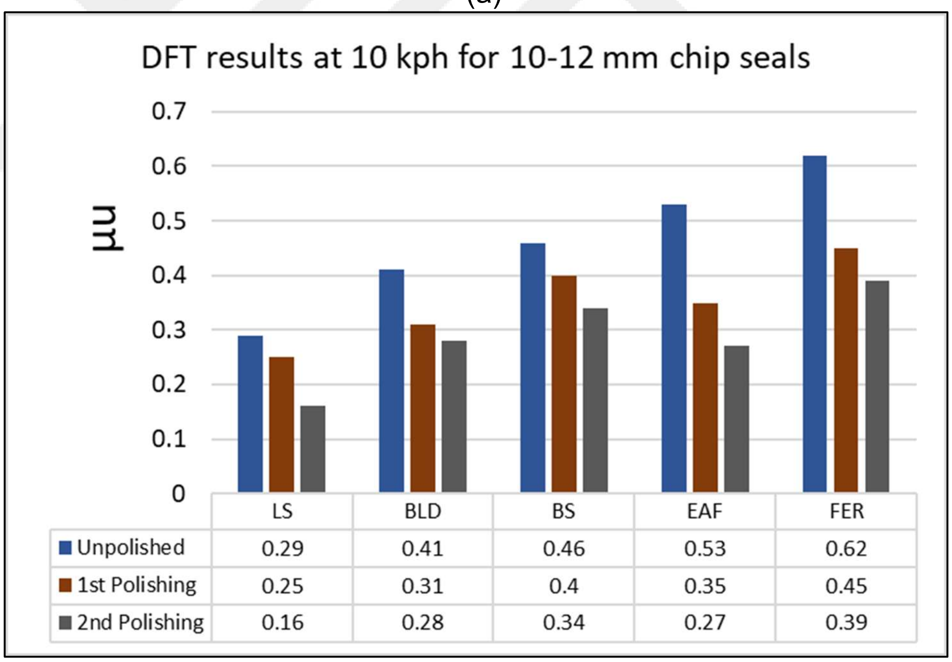
(b)

Figure 4.6 DFT for 8-10 mm (a) and 10-12 mm (b) for chip seals at 2nd polishing level

In the scope of this thesis, it was planned to make comparative analyses between the results gather from different tester. It was thought to be worth to give friction coefficients for the specific speed such as 10, 20, 40, and 60 kph, both numerically and graphically. Following figures were formed due to this concern.

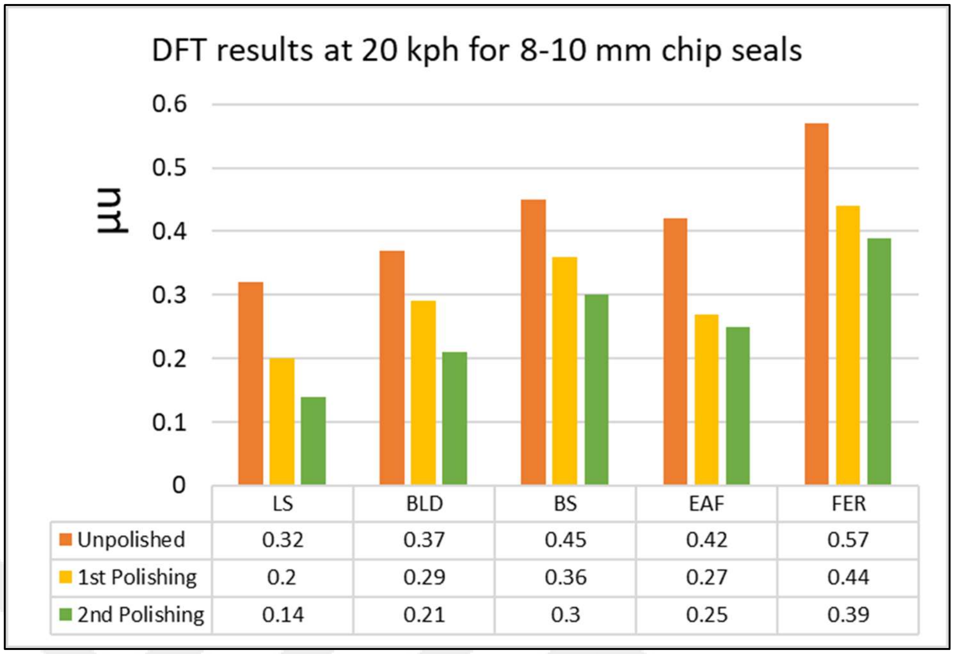


(a)

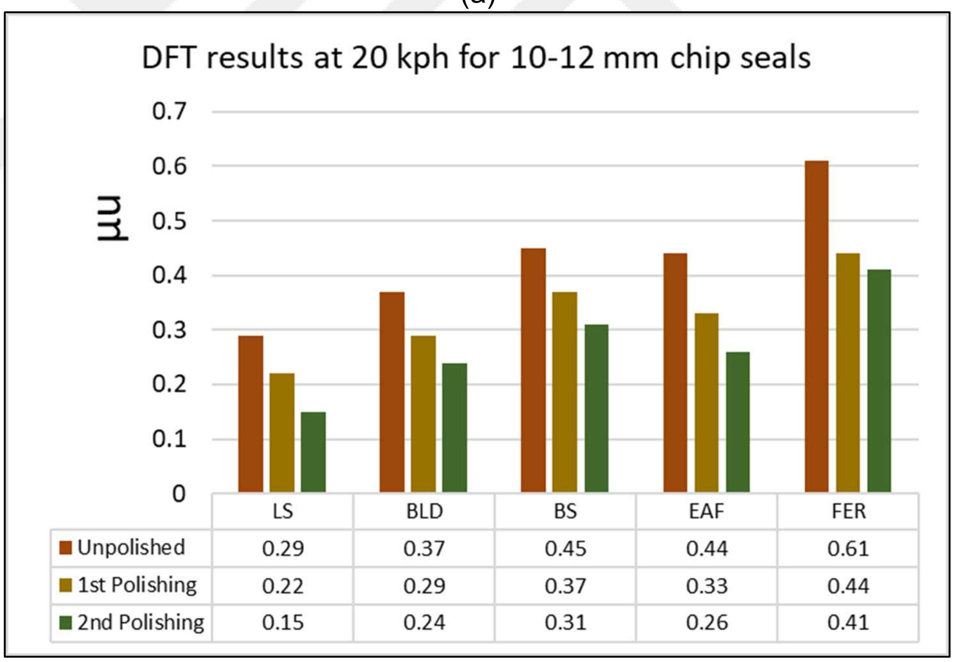


(b)

Figure 4.7 DFT for 8-10 mm (a) and 10-12 mm (b) chip seal samples at 10 kph

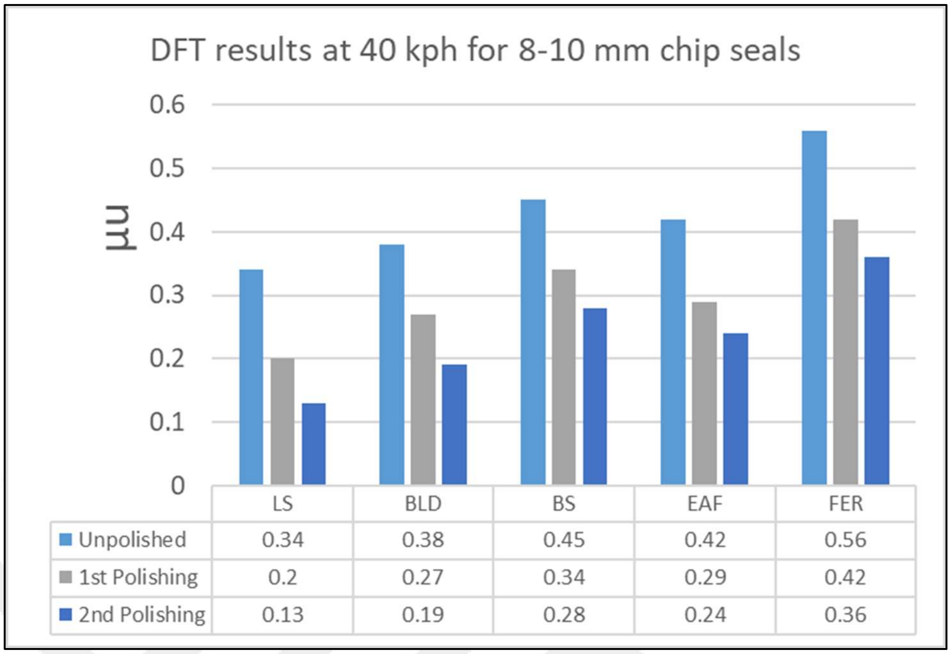


(a)

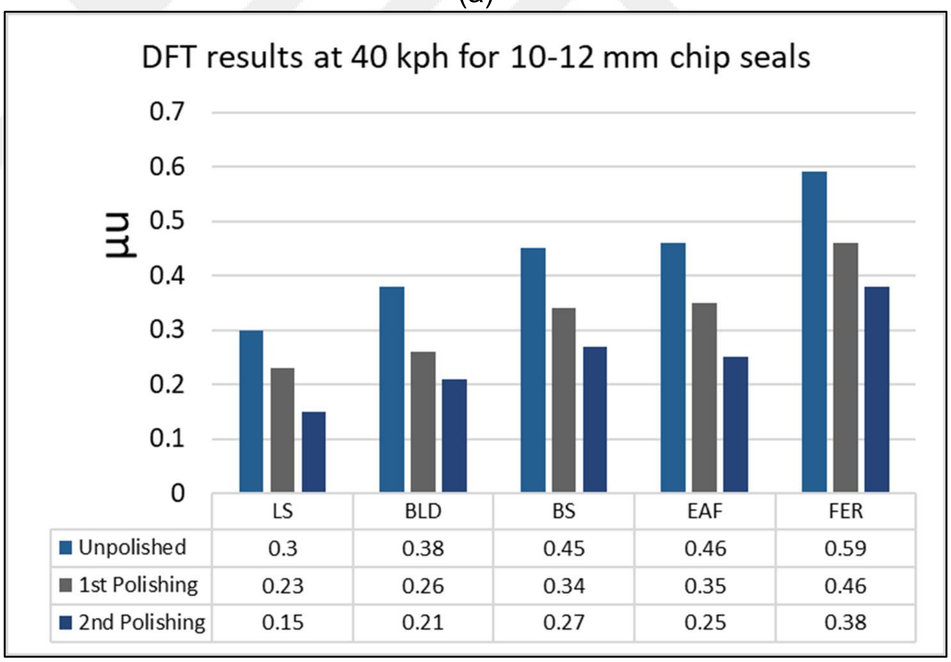


(b)

Figure 4.8 DFT for 8-10 mm (a) and 10-12 mm (b) chip seal samples at 20 kph

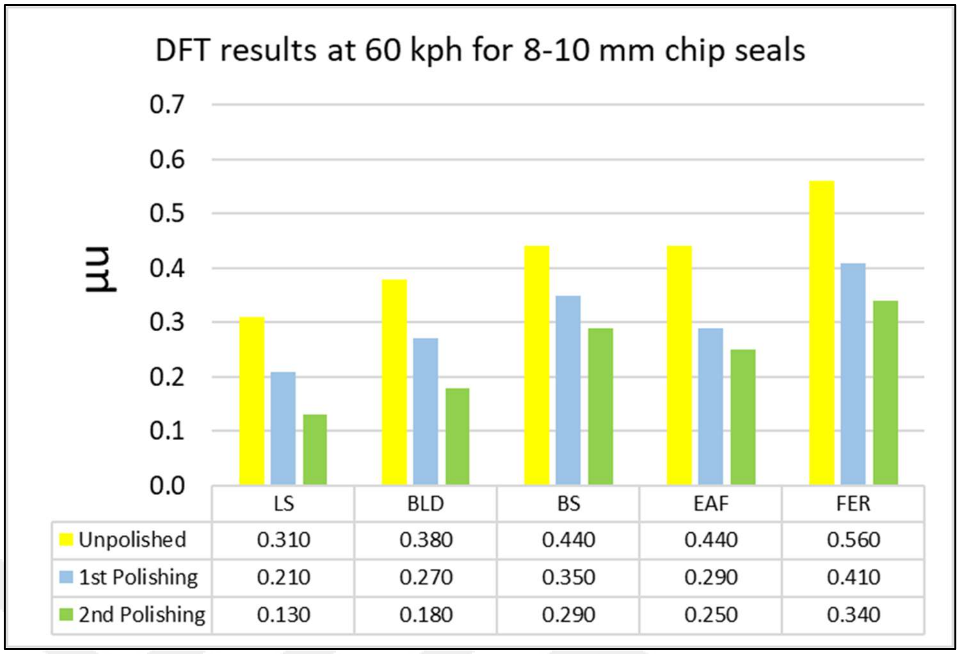


(a)

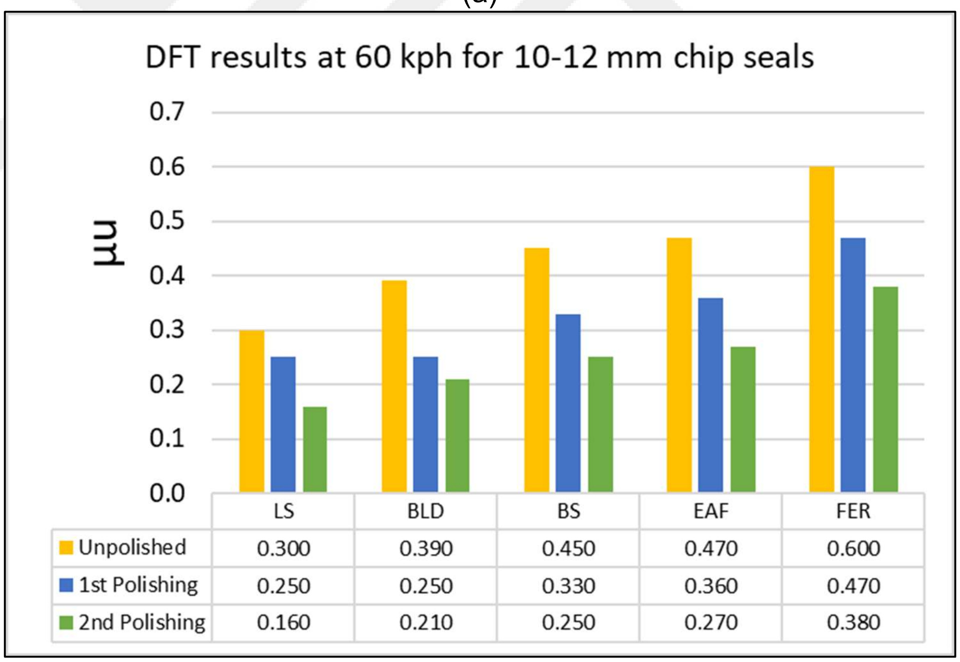


(b)

Figure 4.9 DFT for 8-10 mm (a) and 10-12 mm (b) chip seal samples at 40 kph



(a)



(b)

Figure 4.10 DFT for 8-10 mm (a) and 10-12 mm (b) chip seal samples at 60 kph

To make clear sense about the skid resistance characteristics of samples and to prove chip seals with slags at all polishing level is significantly higher than chip seals with natural aggregates, reporting friction coefficient at 65 kph was thought to be valuable. Relative comparison respect to slags figured out utilizing the data given in the Table 4.3.

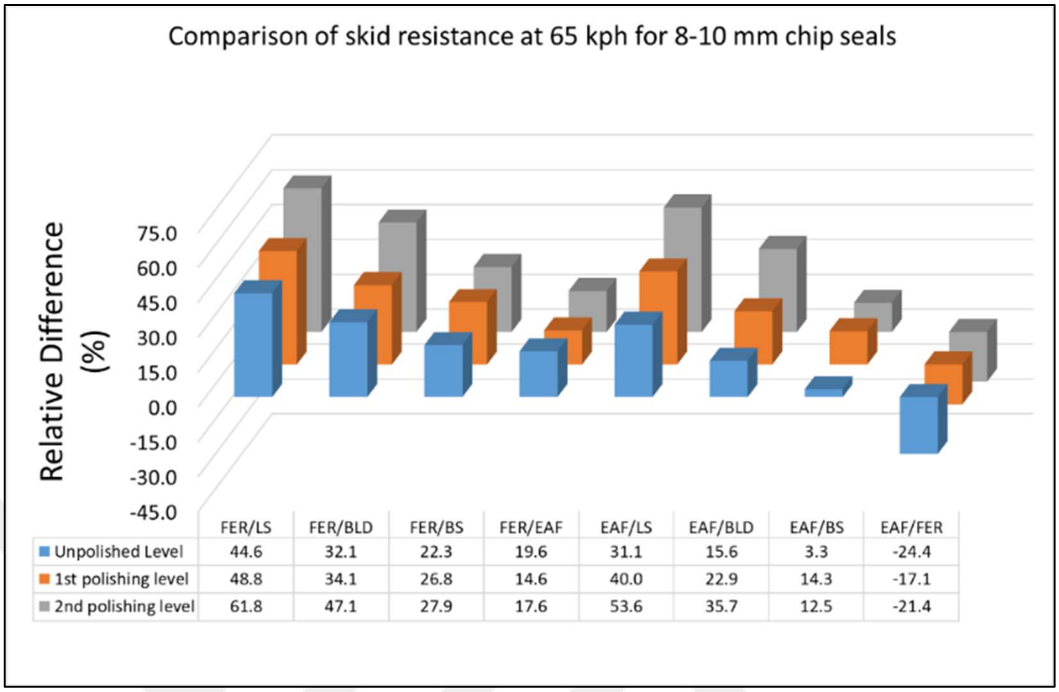
Table 4.3 Friction coefficient at 65 kph

Aggregate Size		8-10 mm			10-12 mm		
Polishing Level		Unpolished	1st	2nd	Unpolished	1st	2nd
		Friction Coefficient (µu)					
Materials	LS	0.31	0.21	0.13	0.30	0.25	0.16
	BLD	0.38	0.27	0.18	0.39	0.26	0.21
	BS	0.44	0.30	0.25	0.45	0.34	0.25
	EAF	0.45	0.35	0.28	0.48	0.37	0.29
	FER	0.56	0.41	0.34	0.60	0.48	0.38

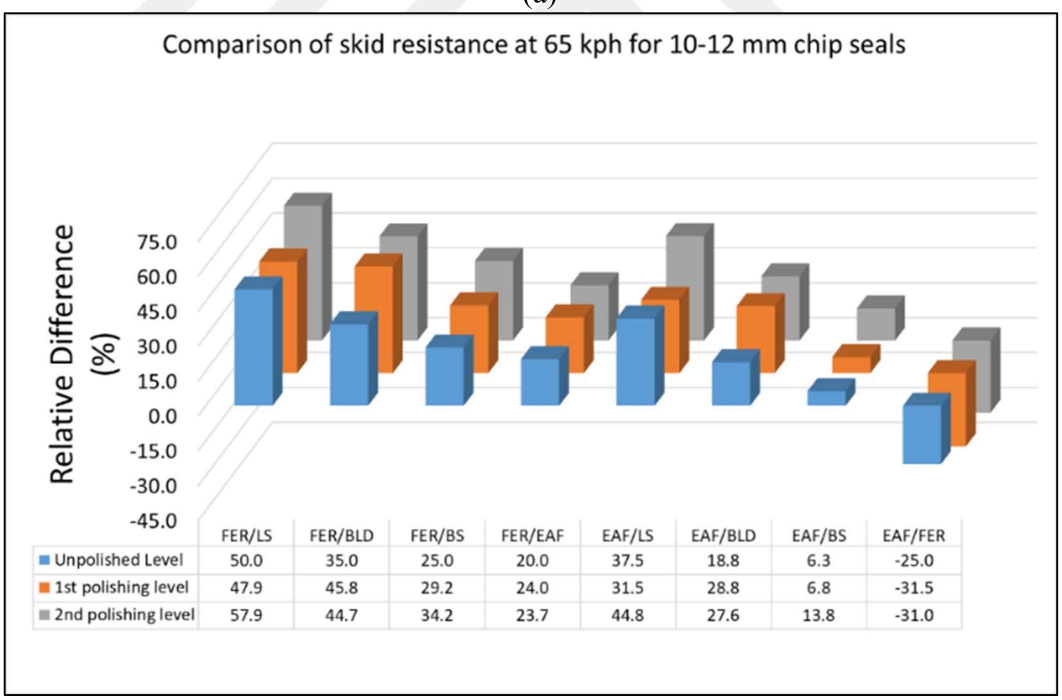
The relative differences were done between the slags and natural aggregate and calculation was done by the following equality

$$\%RD\ FER = ((FER\ \mu_u - LS\ \mu_u) / FER\ \mu_u) \times 100 \qquad (15)$$

To discuss on relative differences, it can be reported that RD for 8-10 mm chip seal is variable and the values ranging between 60 to 3 %, whereas for 10-12 mm chip seal, RD was found out as ranging roughly between 57 to 3 %. In all case, slags exhibited superior skid resistance performance of each self.



(a)



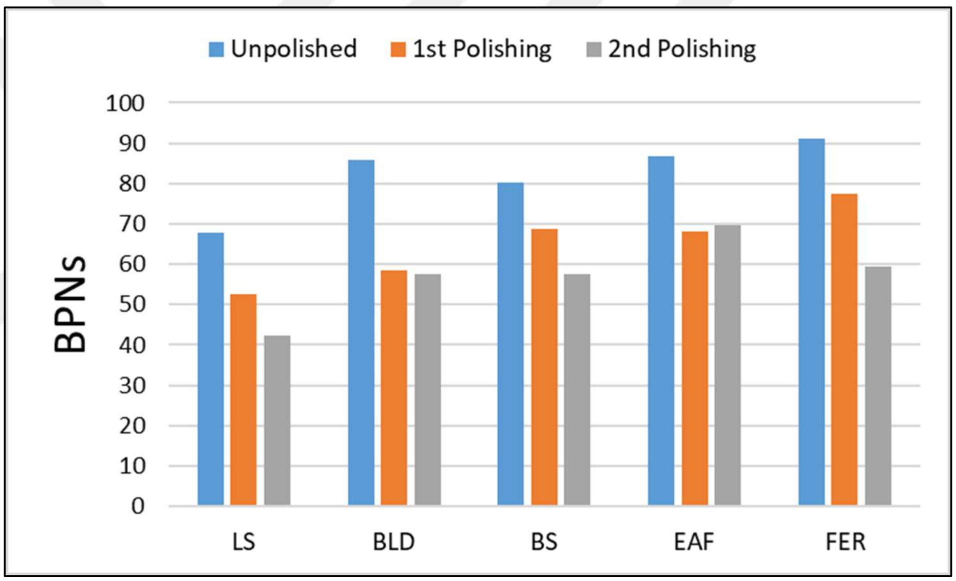
(b)

Figure 4.11 Relative differences for chip seals

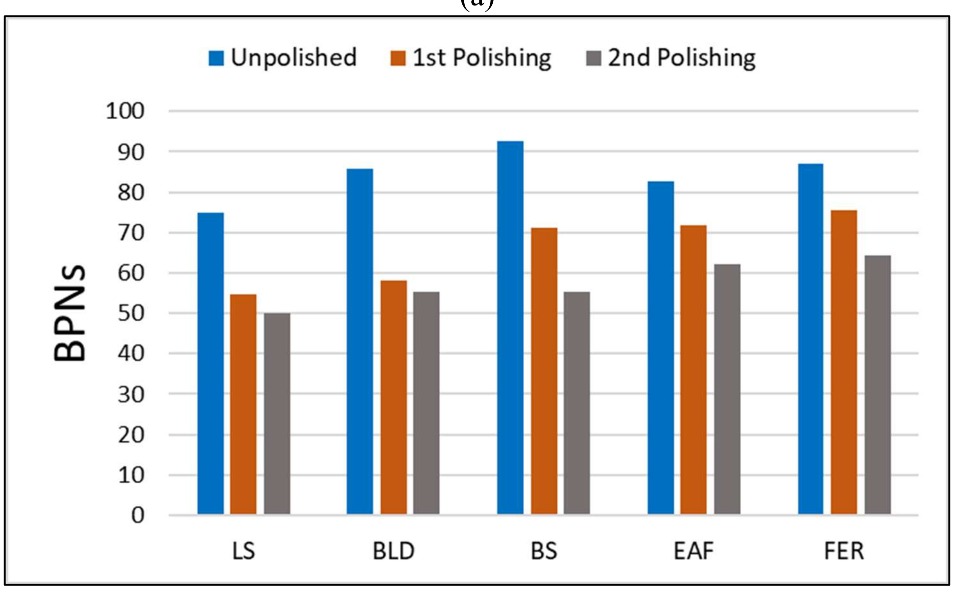
4.4.2 British pendulum tester results

BPT test method is a low speed measurement method and relatively determined the BPNs. Although the tests were performed by a single operator, getting sensitive results is almost not possible. The results of BPNs were given in the following

Figure 4.11 codded with “a” and “b”. Depending on the results, it can be said that there were not any considerable variations between the results both of grain sized chip seals at all polishing level. However, there were observed certain decreases in BPNs as polishing level is increasing.



(a)



(b)

Figure 4.12 Results of BPNs for chip seals

4.4.3 IFI parameters results

It will recall that in the relevant section, where IFI was described, there were two typical parameters of IFI (F(s) and Sp). F(s) were calculated based on DFT friction coefficients results at 60 kph speed and Sp based on MPD values was calculated on the basis of the obtained MTD value with OFM method ,where recommended in ASTM E 1960 (ASTM, 2012b). To show those results based on aggregate type and size and polishing level and to make a numerical representation for those data for mentioned speed, following tables are presented.

Table 4.4 Sp based on calculated MPDs from MTDs for chip seal samples

Grain Size (mm)	Polishing Level	Sp				
		LS	BS	BLD	EAF	FER
8-10	Unpolished	172.072	167.587	159.514	169.381	149.647
	1st Polishing	158.617	142.471	138.883	161.308	138.883
	2nd Polishing	134.398	143.368	129.913	146.956	140.677
10-12	Unpolished	205.261	176.557	174.763	210.643	162.205
	1st Polishing	188.218	158.617	162.205	198.085	160.411
	2nd Polishing	172.072	157.72	151.441	169.381	149.647

Table 4.5 F(s) based on the results of DFT at speed 60 kph

Speed (kph)	Grain Size (mm)	Polishing Levels	F(s)				
			LS	BLD	BS	EAF	FER
60	8-10	Unpolished	0.308	0.359	0.403	0.403	0.491
		1st Polishing	0.235	0.279	0.337	0.293	0.381
		2nd Polishing	0.176	0.213	0.293	0.264	0.330
	10-12	Unpolished	0.301	0.366	0.410	0.425	0.520
		1st Polishing	0.264	0.264	0.323	0.345	0.425
		2nd Polishing	0.198	0.235	0.264	0.279	0.359

4.4.4 Correlational analyses between results of skid resistance methods

Herein, correlational analysis between the results gathered with the skid resistance measurements methods used in the present study were given. These correlations are as following BPT versus DFT, and BPT versus F(s), where s is speed in kph. The speeds taken in to consideration were 10, 20 and 40 kph. Speed for 60 kph was not evaluated here. Because, at that speed, calculated value for F (60) almost equal to the exact value of friction coefficient (μu) gather by DFT. Therefore, correlational analyses between results of skid resistance methods has been limited with 10,20, and 40 kph. Since, F(s) is a parameter that dependent to (μu), no comparison has been made between these two.

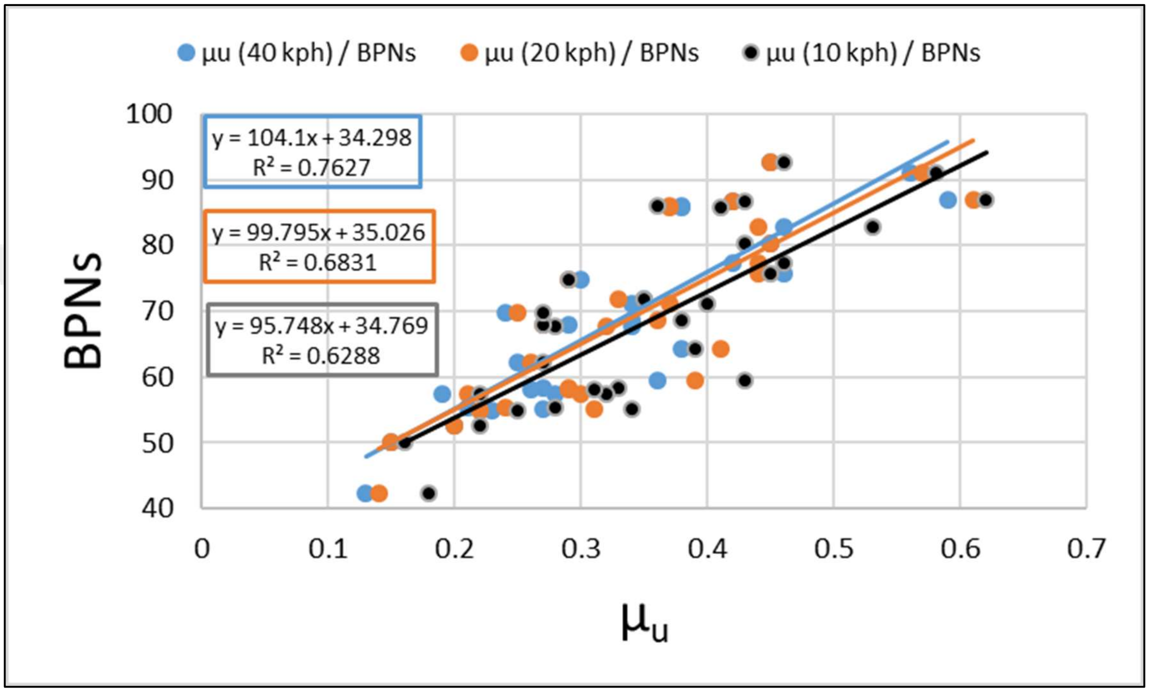


Figure 4.13 Correlation between BPNs and DFT (μu) results at different speeds

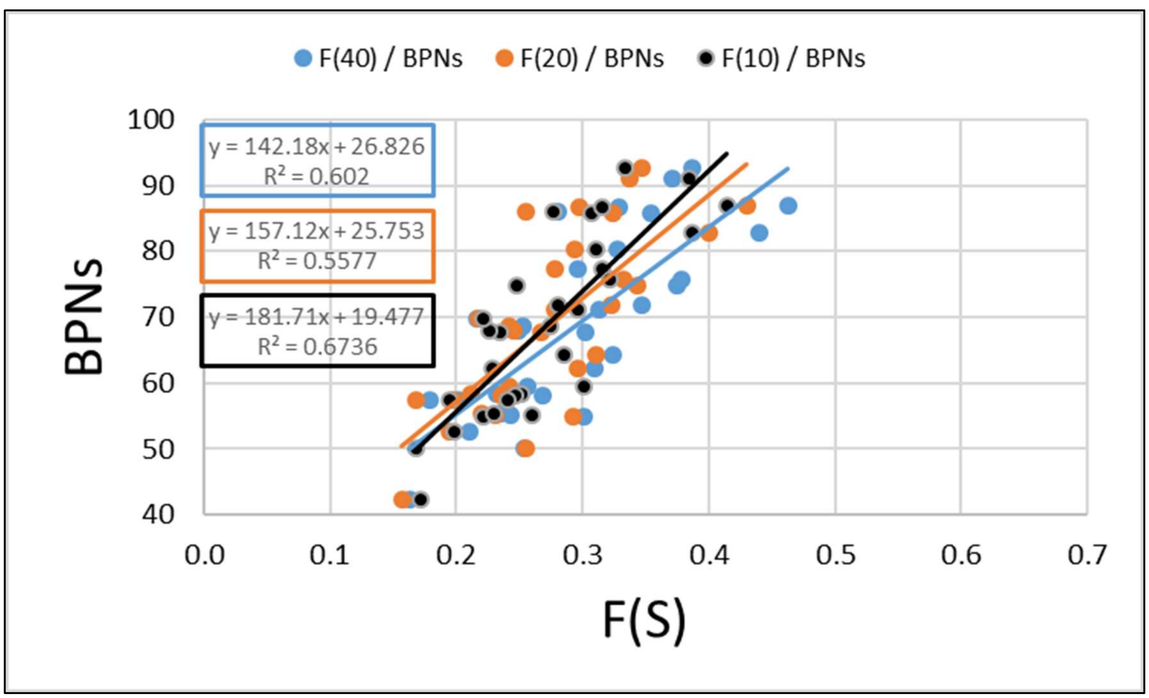


Figure 4.14 Correlation relationship between BPNs and F(s) results at different speeds

To make brief comment on the correlational relation between the tests, author can report followings:

- R^2 were found 0.62 to 0.76 for the BPN- DFT pairs and interestingly the highest R^2 were observed for the speed 40 kph. However, the expected higher ones were taught to be seen for the lower speeds (10, 20 kph).
- R^2 were found to change from 0.55 to 0.67 for BPN-F(s) pairs. Unlike R^2 between BPN- DFT pairs, the highest one were observed for the speed 10 kph, that was the expected. However, another expected case for 20 kph were not seen. On the contrary, the lowest R^2 has been found out.

CHAPTER 5. CONCLUSION

Skid resistance performance of chip seal was investigated in case of multiple variables such as aggregate type, grain size, polishing at different levels on the samples produced in the laboratory. In this research, five types of aggregate in different origin including natural and industrial by-products were used. Initially, aggregate characteristic features, by means of physical, mechanical, chemical and mineralogical, were determined according to the related EN norm standards. Additionally, micro texture of aggregates was analyzed visually using scanning electron microscope for each polishing level to reveal the in porous structure, clearly. To produce chip seal samples, aggregates were sieved at 8-10 and 10-12 mm grain sizes in cubical form in case of both original and polished conditions. Polishing of aggregate was done using Micro-Deval apparatus following a standard test method as specified in ASTM D 6928. To provide polishing at different levels, the method's revolution numbers (RNs) were modified. For first polishing level RNs was determined as 10500 as also identified in the related standard, but for the second polishing level, 31500 RNs was adopted in the scope of this study. Skid resistance of the produced samples was analyzed using two common testers, which are Dynamic Friction Tester and British Pendulum tester. Moreover, macro texture of each samples were measured using outflow meter test. The mentioned tests were conducted on each samples following ASTM standards. Finally, International Friction Index values were calculated based on the skid resistance and macro texture depth results. After the data obtained and examined during all studies requiring intensive labor and time, the following results can be concluded.

1. The results gathered from the certain physical and mechanical features of aggregate showed that the resistance to abrasion and polishing are better for slags. This case was also proved by visual analysis of micro texture using scanning electron microscope.
2. Polishing of aggregates causes significant decrease in skid resistance. At all polishing level, the highest skid resistance performances were observed in slags whereas the lowest was monitored in natural ones. If a ranking is to be made, it will be seen that the worst performance is of limestone while the best is of ferrochrome slags.
3. Skid resistance of 10-12 mm grain size chip seal for almost all aggregate were observed higher than the 8-10 mm grain size. However, there was a minimal difference between the two results for each aggregate, individually.

4. Macro texture depths for the 10-12 mm grain size chip seal was higher than the 8-10 mm grain size chip seal samples. Due to polishing, a non-significant decrease was observed. However, it is known from the literature that the change in texture depth on a hot mix asphalt road surface is seen in reverse. The reason is that samples are produced in a controlled manner at laboratory.
5. There were found a significant relationship between BPNs-DFT and BPNs-IFI pairs. For BPNs-DFT pairs, as examination speed increases, the correlation coefficients also increase. However, for evaluation of BPNs-IFI pairs it is not observed a regular increase in their R^2 values, where at 20 kph there was found less value compared with 10 kph results, but the R^2 increase at 40 kph analysis.
6. Considering that the samples made within the scope of this study simulated the road surface coating, the samples produced with the slag were found to have both longer and higher level of sliding resistance.
7. One of the objectives considered is reveal the superiority of the slag in polishing resistance and therefore its superiority in skid resistance utilizing chip seal samples at different polishing cases. In this thesis, this superior aspect of the slags compared to natural ones was clearly revealed. So, it is thought that the slag stored in the waste sites will be used as an alternative type of aggregate on the highways and provide economic, environmental, and aesthetic benefits.
    - From the point of view of economic benefits, it is possible to obtain an economic gain due to the use of fragmented slag in the production of industrial products (metal within the scope of this thesis). In this case, the cost arising from supplying the natural aggregates from their quarries and reduction of their size for usage aim will be reduced. This will lead to a significant drop in initial production costs for road construction at the beginning. In this way, there may be more production with less cost. Furthermore, the industrial material producers will effectively remove the wastes that are returned as an additional cost to themselves, and they will also be able to earn a significant amount of economic profit from their sales due to slag's superiority properties.
    - From point of view of environment benefits, if considering the geological location of our country, it will be seen that most of the aggregate sources are limestone. As previously stated, such aggregates have low polishing resistance. It is obvious that the use of such aggregates in the road structure will lead to low skid resistant

surface. The need to provide aggregates with better properties for safer roads is obvious. This will result in the transfer of quality aggregates from long distances. Long distance means the emission gas generated by the use of high amounts of fuel. Extracting of the natural sources means emergence of noise, dust and contaminated water sources. Therefore, the use of aggregates, which constitute almost 95% of the road structure as slag origin, will ensure the protection of natural aggregate resources or the proliferation of the longer term use and healthier environment.

- From point of view of aesthetic benefits, it can be said that aggregate quarries cause large pits in nature and the slag in the waste class can form artificial mountains. This situation disrupts the natural balance of the regions where both situations are formed. If the related areas are one that has touristic importance, the areas lost their attractiveness

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