DESIGN AND PERFORMANCE OF OPEN GRADED FRICTION COURSE MIXES WITH ELECTRIC ARC FURNACE STEEL SLAG

A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

By

Madhu Lisha Pattanaik

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
GUWAHATI-781039, INDIA

JANUARY 2019


भारतीय प्रौद्योगिकी संस्थान गुवाहाटी
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Dedicated to my Loving Parents


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CERTIFICATE

This is to certify that the thesis titled “Design and Performance of Open Graded Friction Course Mixes with Electric Arc Furnace Steel Slag”, submitted by **Madhu Lisha Pattanaik** (Roll No. 146104008) to Indian Institute of Technology Guwahati, for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by her under our supervision and guidance. The thesis work in our opinion, has reached the standard for fulfilling the requirements for the award of the Degree of **Doctor of Philosophy**. This work has not been submitted earlier for the award of any degree to the best of our knowledge and belief.

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DECLARATION

I declare that this written submission represents my ideas in my own words and where other ideas and words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principals of academic honesty and integrity and have not misinterpreted or fabricated or falsified any idea/ data/ fact/ source in my submission. This thesis, in any way, does not purport to endorse any proprietary products or technologies.

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ABSTRACT

India has the second largest road network in the world with over 5.6 million km of roadways spread across the country. Currently, 98% of the Indian roads are flexible pavements, constructed using dense graded bituminous mixes as wearing course. The dense graded bituminous mixes are to be impermeable to water with an air void content in the range of 3–5% by mix volume and are designed using well-graded aggregates and bituminous binders. During rain due to surface water flow dense graded mixes raises concerns related to hydroplaning, skidding, and splash and spray. Dense graded bituminous surfaces during rain also have reduced visibility and increased glare due to presence of surface water film, which has a significant effect on the road safety aspects. It has been estimated that 20% of road accidents occur during wet weather conditions and mainly attributed to lack of skid resistance, visibility, splash and spray, etc. Hence, in high rainfall and hilly regions it will be quite helpful to have wearing courses that have high permeability and can quickly drain out the surface water, without compromising the performance aspects. Open graded friction course (OGFC) is a special type of hot mix asphalt (HMA) mix that acts as a drainage layer to permit the surface water to migrate laterally to the edges of the pavement. OGFC has benefits in terms of improved skid resistance, higher visibility, reduced hydroplaning, reduced glare, lower tyre-pavement interaction noise and enhanced safety. OGFC has been in use in various parts of the United States and European countries, but in India its use is still not established. Unlike other developed countries, there are no well-formulated specifications/guidelines for implementing the OGFC technology in India.

OGFC mixes are designed for a high percentage of air voids content, generally above 18% of mix volume. To attain the high proportion of air voids, OGFC generally uses a uniform grading of aggregates. The coarse aggregates in OGFC comprise more than 90% of the total aggregates. The macro-texture derived from the aggregates of OGFC surface also promotes frictional characteristics of the road surface. The coarse aggregate skeleton in OGFC mixes provides the stone-on-stone contact necessary for the distribution of traffic loads and hence these mixes demand high quality aggregates for desired performance and service life. Construction of a vast capacity of infrastructure in India has not only imposed pressure on natural aggregates but has also led to severe environmental challenges because of large-scale mining and quarrying. Further, in many regions environmental concerns have put restrictions on exhausting mountains and rivers for extraction of natural aggregates. Moreover, the quest for achieving sustainability in highway construction has compelled researchers to explore alternative aggregate materials. The use of the waste materials and industrial by-products as an alternate aggregates is gaining widespread interest as an encouraging approach to meet the rising aggregate demands. Waste material utilisation has the simultaneous benefits of reducing the dependency on natural aggregate sources while advancing environmental and economic stewardship. India is the world's third largest steel producer (after China and Japan) with 101.4 million tonne (MT) steel production in 2017. Steel slag is a by-product of the steel manufacturing industries. About 12 MT of steel slag is generated annually in India, but merely 20% is put to applications and the rest is indiscriminately dumped in nearby landfills as a waste.

With this background, the current study set out to investigate OGFC mixes with electric arc furnace (EAF) steel slag (a waste from steel industry) as partial replacement of coarse natural aggregates. Experimental variables in the present research included two types of aggregates (natural and EAF steel slag), two types of modified binders (PMB: polymer modified binder and CRMB: crumb rubber modified binder) and five substitution percentages (0%, 25%, 50%, 75% and 100%) of coarse natural aggregates with EAF steel slag aggregates. The present study began with characterisation of EAF steel slag aggregates in terms of physical properties, chemical composition, morphological analysis, and toxicity evaluation. This was followed by design of OGFC mixes at all EAF slag percentages to determine the following design attributes: stone-on-stone contact condition, air voids content, unaged abrasion loss, aged abrasion loss, and binder draindown. The OGFC performance parameters evaluated in this study were resistance to moisture-induced damage, frictional characteristics, permeability and clogging characteristics, resistance to permanent deformation (static creep, dynamic creep, Hamburg wheel tracking and stiffness modulus), and fatigue life. The properties of EAF steel slag-OGFC mixes were compared with those of control mixes (with no steel slag).

Favourable physical and chemical characteristics of EAF steel slag aggregates in terms of higher angularity, rough surface texture, high specific gravity, low flakiness and elongation index and high calcium oxide content, enabled them to show a desirable performance as a coarse aggregate in OGFC mixes. In comparison to OGFC mixes with natural aggregates, increase in EAF steel slag content up to 75% resulted in improvement in OGFC mix properties including air voids content, stone-on-stone contact, and abrasion loss in unaged and aged conditions for both PMB and CRMB binders. Even after 100% replacement of coarse natural aggregates by EAF steel slag, OGFC mixes met all design requirements and showed performance comparable to the OGFC mixes with natural aggregates. Both PMB- and CRMB-OGFC mixes on substitution of coarse natural aggregate with EAF steel slag showed improved performance when evaluated using static creep, dynamic creep, Hamburg wheel tracking, stiffness modulus and fracture life tests. OGFC mixtures with 75% substitution of coarse natural aggregates with EAF steel slag presented the best performance in terms of permanent deformation, stiffness modulus and fracture life among all the combinations studied. The study concludes that 75% is the optimum content for replacement of the coarse natural aggregates with EAF steel slag in OGFC mixes with both PMB and CRMB binders. Replacement of the natural aggregates with EAF steel slag aggregates in OGFC mixes may be considered as an encouraging option, which can save the rapidly diminishing natural aggregates, and can be a significant step in the direction of sustainability in highway construction.

Keywords: *electric arc furnace steel slag; open graded friction course; polymer modified binder; crumb rubber modified binder; waste reuse.*

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LIST OF ABBREVIATIONS

AAL	Aged Abrasion Loss
ANOVA	Analysis of Variance
AV	Air Voids
BC	Bituminous Concrete
BOF	Basic Oxygen Furnace
BPN	British Pendulum Number
BT	Binder Type
CAGR	Compound Annual Growth Rate
CRMB	Crumb Rubber Modified Bitumen
DGBC	Dense Graded Bituminous Concrete
EAF	Electric Arc Furnace
FESEM	Field Emission Scanning Electron Microscopy
FHWA	Federal Highway Administration
FT	Freeze-Thaw
HMA	Hot Mix Asphalt
HWTD	Hamburg Wheel Tracking Device
IRC	Indian Roads Congress
ITFT	Indirect Tensile Fatigue Test
ITS	Indirect Tensile Strength
ITSM	Indirect Tensile Stiffness Modulus
LVDT	Linear Variable Displacement Transducer
LWE	Left Wing Extremism
MoRTH	Ministry of Road Transport and Highways
MT	Million Tonnes
NAPA	National Asphalt Pavement Association

NCAT	National Centre of Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NH	National Highway
NHDP	National Highways Development Project
NHIIP	National Highways Interconnectivity Improvement Project
NMAS	Nominal Maximum Aggregate Size
OBC	Optimum Binder Content
OGFC	Open Graded Friction Course
PA	Porous Asphalt
PEM	Permeable European Mix
PFC	Porous Friction Course
PMB	Polymer Modified Bitumen
QA	Quality Assurance
QC	Quality Control
SARDP-NE	Special Accelerated Road Development Programme for the North East Region
SC	Slag Content
SGC	Superpave Gyratory Compactor
S-O-S	Stone-on-stone
SSD	Saturated Surface Dry
TD	Texture Depth
TSR	Tensile Strength Ratio
TWD	Theoretical Water Depth
UAAL	Unaged Abrasion Loss
UTM	Universal Testing Machine
VCA_{drc}	Voids in Coarse Aggregate for the Dry-Rodded Condition
VCA_{mix}	Voids in Coarse Aggregate for the Compacted Mix
WAL	Wet Abrasion Loss
WHO	World Health Organisation

LIST OF SYMBOLS

a	Cross-Sectional Area of Standpipe
A	Cross-Sectional Area of the Specimen
$CR_{initial}$	Initial Clogging Rate
$CR_{secondary}$	Secondary Clogging Rate
D	Average Diameter
d	Diameter of Sample
Δh	Axial Deformation
ε	Axial Strain of the Specimen
F	Peak Value of the Applied Vertical Load
γ_s	Bulk Density of the Coarse Aggregate Fraction
γ_w	Density of Water
G_{CA}	Bulk Specific Gravity of the Coarse Aggregate
G_{CA}	Bulk Specific Gravity of the Coarse Aggregate Fraction
G_{mb}	Bulk Specific Gravity of the Compacted Mixture
G_{mm}	Theoretical Maximum Specific Gravity
h	Specimen Height
$\mathrm{ITS}_{\mathrm{dry}}$	Indirect Tensile Strength of the Dry Subsets
$\mathrm{ITS}_{\mathrm{wet}}$	Indirect Tensile Strength of the Wet Conditioned
$\mathrm{K}_{\mathrm{clogged}}$	Initial Clogged Permeability of OGFC Mixes
$\mathrm{K}_{\mathrm{initial}}$	Initial Permeability of OGFC Mixes
L	Specimen Height (Mm)
$\mathrm{m}_{\mathrm{sand}}$	Mass of the Graded Sand
μ	Poisson’s Ratio
P_{CA}	Percent Coarse Aggregate in the Total Mixture

S_m	Stiffness Modulus of the Specimen
t	Time
T	Temperature
V	Sample Volume
W_a	Dry Weight of the Aggregate
W_{cab}	Weight of the Bitumen Covered Aggregate
W_{fp}	Detached Quantity of Aggregate
z	Amplitude of the Horizontal Deformation

Chapter 1
INTRODUCTION

1.1 GENERAL

India has the second largest road network in the world. The entire road length of India increased significantly from 3.99 lakh km (0.399 million km) in 1951 to 54.72 lakh km (5.472 million km) in 2015. The road length of India is increasing at a compound annual growth rate (CAGR) of 4.01%, while the population of all types of vehicles is increasing at a CAGR of 10.76% (PIB, 2012). The percentage of paved roads in India is 61.05% and lags behind both the US and China. National Highways (NHs) constitute the most important category of roads in India that connect state capitals, main cities, and places of strategic importance, but occupy a share of only 2% of the total road network (MoRTH, 2018). This indicates the need for expansion and growth of Indian road network to cater for the increasing vehicle population. The Ministry of Road Transport and Highways (MoRTH) in India has considered the development of NHs as of prime importance and need. MoRTH is making ambitious efforts to improve, upgrade and strengthen the highway network of the country. In this direction, an array of road development projects have been launched such as: National Highways Development Project (NHDP), Special Accelerated Road Development Programme for the North East Region (SARDP-NE), National Highways Interconnectivity Improvement Project (NHIIP), Bharatmala project, Special Programme for Development of Roads in the Left Wing Extremism (LWE) affected areas, etc.

(MoRTH, 2018).

A road pavement generally consists of different layers, comprising mainly of subgrade, sub-base, base, and a surface course. Pavements are mainly of two types: rigid and flexible pavements. Currently, 98% of the Indian roads are of flexible type (Kumar, 2010; Shivkumar and Nagakumar, 2014). The topmost layer of the flexible pavement commonly known as surface or wearing course, is mainly constructed using dense graded bituminous[1] mixtures in India. Dense graded bituminous mixtures are designed with a combination of well-graded aggregates and bituminous binder aiming to achieve an air void content in the range of 3–5% by volume of the mix to make them structurally sound and impermeable to water. The design of roads is generally aimed towards developing a structurally sound pavement scheme that can withstand repetitive traffic loading over its design life without excessive damage. A road should satisfy all structural and functional requirements that it is intended to perform. The structural requirements include an adequate strength and stability under traffic load as well as high resistance to distresses. On the other hand, the two main functional requirements are adequate skid resistance and riding comfort. Safety, good visibility, high drainage capability and low noise are also important functions of a wearing course. Dense graded bituminous mixtures are usually associated with some concerns with regard to their functional performance, especially during wet weather conditions. Over a dense graded surface course, rainwater moves to the sides with the help of camber or cross slope in straight sections and due to super elevation at curves and a combination of both. However, during rains, the movement of water to sides takes time and it continues to stand on the surface of the dense graded surface course, which increases the risk of hydroplaning and also leads to poor wet weather skid resistance, splash and spray,

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[1] Bitumen and asphalt are synonyms of each other and both terms have been used interchangeably in this thesis. Similarly, bituminous mixes and asphalt mixes are used interchangeably.

and low visibility. Presence of water on dense graded surface courses also results in glare during night driving, which is hazardous from the road safety viewpoint. Based on a survey of 30,000 road accidents in China, it was reported that wet weather accident rate is 3.5 times than the dry weather rate (Liu and Cao, 2009).

Road related accidents have been deemed to be one of the major causes of deaths around the world with 1.35 million deaths per year (WHO, 2018). Causes of these road accidents pertaining to pavement related aspects include improper design of road geometries and inferior road surface quality. Also, as per the 'Road Accidents in India – 2015' report, published by MoRTH, total accidents, persons killed and persons injured in road accidents caused due to lack of skid resistance, occupied a share of 26126, 7167 and 27107, respectively (MoRTH, 2015). Roads in hilly and high rainfall regions having frequent sharp curves with steep slopes, are more vulnerable to accidents, and have high fatality rates compared to those in plain and low rainfall regions. Wearing courses having high frictional resistance that can facilitate quick drainage of surface water can be constructed in these regions. Since the last few decades, Open Graded Friction Course (OGFC) mixtures[2] have been in use in many European (*e.g.*, Belgium, Spain, Switzerland, and the Netherlands) and other countries like Japan, the United States, *etc*. Their use is preferred mainly to facilitate quick drainage of surface water the pavement surface drainage during wet weather conditions, to increase the skid resistance and for reduction in hydroplaning, splash and spray and tyre-pavement interaction noise.

OGFC mixes are a special type hot mix asphalt (HMA) characterised by high percentage of interconnected air voids (generally higher than 18% of the mix volume) and

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[2] The terms 'mixtures' and 'mixes' are also used interchangeably in this thesis and refer to a blend of different materials (mainly aggregates, bituminous binder and an additive).

coarse granular skeleton with proper stone-on-stone contact. OGFC is also known as Permeable European Mix (PEM), Porous Friction Course (PFC), and Porous Asphalt (PA), and has been under use in Europe (*e.g.*, the Netherlands, France, and Germany), Asia (*e.g.*, China, Japan, and Korea), and the United States for decades (Alvarez *et al.*, 2011). High air void content makes the OGFC mixes permeable to the flow of rainwater laterally through the surface course itself to the day-lighted pavement edges. To attain the high proportion of air voids, OGFC uses a uniform grading of aggregates. Uniform grading comprises an aggregate blend dominated by single sized aggregates. Normally, 50–60% of the aggregate particles are almost of the same particle size with just 2-5% filler (materials finer than 0.075 mm) (Kandhal and Mallick, 1998). The coarse macro-texture of OGFC also enhances the frictional characteristics of the road surface. These characteristics have a significant positive effect on the road safety aspects for the road user. OGFC mixes have several established benefits that include: improved frictional resistance, mitigation of hydroplaning due to quick drainage of water from the pavement surface, minimisation of splash and spray, reduction in headlight glare, and better visibility of pavement markings, especially during wet weather events (Mallick *et al.*, 2000; Kandhal, 2002; Alvarez *et al.*, 2011). The presence of high content of air voids also helps in absorbing the noise generated from the tyre-pavement interaction and thus leads to quieter pavements. Due to these associated benefits, OGFC mixes are strongly suggested for high volume, high speed roads and expressways, especially in the regions of high rainfall. The main component in any asphalt mixture in terms of weight and volume is the aggregate. More so for OGFCs, the coarse aggregates (>2.36 mm) comprise more than 90% of the total aggregates. The coarse aggregate skeleton in OGFC mixes provides the stone-on-stone contact necessary for the distribution of traffic loads and hence it is desirable that the aggregates are angular and possess high resistance to abrasion, crushing, and polishing. OGFC mixes therefore demand high quality aggregates for desired performance and service life (Kandhal, 2002).

In India, about 15,000 tonnes of aggregates are consumed per km construction of an NH (Mallick, 2010). To sustain the development of highway infrastructure, the demand for good quality aggregates has been continuously growing. As per recent estimates, India consumed 3330 million tonnes (MT) of total aggregates (in all sorts of constructional activities) in 2015 and will further require 5075 MT of aggregates by 2020 (JSW Steel, 2018). Construction of a vast capacity of infrastructure not only imposes pressure on the supply of natural aggregates but also poses severe environmental problems because of large-scale mining and quarrying. Further, in many regions of the country, environmental concerns have put restrictions on exhausting mountains and rivers for the extraction of natural aggregates. The goal for achieving sustainability in highway construction has compelled researchers to explore alternative highway materials. The use of waste materials and industrial by-products as alternative aggregates in road construction is gaining widespread interest as an encouraging approach to meet the rising aggregate demands. Waste material utilisation has the simultaneous benefits of reducing the dependency on natural aggregate sources while advancing environmental and economic stewardship.

India is the world’s third largest steel producer (after China and Japan) with 101.4 MT steel production in 2017 (World Steel, 2018). The total steel production of India increased significantly from 95.5 MT in 2016 to 101.4 MT in 2017. Steel slag is a by-product of the steel manufacturing industries. One tonne of steel slag is produced during the production of three tonnes of stainless steel (Proctor *et al.*, 2000). It has been reported that the total amount of steel slag produced in 2002 was about 50 MT per year and in 2011, it was about 149-223 MT from different steel industries worldwide (Altun and Yilmaz, 2002; Yildirim *et al.*, 2015). Around 12 MT of steel slag is generated every year from steel industries in India (FICCI, 2014). With rapid growth in the steel sector to meet the rising steel demand, slag production is also expected to increase manifold. However, most slag produced in India is considered as a waste and is discarded. The Ministry of Steel (Govt. of India) has also expressed serious concerns on non-achievement of proper utilisation practices for steel slag generated from the steel industries (FICCI, 2014). Based on the steel production process employed, steel slag is generally classified in two main categories, namely Electric Arc Furnace (EAF) slag and Basic Oxygen Furnace (BOF) slag. EAF and BOF processes have a share of 56.8% and 43.2% in the steel production in India, respectively (World Steel, 2018). The chemical composition of steel slag essentially consists of iron oxides (FeO, Fe_2O_3), lime (CaO), silica (SiO_2), magnesia (MgO) and alumina (Al_2O_3). Due to the presence of significant amount of free iron, steel slag is hard and dense and hence possesses high specific gravity and abrasion resistance. These characteristics make steel slag a potential candidate for total/partial replacement of natural aggregates in asphalt mixes.

1.2 PROBLEM STATEMENT

In India, the wearing course of flexible pavements are mainly constructed using dense graded bituminous mixes. One main functional problem with conventional dense graded bituminous mixes when being used as wearing course is hydroplaning, especially in high rainfall regions, due to the standing water film on the road surface, and it constitutes a major road safety hazard. Hydroplaning is a phenomenon in which a sheet of water builds up between the pavement surface and the vehicle tyre, making it difficult to steer and apply brakes. Low skid resistance, poor visibility due to splash and spray and glare due to water film, contribute to accidents predominantly in the regions with heavy rainfall throughout the year. Hence, it is quite beneficial for such regions to consider wearing courses that have high permeability and permit quick surface water drainage without compromising the performance aspects. Open graded friction course (OGFC) is an alternative and potential candidate, due to its benefits in terms of reduced hydroplaning, improved skid resistance, higher visibility, lower noise production and enhanced safety. OGFCs have been in use in various parts of the United States and European countries, but in India its use is still not established. Unlike other developed countries, there are no well-formulated guidelines for implementing the OGFC technology in India.

OGFC mix is a special type of hot mix asphalt characterized by high interconnected air voids and a coarse granular skeleton with proper stone-on-stone contact. The major challenge in the design of an OGFC mix is to achieve adequate durability (i.e., resistance against raveling and moisture damage) and functionality (i.e., ability to maintain the desired permeability) (Alvarez *et al*., 2010; Kandhal, 2002). High air voids and lack of fines in the open-gradation used for OGFC may lead to raveling and moisture-induced damage. Similarly, intrusion of foreign matter such as dirt and debris may lead to clogging of the open channels present in OGFC, thus leading to poor functionality in terms of reduced permeability and noise-reduction capability.

The presence of a larger percentage of internal air voids leads to a relatively high porous structure of OGFC mixes, which helps in quick and effective removal of surface water from the pavement. The hydraulic function served by OGFC mixes renders them to a longer exposure to water. Moisture susceptibility is thus an important characteristic that plays an important role in the long-term durability of open graded mixtures. Binder-aggregate stripping is multifaceted and depends on several factors, such as type and use of the bituminous mix; the type and source of bitumen; aggregate type, source, and gradation; and use of antistripping additives. Aggregate type is a significant factor that influences the moisture damage resistance of bituminous mixes (Zhang *et al*., 2018). Thus it is essential to examine the effect of the aggregate source on the moisture damage potential of OGFC mixes.

The permeability of a bituminous mix is the ability to transmit fluids through the interconnected voids of the structure when it is subjected to a hydraulic gradient. Clogging of pore channels in an open graded friction course takes place owing to deposition of sediments through wind, storm water and vehicles. It happens over time. When the pores of the OGFC gets clogged it decreases the permeability of open graded pavement and reduces its drainage and noise reduction benefits (Yildirim *et al*., 2006; Kowalski *et al*., 2009; Roque *et al*., 2009).

Maintenance practices including cleaning/flushing of voids on a regular basis help to address clogging and to regain the initial permeability. On high-speed roadways, the moving traffic generates a suction when the tyres roll over the pavement surface and thus minimizes the chances of the clogging material settling in the voids of an OGFC mix. Suresha *et al*. (2010) studied the clogging characteristics of OGFC mixes and observed that air voids and permeability followed a power model. Further, pavements with initial permeability of over 100 m/day were found to demonstrate good drainage potential even under clogged conditions. Ruiz *et al*. (1990) reported that the OGFC mixes having more than 20 percent air voids had less chances of being clogged. Rogge and Hunt (1999) also observed that OGFC mixes with initial permeability values of more than 100 m/day ensured good drainage potential even after reaching stable clogged conditions.

Clogging of pores and traffic densification leads to decrease in both the size and quantity of air voids, and thus lowers noise-reduction capability of OGFC mixes. Usually, OGFC mixes with low percentage of air voids are more vulnerable to clogging. Field studies showed that the loss of permeability of OGFCs reduces their noise reduction capability (Bendtsen *et al*., 2002). It was also observed that the amount of clogging did not significantly decrease the ability of OGFC mixes to achieve reduction in pavement noise levels over their service life (usually considered to be between 6 and 8 years).

In some countries, experience on the use of OGFC mixes with neat binders showed that ravelling can be a common distress. The majority of countries where good OGFC performance was reported have used modified asphalt binders. In OGFC mixes the use of modified binders further helps to minimise the binder draindown and to improve the coating over the aggregates. Moreover in India, due to increase in traffic, temperature variations, high axle loads and tyre pressures, the Indian Roads Congress (IRC) has favoured the use of modified binders in wearing courses of flexible pavements (IRC SP-53, 2010).

The massive growth of the road construction industry and large number of road infrastructure projects in India have exponentially raised the demand good quality natural aggregates. A huge extent of non-renewable resources of natural aggregates is exploited every year, leading to serious environmental concerns and challenges. Meanwhile, India is the world's third largest steel maker (after China and Japan) with 101.4 MT steel production in 2017. Around 12 MT steel slag is generated every year from steel industries in India. Enormous quantities of this industrial waste have been generated as a result of metallurgical and mining processing activities in India. However, the greater portion of slag produced in India has been disposed of in dumping areas and is considered as a waste, a practice that is aesthetically unappealing and detrimental to the environment. Moreover, majority of the studies on utilisation of steel slag as an alternative aggregate in asphalt mixes have considered its use in dense graded bituminous mixes and stone matrix asphalt. Very limited studies are carried out on the use of steel slag in porous or open graded mixes.

Construction and use of OGFC mixes with EAF steel slag in India can be a promising solution for hilly and high rainfall regions, from both safety and environmental aspects. Use of different percentages of steel slag with the modified binders under mix design and testing protocols followed in India, will demands specific studies to gain understanding and confidence on the use and performance of OGFC mixes with steel slag.

Under this standpoint, the present study evaluates the effect of percentage replacement of natural coarse aggregates with EAF steel slag on performance of OGFC mixes containing different modified asphalt binders. This study evaluates the mix design parameters such as air voids, stone-on-stone contact condition, unaged abrasion loss, aged abrasion loss and binder draindown and performance parameters such as resistance to moisture susceptibility, frictional characteristics, permeability characteristics, resistance to permanent deformation, and fatigue damage of OGFC mixes with and without EAF steel slag replacement.

1.3 OBJECTIVES OF THE STUDY

The main aim of this research is to evaluate the design and performance characteristics of OGFC mixes with the industrial waste, EAF steel slag, as the coarse aggregate. This study includes two types of aggregates (natural and EAF steel slag), two types of modified binders (PMB: polymer modified binder and CRMB: crumb rubber modified binder) and five slag replacement percentages (0%, 25%, 50%, 75% and 100%) of coarse natural aggregate with EAF steel slag. The specific objectives of the study are as follows:

- Design of OGFC mixes with natural aggregates.
- Design of OGFC mixes with varying percentages of EAF steel slag.
- Evaluation of moisture susceptibility and permeability characteristics of OGFC mixes with and without EAF steel slag.
- Evaluation of skid resistance of OGFC mixes with and without EAF steel slag.
- Evaluation and comparison of permanent deformation and fatigue characteristics of OGFC mixes with and without EAF steel slag.

1.4 ORGANISATION OF THE THESIS

The contents of this thesis have been organised in seven chapters. Chapter 1 presents an introduction to the research area, highlights the research problem and presents objectives framed for the research. Chapter 2 presents an extensive review of literature related to this research and identifies research gaps. The selection of materials, their characterisation, the experimental programme and test procedures used to achieve the framed objectives are explained in Chapter 3. Chapter 4 presents mix design results of OGFC mixes with natural aggregates and with various replacement percentages of EAF steel slag. The results of permeability, clogging and frictional characteristics of OGFC mixes with natural aggregate and with various percentages of EAF steel slag are presented in Chapter 5. Chapter 6 presents the results of moisture susceptibility determination as well as the results of performance tests (stiffness modulus, static creep, dynamic creep, Hamburg wheel tracking, and fatigue characteristics) of OGFC mixes, prepared with five percentage replacement of coarse natural aggregates with EAF steel slag. Finally, Chapter 7 presents the conclusions drawn from the results and analyses, and provides recommendations for future research.

Chapter 2
REVIEW OF LITERATURE

2.1 GENERAL

The use of open graded friction course (OGFC) has been much established in United states as well as European countries because of the benefits associated with it. Many studies have been carried out in different parts of the world to ameliorate upon the design and performance characteristics of OGFC mixes. The usage of steel slag as a replacement of natural aggregtes in bituminous mixes is also gaining popularity among researchers in different parts of the world. This chapter reviews the literature on OGFC and the use of steel slag in bituminous mixes.

2.2 OGFC: HISTORICAL TIMELINE

In the first half of the twentieth century, OGFC evolved from experimentation with plant mix seal coats in the United States. The seal mixes were meant to be an improved performance substitute to chip seals and their popularity raised throughout the US by the year 1970 (Kandhal, 2002). The use of plant mix seal coats became popular, as the chip seal application reported many problems like bleeding, ravelling, and a short life span.

Oregon was the first state in the US to start experiments with plant mix seal coats during the 1930s to improve frictional characteristics. During the 1940s, California also initiated the use of plant mix seal coat as a drainage interlayer and as a substitute to chip seals and slurry seals (Huber, 2000). Their plant mix seal coats used a smaller nominal size aggregate, typically 9.5 to 12.5 mm, and it was mixed with a relatively higher binder content than the traditional paving mixes. The mixes were applied in a thin layer of thickness ranging from 15 to 20 mm. This layer delivered similar benefits like a chip seal, but also had other additional benefits like increased durability, better ride quality and reduced pavement noise.

The use of OGFC to improve surface friction of the existing pavements gained popularity in response to the Federal Highway Administration's (FHWA) program to increase frictional resistance of the pavements (Smith *et al.*, 1974; Watson *et al.* 2003). The term 'open-graded friction course' was coined during this program. By 1998, various states in the US were using OGFC and had knowledgeable understanding of its performance in terms of durability and safety (Kandhal and Mallick, 1998). The major problems which were faced by many state agencies during the initial trials, like ravelling and loss of permeability, had been also solved. This was accomplished by the use of polymer-modified asphalt binders and fibers along with higher asphalt content and relatively open gradations. By the 1960s, UK was using porous pavement in military airfield runways to avoid hydroplaning and skidding in wet weather conditions. With further research, this pavement type was permitted on main roadways by incorporating the use of additives in the mix design (Lavin, 2003).

In Europe, OGFC mix is usually referred as Porous European Mix (PEM). The use of OGFC also began in 1976 in France and by the early 1980's Netherlands introduced OGFC as a wearing course for their highways (Nielsen, 2006; Putman, 2012). The use of OGFC was mainly recommended on the places where the design speed was more than 50 km/h. Now-a-days, most of the agencies using OGFC have implemented coarser gradations and modified asphalt binders along with additives, to increase the durability and performance of the mixes. The European mixes tend to have a slightly higher amount of air voids content (18-22%) than the OGFC (15%) (Nelson, 1995). PEM is slightly more gap graded than OGFC to achieve the higher air voids content requirement of the mix. Over the years, many researchers in the European countries (Belgium, Spain, Switzerland) and other countries like Japan, the United States, *etc*. have assessed the application, performance and effectiveness of OGFC mixtures, but still there are differences, in the mix design methods and aggregate gradations employed in the preparation of these mixes (Kandhal, 2002; Nielsen, 2006; Putman, 2012; Cooley *et al.*, 2009).

2.3 BENEFITS OF OGFC MIXES

There are several benefits of OGFC mixes that have been documented for years as reported in *NCHRP Report 877* (Watson *et al*., 2018) *NCHRP Report 49* (Halstead, 1978), *NCHRP Report 180* (Smith, 1992), and *NCHRP Report 284* (Huber, 2000). The coarse granular skeleton of OGFC mixes helps in quick drainage of surface water that provides better contact points between the pavement surface and vehicle tyres, consequently minimising the potential for accidents during the wet weather conditions. The main benefits associated with OGFC mixes include: reduced potential for hydroplaning, improved wet weather skid resistance, reduced splash and spray, minimised glare, improved visibility of pavement markings and reduced tyre-pavement interaction noise. These benefits are now discussed in more details.

- **Reduced potential for hydroplaning:** The potential of hydroplaning during the rainfall event is enhanced especially in low-lying areas, at the transition of super elevated curves, and paths along which rutting of dense graded bituminous mix has occurred. Owing to the high permeability of OGFC because of the presence of large interconnected voids throughout its thickness, water easily permeates and migrate laterally through the mixture to the edges of the pavement (Kandhal, 2002; Cooley *et al*., 2000). Therefore, no continuous water film is allowed to form on the pavement surface. As no layer of water builds up in between the wheels of the vehicles and the road surface, it eliminates the chances of loss of traction and thus there is enhancement in the safety of the road vehicles under wet weather conditions (Putman, 2012; Kandhal, 2002).

- **Improved wet weather skid resistance:** One of the major benefits from the application of OGFC is improved wet weather skid resistance. Pavement surfaces should be designed to have adequate frictional/skid resistance under wet weather conditions. The presence of high air void content along with the coarser surface texture leads to quick water drainage from the surface of the pavement, and improvement in frictional resistance which effectively improves the road safety. Due to lack of skid resistance, nearly 6000 people are killed and around 445,000 people are injured in the US each year during wet weather events on dense graded bituminous pavements (Watson *et al.*, 2018). A research study estimated the lifetime economic cost for each fatality at $1.4 million (NHTSA, 2014). Hence, any reduction in accidents and traffic fatalities will have a great influence on the society as a whole (NHTSA, 2014). Iwata *et al.* (2002) reported that wet weather accidents decreased up to 80% on roadways with OGFC mixes. According to Shimeno and Tanaka (2010), OGFC significantly reduces the number of fatalities as compared to the dense graded bituminous mix during rainfall events. A reduction of 76% in wet weather accidents and 100% reduction in fatalities were also reported after the application of OGFC (King *et al.*, 2013).

- **Reduced splash and spray:** During wet weather conditions, the motorists often encounter heavy spray of water from the vehicles travelling ahead of them. The spray reduces the visibility for the motorist, forming a potential cause for accidents on high-speed roads. The porous structure of OGFC does not allow any water to stand on the pavement surface that may be picked up by the tyres of the vehicles and thus, reduces the splash and spray in rainy conditions. Huber reported that there is a reduction of 90-95% in splash and spray after application of OGFC mixes compared to the dense graded mixes (Huber, 2000). Figure 2.1 shows a comparison of dense graded mix and OGFC in regard to backsplash and spray in wet weather conditions.

Figure 2.1: Splash and spray in wet weather conditions (Kandhal and Mallick, 1999)

- **Glare:** OGFC mixes also help in reducing the glare from the headlights especially under wet weather conditions (Liu *et al*., 2010; Suresha *et al*., 2010b; Buddhavarapu *et al*., 2015). As there is no surface water, the visibility is improved. OGFC also helps to reduce reflection of light owing to the presence of high macro-texture. This reduction in glare permits the driver to better perceive the pavement markings, especially at night and/or during wet weather conditions, hence providing overall better visibility (Putman, 2012; Kandhal, 2002). Figure 2.2 shows comparison of OGFC and dense graded mix in regard to glare in wet weather conditions.

Figure 2.2: Glare in wet weather conditions (on left: OGFC layer, on right: dense graded layer) (Kandhal and Mallick, 1999)

- **Noise reduction:** High frequency noise is generated when tyres rolling on the road cause air to force away in front and suck from behind. This happens in the area of contact between the tyre and the road, especially when the vehicle speed is more than 45 miles per hour (Watson *et al.*, 2018). The most challenging demand for noise reduction is in metropolitan areas due to the close proximity of business establishments and households to the highways. In the case of OGFC, due to its porous structure, the sound is partly absorbed by the air voids present on the surface thus the noise generated from the pavement is reduced. The difference in noise levels is appreciable when dense graded mixes and OGFC are compared. Placing of an OGFC overlay on existing pavements is also a viable alternative for sound reduction than construction of sound barriers. Noise barriers only reduce the noise up to a certain height but placing OGFC reduces the noise generated from the pavement traffic interaction itself. OGFC mixes are reported to decrease the noise level in a range of 3 to 6 dBA in the urban areas (Alvarez *et al.*, 2006; Alvarez *et al.*, 2007).

2.4 STUDIES ON THE USE OF OGFC MIXES

OGFC mixes are primarily used to improve the skid resistance and to provide free drainage of surface water laterally through the mixture to the edges of the pavement. The performance and characteristics of OGFC mixes are dependent on various factors such as properties of the aggregates, aggregate gradation, properties of the asphalt binder, binder content, stabilising additive type and content, mix design, compaction effort, and so on. Studies carried out by various researchers to evaluate the effect of different parameters on characteristics of OGFC mixes are discussed as follows.

Brown and Haddock (1997) investigated various methods to ensure stone-on-stone contact of the porous asphalt mixtures. Five different methods namely, Marshall hammer method, dry-rodded method, vibrating table method, Superpave gyratory method and vibrating hammer method were studied for determination of voids in the coarse aggregate (VCA) skeleton. The gradation was kept constant throughout the study. Out of all methods, the dry-rodded method showed lowest VCA value. Vibrating hammer method always resulted in highest VCA. The Marshall hammer method resulted in significant amount of aggregate breakdown and thus was not recommended for the determination of VCA. Dry-rodded test was recommended as it is easy to perform and the aggregate breakdown is very minimal.

Fwa *et al.* (1999) conducted a study on the clogging potential of porous asphalt mixtures. In this study, a method was developed to quantify the effect of clogging material on the permeability of porous asphalt mixtures prepared with four different aggregate gradations. The permeability was measured after each addition of clogging material on the surface of the test specimen. It was observed that with the initial application of clogging material, the permeability decreased rapidly and it was followed by a steady decrease in permeability, after that it maintained a constant value. It was also observed that mixes with the coarser, more uniform gradation were less susceptible to clogging than finer, well-graded mixtures.

Hassan *et al.* (2005) investigated the different combinations of OGFC mixes prepared using cellulose fibres and styrene butadiene rubber (SBR). The virgin binder was modified by mixing 4% SBR polymer by weight of the asphalt binder. OGFC specimens were compacted using the Marshall hammer by imparting 50 blows on each side. With the addition of the polymer and/or fibre, a significant reduction in abrasion loss was observed when compared to mixes fabricated using neat bitumen. It was explained by the fact that both fibre and polymer provided stiffness to the mixture. Aged abrasion loss was higher than the unaged abrasion loss for all combination of mixes. The result indicated that the loss of adhesive strength and the hardening of asphalt binder would lead to higher ravelling potential. The polymer addition significantly helped in improving the ravelling resistance of the mixes (Figure 2.3). The addition of fibre showed a more significant reduction of binder draindown than the mixes with polymers alone because fibre helped to retain more asphalt in the mixes. However, mixes combined with both SBR and fibre showed the best results in terms of binder draindown.

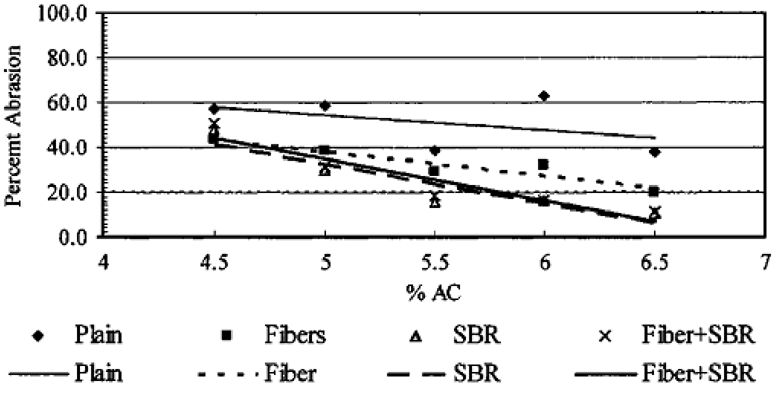


Figure 2.3: Reduction in unaged abrasion with addition of SBR and fibre (Hassan *et al.*, (2005)

Hassan and Al-Jabri (2005) evaluated the effect of date-palm and textile fibres on the performance of OGFC mixes. Both fibres were processed by their manual chopping into approximately 6 mm length. The dosage rate was 0.4% by weight of the mixture for both organic fibres. Six combination of mixes were prepared: control mix without any additive (N), mixes with textile fibre (TF), mixes with date-palm fibre (PF), mixes with SBR polymer (P), mixes with textile fibre and polymer (TFP) and mixes with date-palm fibre and polymer (PFP). Specimens were prepared as per Marshall method of mix design by applying 50 number of blows on both side of compacted OGFC mixes. The reduction in draindown of the binder from the mix was significant especially for the mixes using textile fibres. With the use of the fibres along with modified binder, the unaged as well as aged abrasion loss reduced significantly. The reduction in abrasion loss was higher for the mixes using date palm fibres. The mixes with textile fibres showed better performance in terms of moisture susceptibility when compared to the mixes with date palm fibres.

Shao-peng *et al.* (2006) evaluated the effects of cellulose and polyester fibres on the properties of porous asphalt mixes. The draindown of the mixes using cellulose fibres was less than those using polyester fibres. The surface texture of the fibres was examiner using a scanning electron microscope and was reported that the rough surface texture as well as a branched structure of cellulose fibres increased their surface area appreciably (Figure 2.4).The rough surface of the cellulose fibres and stronger asphalt absorption attributed to the improved performance. The higher absorption of asphalt by cellulose fibres also resulted in mixes with high air voids content. The abrasion loss was lower for the mixes using polyester fibres. The TSR value of the mixes using cellulose fibres showed acceptable results.

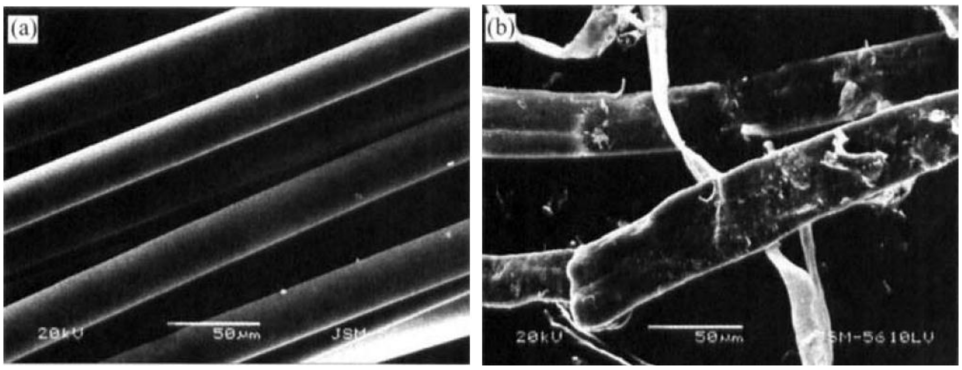


Figure 2.4: SEM micrographs: (a) polyester fibres; (b) cellulose fibres (Shao-peng *et al.*, 2006)

Herrington and Alabaster (2008) examined the effect of epoxy modified binder on the performance of open-graded porous asphalt (OGPA). The epoxy bitumen was a two-part product having 14.6% by weight of epoxy resin and the rest was bitumen as a curing agent. The cohesive properties of the cured epoxy OGPA helped to reduce abrasion loss of OGPA mixes compared to control mixes. The mixes were heated at 85 °C for 38 days to simulate the aging that will occur in the field conditions. The epoxy mixes remain unaffected to the aging simulated in the laboratory for aged abrasion loss. The use of epoxy modified OGPA resulted in higher service life and lower ravelling. The curing and oxidation of epoxy binder in the mix were also monitored through infrared spectroscopy. The test sections prepared using epoxy OGPA remained unaffected by trafficking, whereas the control section showed signs of rutting after 175,000 passes of the test wheel of the accelerated pavement tester.

Masad *et al.* (2009) studied frictional characteristics of three different gradations; namely – Type C: conventional dense graded mix with a maximum aggregate size of 19 mm, Type D: dense graded mix with a 12.5 mm maximum aggregate size, and Porous Friction Course (PFC) comprised of different types of aggregates (sandstone, granite, crushed gravel and two sources of limestone). Sand patch method, British Pendulum Tester, and Dynamic Friction Tester (DFT) were used to evaluate the frictional characteristics after different polishing intervals. Type D mixes were found to be most susceptible to ravelling after 5000 polishing cycles. Based on the British Pendulum test results, PFC mixes were found to exhibit higher BPN values than Type C mixes. F60 value, frictional resistance reported by a dynamic friction tester (DFT) at a test speed of 60km/h, of PFC mixes were mostly larger than the Type C mixes when measured through the DFT.

Kowalski *et al.* (2009) did a comparison study of three different type of pavements including dense graded asphalt (DGA), stone matrix asphalt (SMA) and porous friction course (PFC) by long-term observation of noise and frictional characteristics. The DGA and SMA mixes were designed to achieve 4% air voids while the PFC was designed to achieve an air void content of 23% using Superpave gyratory compactor. All three kinds of highway sections were monitored for performance evaluation in terms of friction, texture depth (TD) and noise properties over a period of 4 years. From texture depth test results, it was observed that PFC mixes had the highest TD of 1.4 mm followed by SMA (1.1 mm) and DGA (0.5 mm). TD measurements on PFC and SMA pavements in initial stages after construction and those taken on a later stage after opening to traffic, were mostly similar. However, the TD increased for the DGA pavement with time. From dynamic friction tester results it was observed, that the friction coefficient for PFC and SMA sections after opening to traffic were larger than those measured at the initial stage. This finding may be attributed to the reduction in binder coating on the aggregate surface. The newly constructed pavement had lower micro-texture due to good binder coating on the aggregate, however when the same got detached by polishing action of vehicle tyre, it resulted in increased friction value. Based on the visual observation of the pavement performance during heavy rain, the drainage benefits and improvements in the splash and spray condition with PFC pavements were recognised. The reduction in splash and spray was significant especially during the heavy vehicle movement, as they typically yield a large amount of splash and spray. It was also found that the PFC section was the quietest followed by SMA and DGA.

Suresha *et al.* (2009a) evaluated the effect of various binders namely neat bitumen, polymer modified bitumen of plastomeric base (PMB-P), polymer modified bitumen of elastomeric base (PMB-E) and crumb rubber modified bitumen (CRMB) on the performance and durability of porous friction course mixes at laboratory scale. The mixes with modified binders had higher G_{mb} values when compared to the mixes with neat bitumen. The mixes with modified binders subsequently had lower air void content and permeability. The abrasion loss of mixes with modified binders was significantly lower than the mixes with neat bitumen and this effect was prominent in case of aged abrasion loss. The performance of mixes with CRMB was much better when compared with other modified binders. The mixes with all the modified binders had higher moisture-induced damage resistance compared to neat bitumen, when evaluated using wet abrasion loss test (Figure 2.5). In the figure, G and BT in the x-axis stands for the three different gradations and four different binder contents used in the study. The moisture damage in mixes with modified binders was less and among the modified binders, PMB-P showed best moisture resistance compared to PMB-E and CRMB.

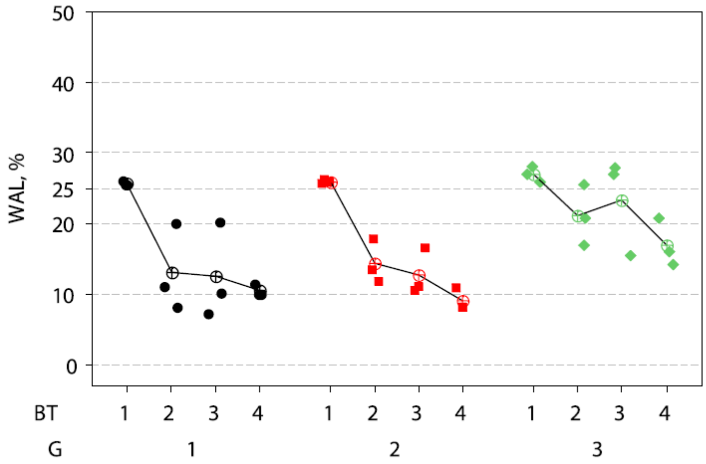


Figure 2.5: Results of wet abrasion loss (WAL) tests (Suresha *et al.*, 2009a)

Suresha *et al.* (2009b) examined the effect of gyration levels on the performance of the porous friction course (PFC) mixes. The concept of aggregate locking point (N_{LP}) was used for determination of the compaction level required for the mixes. Aggregate locking point is defined as the number of gyration that leads to the aggregate skeleton locking together and beyond which further compaction results in aggregate degradation. The mixes didn't show a specific value for N_{LP}, it varied in the range of 50 to 75 gyrations. An increase in the gyration level resulted in an increase in the bulk specific gravity of the mixes. The mixes compacted at lower gyrations levels were not able to meet the stone-on-stone contact criterion; whereas the mixes compacted at higher gyration levels showed low air void content than the minimum requirement. The authors also stated that there is no need to check the stone-on-stone contact of mixes, when they are compacted for aggregate locking point.

Liu and Cao (2009) evaluated the effect of binder type (neat bitumen, styrene-butadiene-styrene modified bitumen and high viscosity bitumen) on the performance of porous asphalt mixes. The mixes prepared with neat bitumen were found to be poor-performing with the highest abrasion loss and lowest resistance to moisture damage. The mixes using high viscosity bitumen had the lowest abrasion loss, high resistance to moisture susceptibility and rutting.

Suresha *et al.* (2010a) investigated the properties of porous friction course mixes for six different aggregate gradations. Aggregate gradations with higher fine content showed lower abrasion loss compared to gradations having comparatively coarser gradations. However, permeability of the mixes on measurement through a falling head permeameter, was found to be significantly higher for coarser gradation. The mixes that did not satisfy the stone-on-stone contact requirement owing to the existence of greater fines proportion, showed comparatively better strain recovery and improved resistance to permanent deformation, when evaluated through the static unconfined creep test.

Hsu *et al.* (2010) conducted a laboratory study to see the effect of high-viscosity graded binder and asphalt rubber on the performance of porous asphalt mixtures. Asphalt rubber (AR) binder was produced by incorporating 20% ground rubber by weight of the base asphalt binder. The specimens of porous asphalt mixtures were prepared as per Marshall method of mix design, by applying 50 blows on each side of the specimen. The mixes prepared with AR binder had higher air void content and higher coefficient of permeability. Slightly lower draindown value of the AR mixture was found while compared to the neat binder. From the results, it was observed that the dynamic modulus increased with a decrease in the loading time and temperature (Figure 2.6). The addition of asphalt rubber improved the rutting resistance of porous asphalt mixtures. The rutting resistance checked using wheel tracking permanent deformation test showed that the mixes with modified binder had lesser rut depths.

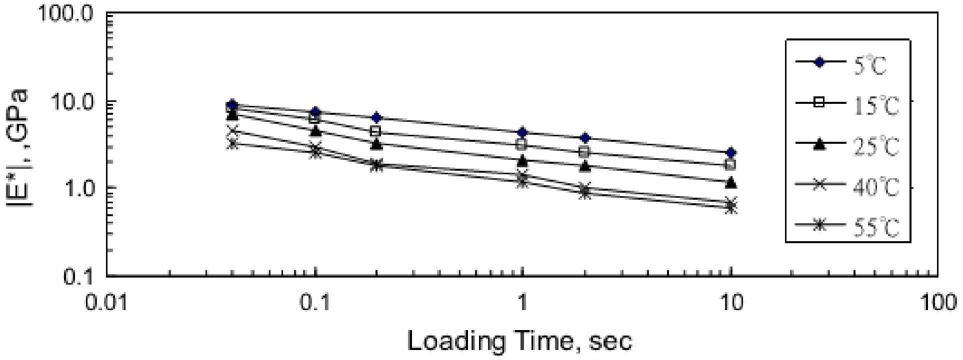


Figure 2.6: Dynamic modulus versus loading time for different temperatures (Hsu *et al.*, 2011)

Punith and Veeraragavan (2011) investigated the viability of the use of reclaimed polyethylene fibres obtained from low-density polyethylene (LDPE) bags in OGFC mixtures. Fibres were shredded to a size of 2 × 2 mm and were used at a dosage rate of 0.3% by weight of the mixture. The addition of polyethylene (PE) fibres reduced abrasion loss under both aged and unaged conditions due to improvement of binder stiffness. A higher percentage of abrasion loss was reported for aged samples due to hardening of asphalt binder and as well as weakening of the adhesive strength after aging. The binder draindown also found to decrease with the addition of PE fibres. The air void content in the mixes with PE fibres were lower than the conventional OGFC mixes and thus also resulted in lower permeability values. The mixes with PE fibres had higher resistance to moisture induced damage when found in terms of tensile strength ratio (TSR) values. No visual stripping was observed for mixture with PE fibre whereas 8% stripping was observed for unmodified mixes when tested through boiling water test. Mixtures with PE fibres showed considerable enhancement in their performance against fatigue-induced damage at all test temperatures. Results of Hamburg wheel tracking device test showed that the mixes prepared using PE fibres had better resistance to permanent deformation. The higher resistance to plastic deformation was attributed to the stiffening effect due to addition of PE fibre to the binder.

Putman and Kline (2012) compared various mix design procedures for porous asphalt mixtures. Around 20 mix design procedures of OGFC prevalent throughout the United States were grouped into three categories based on the method adopted for determination of optimum binder content (OBC). The three categories of OBC determination included: procedures using compacted specimens; procedures using oil absorption test; and procedures using visual observation of the loose mix. The OBCs determined using compacted samples were found to be less than those obtained from oil absorption or visual determination. Also, the variability in the range of OBC using compacted samples was very high in the range of 5-7%. The OBC obtained from the other two procedures resulted in a single value only. Visual determination procedure was finally recommended for determination of OBC values for porous mixes.

Punith *et al.* (2011) conducted a laboratory investigation on OGFC mixes containing polymers and cellulose fibres. In this study, the influence of modification by means of CRMB, reclaimed polyethylene modified binder (RPEB) and cellulose fibre along with the influence of number of compaction blows on the performance of OGFC was assessed. The use of modified binder resulted in a reduction in abrasion loss of 26% for CRMB binders and 29% for RPEB binders because of the stiffening effect of modifiers. The use of compaction blows of 50 on one side resulted in a reduction of abrasion loss of 8-12% compared to the mixes compacted by using 25 compaction blows on each side. The use of modified binders helped in avoiding the draindown of the binder from the mix. The polymer modified binder mixes (without fibre) as expected showed higher stiffness compared to the conventional mixes with fibre alone. The use of CRMB and RPEB enhanced the resilient modulus of OGFC mixes compared at both compactive efforts (25 and 50 blows). A higher indirect tensile strength (ITS) was observed for mixtures compacted at 50 blows on one side than the mixtures compacted by 25 blows on each side. The TSR values were also quite higher for OGFC mixes with modified binders. The fatigue life was found in the range of 15158 -29138 repetitions, when tested through indirect tensile fatigue test, for the OGFC mixtures. The use of modified binder increased the fatigue life by 40% and 67% respectively for CRMB and RPEB compared to the fatigue life of the mixture with neat 60/70 grade binder with fibres. When tested for Hamburg wheel tracking test (HWTT), the use of modified binders was reported to reduce the plastic deformation. The OGFC mixtures compacted by 50 blows on one side were showed better results with respect to abrasion and other parameters tested.

Goh and You (2011) investigated the mechanical properties of porous asphalt pavements with warm additives (Advera warm mix additive added at a rate of 0.25%) and RAP (15%). One single aggregate gradation and one binder type were used in the study. It was observed that the porous asphalt mixture, both with and without RAP, on using WMA technology showed lower compaction energy index (CEI) value compared to control mixtures. In this study, two control mixtures were used prepared with PG 58 – 34 grade bitumen using 0 and 15% of RAP. Mixes with RAP had higher CEI value Results of permeability indicated that HMA mixes with RAP had the lowest permeability whereas HMA mixes without RAP had highest permeability. However, all mixtures were found to meet the minimum permeability requirements. From the indirect tensile strength test results, WMA mixtures with and without RAP were reported to have the highest and the lowest tensile strength respectively. Utilisation of a higher percentage of RAP content was recommended in design of porous asphalt mixtures with a use of WMA technology to reduce production temperatures for mixtures with RAP.

Mansour and Putman (2012) investigated the effect of aggregate gradations on the performance of porous asphalt mixtures. Based on NCHRP Report 640, 29 different aggregate gradations were identified and grouped together on the basis of mid-point percent passing for each sieve in 10 gradation groups. The porous mixes were prepared with the 10 gradations, SBS modified PG 76-22 asphalt binder and cellulose fibre as an additive. A good correlation was observed between the average porosity/air void content and the void ratio of the coarse aggregate skeleton. As the aggregate source remained same, so the aggregate void ratio was affected by the gradation only Mixes with higher void ratio showed higher abrasion loss. The mixes with coarser gradation resulted in higher permeability than the mixes with finer gradation as finer gradations resulted in more closely packed aggregate particles that ultimately reduced the air void content in the mix. Finer mixes exhibited higher tensile strength because of the more closely packed aggregate particles. Porous asphalt mixes with highest void content showed lowest tensile strength vales. The same trend was observed for both dry as well as conditioned samples. No conclusive relationship was found between the aggregate gradation and rutting resistance in the study.

Wurst and Putman (2012) studied the feasibility for use of WMA technologies to produce OGFC mixtures without incorporating fibres Two HMA, two Evotherm-WMA (with and without fibre), and foamed WMA (without fibre) along with one binder PG 76-22-SBS modified were used in this study. Lower draindown value of WMA mixes without fibre showed that the use of WMA additive could fulfill the primary purpose (*i.e.* minimise draindown) of using fibres in porous mixes. It was found that WMA mixtures without fibre had higher permeability compared to HMAOGFC mixtures with fibre due to increased mixture porosity. Foamed WMA mixtures without fibre and HMA mix with fibre performed similarly with respect to aged abrasion resistance, whereas HMA mix without fibre showed poor resistance to abrasion than WMA mixture. No noticeable stripping was observed for all combination of mixes when tested through boiling water test. This result was attributed to the use of good quality along with the inclusion of hydrated lime as an antistripping additive. Overall from different tests (durability, aging, abrasion resistance, permeability) conducted WMA mixes without fibre were concluded to have good resistance than HMA OGFC mixes with fibre. It was concluded that the use of fibre can be skipped while using the WMA technology in OGFC mixes.

Cetin (2013) evaluated the effect of crumb rubber size (Sieve No.: 4-20, 20-200, 4-200) and concentration (10%, 15%, and 20% by weight of the optimum bitumen content) on the performance of porous asphalt mixtures. Crumb rubbers sizes were obtained through tyre buffing. The fibre-like shape and texture of the crumb rubber particles, as observed through a scanning electron microscope, reduced the binder draindown of porous mixtures due to the reinforcing effect. Small size of rubber particles reduced air void content and subsequently the coefficient of permeability. Cantabro abrasion loss of the porous mixtures was found to be increase with increase in rubber content for all particle sizes, as larger sixe particle sizes lead to discontinuity in the bitumen matrix. A similar observation was found in case of the resilient modulus test results. The discontinuity in the matrix formed by large size rubber particle also showed a negative impact on the cohesion and indirect tensile strength. No improvement was observed in moisture susceptibility results by the addition of crumb rubber while tested through Modified Lottman test. From the test results, optimum rubber content was found to be 10% by weight of the optimum binder content for all sizes of crumb rubber. In general, it was found that an increase in the crumb rubber content and size declined the performance characteristics of the porous asphalt mixtures.

Lyons and Putman (2013) examined the effect of different stabilising additives on the performance of porous asphalt mixes. The additives evaluated were cellulose fibres, styrene-butadiene-styrene and crumb rubber. Hydrated lime was also used (1% by weight of the aggregates) as an antistripping additive. Designation of the mix types considered in the study was: ‘C’ for control mix with PG 64-22 binder; ‘C-F’: mix with PG 64-22 binder and fibres; ‘SBS’: mix with SBS modified binder; ‘SBS-F’: mix with SBS modified binder and fibres; ‘CRM5%’: mix with 5% crumb rubber modified binder; and ‘CRM12%’: mix with 12% crumb rubber without fibres. Addition of cellulose fibre (0.3% by mix weight) resulted in reduction in binder draindown. The cellulose fibre alone (without modified binder) was not effective in improving the abrasion resistance of the porous asphalt mixtures. With the use of additives, the OBC of these mixes were much higher than the control mixes (Figure 2.7). Although the addition of cellulose fibres and crumb rubber helped in increasing the resistance to abrasion loss of the mixes, the permeability of the mixes reduced, as these additives filled up the voids and broke their interconnectivity. The porous mixes with crumb rubber modifier had superior performance in terms of resistance to moisture susceptibility, compared to mixes with cellulose fibres. However tensile strength ratio values of all porous mixes when evaluated as per AASHTO T283 guidelines, were found to be higher than 80%. The long term draindown and permeability characteristics were also studied by keeping the compacted samples at 60 °C for 56 days and simultaneously testing them for permeability at 7, 14, 28, 42 and 56 days. The binder draining to the bottom of the samples clogged the voids in the mix, thereby resulting in permeability loss. The use of fibres resulted in an increase in the rutting resistance evaluated through asphalt pavement analyser. The mixes using SBS-F had the lowest rut depths followed by control with fibre. SBS modified, CRMB modified and the control mix.

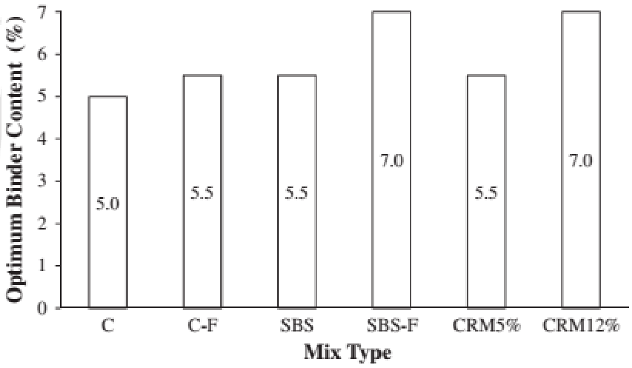


Figure 2.7: Optimum Binder Content of the OGFC mixes (Lyons and Putman, 2013)

Chen *et al.* (2012) investigated the effect of binder type and additives on the performance of porous friction course (PFC) mixes. Three binder types: conventional asphalt rubber AR-80, polymer modified asphalt (PMA) and high-viscosity asphalt (HVA) and two additives: cellulose fibre and hydrated lime were used in the study. The PFC mixes treated with hydrated lime and fibre resulted in lower air void content than the mixes with an untreated conventional binder. The addition of lime decreased the permeability of PFC mixes due to reduction in the interconnected voids, as lime itself occupied the voids of PFC mixes. The air void content of mixes with HVA were highest and in turn, the permeability was also the highest for these mixes. The resistance of PFC mixes to moisture susceptibility (in terms of tensile strength ratio) was higher for HVA binder compared to those with AR.

Addition of lime and cellulose fibres slightly improved the indirect tensile strength. Wheel tracking test results showed that the mixes with modified with lime as an additive enhanced its performance against moisture induced damages (Figure 2.8).

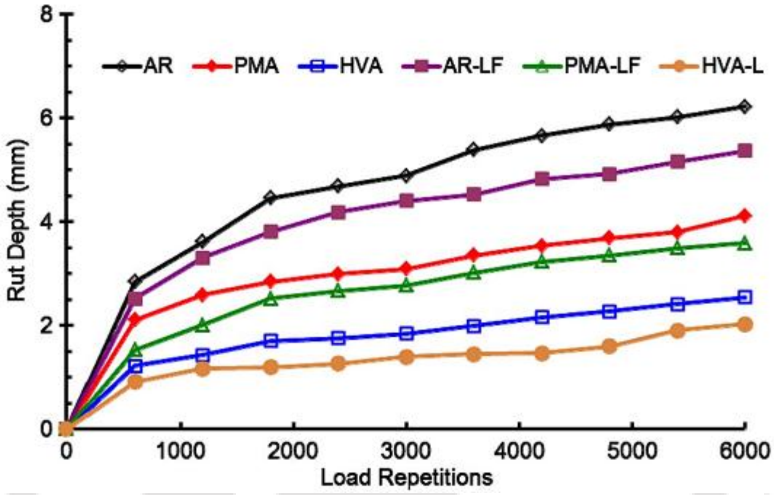


Figure 2.8: Rut depth of PFC mixes in wet conditions (Chen *et al.*, 2012)

The abrasion loss in PFC mixes with AR was higher than those using HVA, and this difference was more significant under aged conditions. The abrasion loss (under unaged condition) with the HVA was about 0.88 times that of with respect AR. The surface friction remained unaffected by the binder and additive type indicating that the friction is primarily affected by the aggregate gradation.

Hasan *et al.* (2013) investigated the effect of nominal maximum aggregate size (NMAS) and break point (BP) sieve on the performance of porous asphalt mixes. BP refers to the sieve size that corresponds to an abrupt directional change in the curve of aggregate gradation. A total of 9 gradations were selected with 3 NMAS of 14 mm, 20 mm and 25 mm. The break point sieve sizes were 3.35 mm, 5.0 mm and 6.3 mm respectively for 14 mm, 20 mm and 25 mm NMAS mixes. By increasing the NMAS and BP, the mixes produced had higher air voids content and higher coefficient of permeability. Mixes with higher NMAS and BP sieve size showed higher air voids and coefficient of permeability. However, this advantage was counterpoised with the increase in abrasion loss due to the higher air voids created in the mix because of the coarser gradation. Larger air voids in coarse graded mixes allow easy entry of air when comes in contact with the binder, results in an early aging and brittleness of the binder. The indirect tensile strength of the porous asphalt mixes decreased with increase in NMAS and BP due to higher air void content. However, mixes with larger NMAS and BP showed higher values of resilient modulus, which was attributed to the fact that larger aggregates had higher stone-on-stone contact in the coarse aggregate skeleton than the finer aggregates.

Martin *et al.* (2013) also investigated the influence of aggregate gradation on the clogging characteristics of porous asphalt mixtures. Ten representative gradations were used that covered most of the gradations used in United States for OGFC mixes. From porosity results of the compacted samples it was observed that the mix with the finest gradation had the lowest porosity and the mix with the coarsest gradation had the highest porosity. The macro texture depth (TD) was found to have a strong correlation with the percentage passing 4.36 mm sieve size and D_{15} (sieve size corresponding to 15% passing) of the gradation. A falling head permeability device was used for permeability measurement of OGFC samples. Coarser gradations showed higher permeability. The clogging of the mixes was attempted by using graded sand and the permeability was measured under clogging, de-clogging and stepwise clogging status. The permeability of the samples decreased significantly after clogging but the value never went down to zero. After attempting de-clogging using reverse flushing, only 69% of the initial permeability of the samples was restored. The permeability first kept on decreasing even after subsequent backwashing and then finally attained a constant value. The initial rate of clogging was twice that of the subsequent clogging, and the loss in permeability was highest during the initial clogging.

Putman and Lyons (2015) studied the long term draindown of porous asphalt mixtures with various additives. Three mixes: control mix (PG 76-22 – SBS modified) with cellulose fibre, ground tyre rubber (GTR) modified mix without fibre and warm OGFC mixes without fibre. It was observed that for all types of mixes, the permeability decreased over the first 56 days and then leveled off or increased for next 28 days. The authors were not able to state the exact reason for these behaviour. However, they have stated two hypotheses for these behaviour attributed to the binder film thickness and binder viscosity.

Villani *et al.* (2014) studied the frictional characteristics of three different kind of asphalt concrete mixes namely Stone Mastic Asphalt (SMA), Dense Graded Mix (AC10) and Porous Asphalt (PA) mix. All combinations of mixes were designed for the same maximum aggregate size. Asphalt slabs were compacted in the lab using a laboratory roller compactor and tested with the help of Skid Resistance Interface Testing Device (SR-ITD). The friction coefficients were measured at 60 km/h for three different number of wheel passes (54,000, 324,000 and 1296,000 passes). From the results, it was perceived that SMA and PA mix exhibited 20-25% higher friction than AC10 mix. The mixtures were subjected to polishing action with the help of three rolling wheels moving at a speed of 20 km/h. However, the SMA and AC10 mixes attained similar friction coefficients after the polishing cycles. On the other hand, the porous asphalt mix maintained a higher friction coefficient even after the increase in the polishing cycles. It was concluded that the PA mix had a higher coefficient of friction among the three mixes and was more resistant to polishing.

Qureshi *et al.* (2015) assessed the premature failure of five different OGFC pavements located within the state of Alabama, located within the south eastern region of the US. The research involved both lab investigations and field work. Field work involved a field distress survey on the selected projects whereas laboratory study evaluated air voids, gradation and percentage asphalt content of the extracted cores. The variation of air void along the depth of the OGFC pavement was analysed through X-ray images of cores. An analysis of variance (ANOVA) carried out on air voids (AV) and indirect tensile strength test (ITS) results showed that both AV and ITS parameters played a significant role in determining the reason of failure in early ages of the OGFC pavement. A relatively higher value of ITS and lower air void content was reported in good performing parts of pavement section as compared to bad performing parts. Granite aggregates were able to meet the functional requirements while used in OGFC mixes. The inadequate rate of tack coat application and asphalt draindown were considered as quite important concerns related to performance of OGFC mixes.

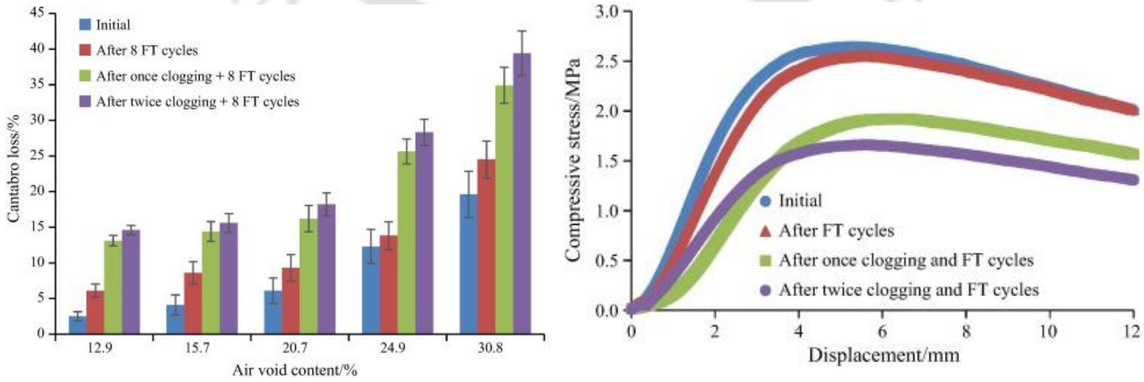
Chen *et al.* (2015) measured the permeability loss of OGFC mixes due to deformation and particle related clogging using a falling head permeameter. Eight combinations of OGFC mixtures with different NMAS, gradations and air void contents were prepared for evaluation of deformation-related clogging. OGFC samples were subjected to wheel rutting tests with different loading times under two load levels (700 kPa, and 900 kPa) at two test temperatures (of 45 °C and 60 °C), and then the permeability was measured. In a similar way, seven types of suspension liquids were prepared for assessment of particle-related clogging. For each type of solution, the quantity of materials trapped within the OGFC specimen, passing OGFC specimen, and retained on the top of sample surface, were determined after permeability tests to conclude the critical sizes of suspended particle, attributing to particle-related clogging. From the results, it was observed that the permeability of OGFC mixture showed a steady reduction after a sharp initial decline with the increased wheel loading times. Permeability loss due to deformation-related clogging could be reduced effectively by using larger nominal maximum aggregate size and higher air void content. Values of 0.15–0.3 mm and 1.18–2.36 mm were the crucial sizes of trapped particles in OGFC mixtures.

Jiang *et al.* (2015) studied the composition, microscopic void features, and performance characteristics of porous asphalt concrete (PAC) made with penetration grade 70 and high-viscosity asphalt modifiers. High viscosity asphalt binder was prepared by adding Tafpack-Super at a rate of 12% by the mass of neat asphalt binder (penetration grade 70). Porous mixes were designed to have an air void content of 20%. The coefficient of permeability of the porous mixes was found to be greater than 10^{-2} cm/s (86.4 m/day). Porous mixes containing asphalt-rubber binder showed higher dynamic modulus for both the unconfined and confined conditions. Mixes with asphalt rubber also showed higher resistance to permanent deformation measured through the wheel tracking test.

Shirini and Imaninasab (2016) studied the influence of crumb rubber (CR) on the performance of porous mixes in terms of resistance to draindown, permeability, moisture susceptibility, skid resistance and rutting resistance. Mixes were fabricated with asphalt binder containing 10%, 15%, and 20% CR, and then the was compared with control (without crumb rubber or SBS) and 5% SBS modified ones. It was observed that mixes with CR and SBS reduced permeability but improved rutting resistance and binder draindown significantly. Mixes incorporating CR showed enhanced resilient modulus, frictional characteristics and moisture resistance at initial content (10%) and then showed negative impact with further CR addition.

Sangiorgi *et al.* (2017) assessed the effectiveness of adding crumb rubber by dry method in porous asphalt mixtures. In this study, crumb rubber (1% by weight of aggregates) was incorporated into SBS modified asphalt binder and then rubberised porous asphalt mixtures were prepared for performance evaluation. Permeability and permanent deformation decreased with the addition of crumb rubber. However, the addition of crumb rubber improved the moisture resistance, abrasion resistance and reduced the binder draindown. The use of crumb rubber decreased the indirect stiffness modulus value at low tested temperature (5°C), which showed their higher resistance to thermal cracking as compared to the control mixes without crumb rubber.

Chen *et al.* (2018) studied the volume change and mechanical degradation of clogged OGFC specimens when subjected to freeze-thaw cycles. In this study, the OGFC samples were fabricated at five different air void contents and were clogged by fine soils at two clogging levels. The two clogging levels included: clogging by manual grout of soil of particle size 0.15 to 0.3 mm; and clogging by fine soil using vacuum infiltration. The X-ray computed tomography technique was used to determine the total and connected air void content of clogged and unclogged OGFC specimens. Clogged and unclogged OGFC specimens were first subjected to eight freeze-thaw (FT) cycles and were then tested for permeability, Cantabro abrasion loss, and uniaxial compressive strength. It was observed that the expansion rate of OGFC mixes during freezing condition was higher than the contraction rate owing to the melting of ice, and therefore residual expansion deformation occurred during each cycle. Increase in abrasion loss and decrease in compressive strength of OGFC specimens was observed with the introduction of FT cycles (Figure 2.9). The residual deformation and mechanical performance degradation of OGFC mixes after FT cycles increased with the increase in void content and clogging level.



(a) (b)

Figure 2.9: (a) Cantabro mass loss and (b) compressive stress curves of OGFC specimens (Chen *et al.*, 2018)

Gu *et al.* (2018) evaluated and compared the benefits of OGFC through two field projects, namely Las Vegas and Elko constructed by the Nevada Department of Transportation. Each project consisted of both OGFC and dense graded bituminous concrete (DGBC). Elko project was situated in the urban area of the Elko town whereas Las Vegas project was located in a rural area. Laboratory tests such as Cantabro test, tensile strength ratio test, and Hamburg Wheel-Track test (HWTT) were implemented to assess the durability, moisture-susceptibility and rutting performance of OGFC mixtures. Las Vegas OGFC mixtures were found to satisfy all the performance parameters whereas Elko mixes were not able to meet the HWTT criterion (Minimum of 20,000 passes before reaching to a rut depth of 12.5-mm rut). The field performance parameters in terms of permeability, friction, and noise of both OGFC mixes were assessed through NCAT falling head permeameter, locked-wheel skid trailer, and On-Board Sound Intensity meter, respectively. On the basis of field performance test results, it was concluded that the Las Vegas OGFC pavement showed better performance in terms of permeability, friction, and noise reduction compared to the DGBC pavement, whereas the Elko OGFC pavement displayed similar performance with the DGBC pavement even after two years of service. Finally, a cost-benefit analysis was attempted and it was found that application of OGFC in Los Vegas minimised the net present value by 36% as compared to the DGBC, whereas the OGFC pavement in Elko increased the net present value by 86%. It was found that application of OGFC was cost-effective in rural highways but impractical in urban or town areas as the OGFC sections in urban areas got clogged at very rapid pace compared to OGFC sections in rural highways.

2.5 INTRODUCTION TO STEEL SLAG AND ITS MANUFACTURE

India is the world's third largest steel maker (after China and Japan) with 101.4 MT steel production in 2017 (World Steel, 2018). The electric arc furnace and basic oxygen furnace processes of steel production occupy share of 56.8% and 43.2%, respectively, in India (World Steel, 2018). Steel production is a two stage process: 1) purification of iron ore in blast furnace, 2) production of steel from the purified iron. Slag is generated during each of the two stages and is termed as blast furnace slag and steel making slag, respectively. Blast furnace slag is a by-product of pig iron in the blast furnace and is mainly composed of silicates and alumino-silicates of calcium. The pig iron obtained from iron ore or pellets may be further processed (secondary process) to produce steel. Steel slag is a by-product of steel making industries. Around 12 million tonnes of steel slag is generated every year from steel industries in India (FICCI, 2014). Based on the two most common steel production processes employed, steel slag is usually classified in two main categories, namely Electric Arc Furnace (EAF) steel slag and Basic Oxygen Furnace (BOF) steel slag (Wu *et al.*, 2007; Sofilic *et al.*, 2010). The manufacturing process of steel slag is summarised in Figure 2.10.

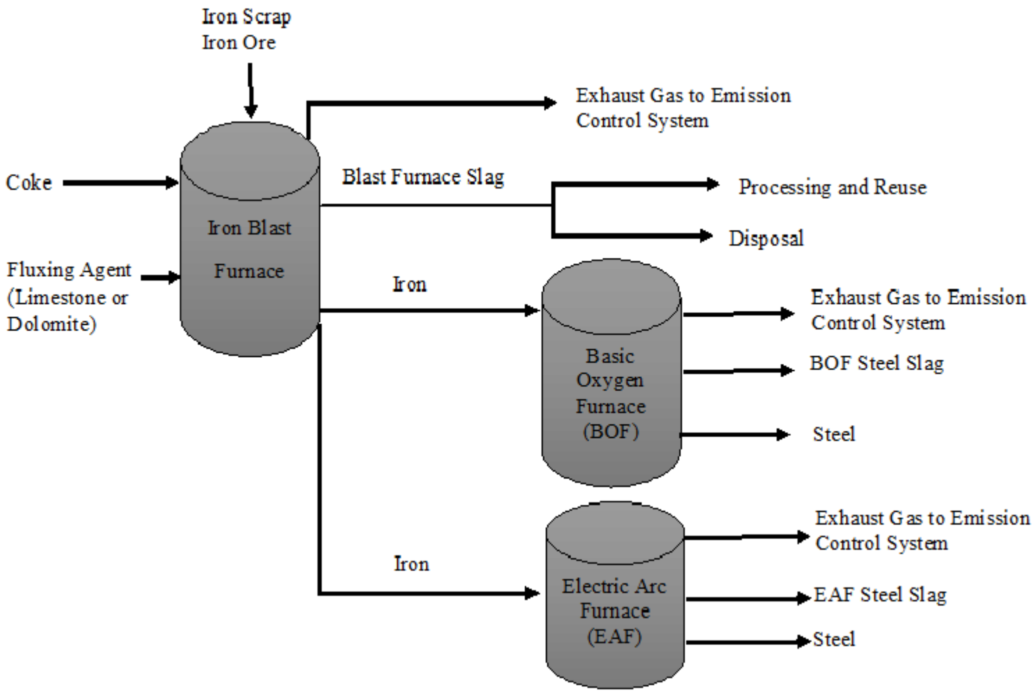
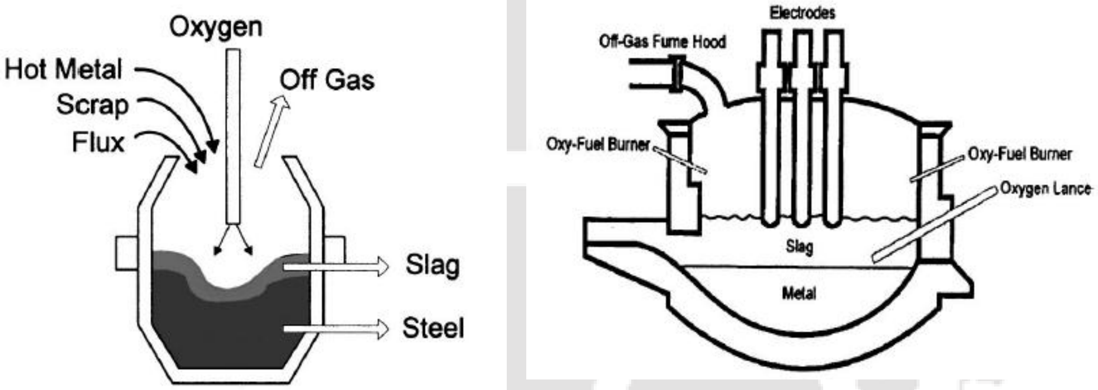


Figure 2.10: Steel and steel slag production

In case of BOF process, the liquid hot iron coming from blast furnace, scrap, and fluxes (lime and dolomite) are charged together to the basic oxygen furnace. A lance is lowered into the furnace and high pressure oxygen is passed, that combines with raw materials and removes the impurities in the charges (Shen *et al*., 2009). The basic oxygen furnace is shown in Figure 2.11a. The obtained impurities are composed of carbon as gaseous carbon monoxide, manganese, phosphorus, silicon, and some iron as liquid oxides, which combine with the fluxes (lime and dolomite) to form the BOF steel slag. As a result, this process produces a high quality of steel and the by-product BOF steel slag.



(a) (b)

Figure 2.11: Type of furnace used for steel slag (a) BOF and (b) EAF

In this process, steel scrap, pig iron, and fluxes are charged into the furnace. Figure 2.11b shows an EAF furnace which is a kettle shaped structure with a removal lid. During the production process graphite electrodes are lowered down to furnace that pass heat at high temperature through the lid (Airey *et al*., 2004; Xie *et al*. 2013). At these high temperatures the scrap melts. During the production process other metals like ferro–alloys, magnesium, aluminium and silicon are added to the steel to obtain the required chemical composition as per the requirements. After that the furnace is tilted to collect the slag that floats on the surface of the molten steel. Steel is there after collected by tilting the furnace in opposite direction by pouring into a ladle for further processing in order to remove additional existing impurities within the steel. The blast furnace slag is used in cement industries since a long time. The presence of tricalcium silicate (C3S), dicalcium silicate (C2S), and tetracalcium aluminoferrite (C4AF) in blast furnace slag makes it suitable to be used as a cementitious material (Sezer and Gulderen, 2013). However, in case of steel slag (BOF and EAF), the pozzolanic activity of these minerals is very less due to lower cooling rate of steel slag as compared to the cement. Therefore, the setting time is prolonged and early strength is minimised when the steel slag is blended with cements. So the (EAF and BOF) steel slags are not suitable for cement industries and they have no well-established channels for reuse.

2.5.1 Chemical composition of steel slag

The major chemical components in steel slag include: iron oxides (FeO, Fe_2O_3); lime (CaO); silica (SiO_2); magnesia (MgO); and alumina (Al_2O_3). The concentration of these oxides in steel slag may vary slightly with process type and source of raw material, and it lies in the range of 88-92%. Steel slag can be simply denoted by $CaO–MgO–SiO_2–FeO$ quaternary system. Based on the furnace conditions and the quantity and type of raw materials, the chemical composition of steel slag also varies. Due to the presence of significant amount of free iron, steel slag is hard and dense and hence possesses high crushing and abrasion resistance. It also has a rough surface texture and high strength that make steel slag a potential candidate for total/partial replacement of natural aggregates in asphalt mixes. Table 1 shows the chemical composition ranges for BOF and EAF slags reported in different studies. During the steel manufacturing process, CaO/SiO_2 ratio is quite often used to characterise the level of alkalinity of steel slag aggregates. A higher CaO/SiO_2 ratio is expected to improve the bond with asphalt binder, which is generally slightly acidic, and thus the resistance to moisture-induced damages of asphalt mixtures (Xie *et al*., 2012; Chen *et al*., 2015).

Table 2.1: Chemical properties of steel slag

Steel slag	**CaO**	**SiO_2**	**Al_2O_3**	**FeO/ Fe_2O_3**	**MgO**	**MnO**	**TiO_2**	**SO_3**	**P_2O_5**	**Free CaO**	**Reference**
BOF	47.88	12.16	1.22	26.30	0.82	0.28	-	0.28	3.33	-	Das *et al.* (2007)
BOF	45.41	13.71	3.8	21.85	6.25	3.27	-	-	1.42	-	Xue *et al.* (2006)
BOF	47.5	11.8	2.0	22.6	6.3	1.90	0.50	-	2.70	-	Mahieux *et al.* (2009)
BOF	39.4	11.97	2.16	30.23	9.69	2.74	0.4	0.12	1	-	Yildirim *et al.* (2015)
EAF	29.27	12.86	9.138	33.37	3.617	5.174	0.347	-	--	-	Pasetto and Baldo (2013)
EAF	30-40	10-20	<10	15-35	<10	10		<0.25	<2	<1.5	Miklos (2000)
EAF	29.49	16.11	7.56	35.26	4.96	4.53	0.78	0.63	0.55	-	Barra *et al.* (2001)
EAF	35.7	17.53	6.25	26.36	6.45	2.5	0.76	-	-	--	Tsakiridis *et al.* (2008)

2.6 STUDIES ON THE USE OF STEEL SLAG IN BITUMINOUS MIXES

The properties and performance of bituminous mixtures mainly depends on parameters including aggregate type, source and gradation; binder source, type and content; additive type and content; mix design method; and the compactive effort used. In the present study, the coarse natural aggregates were replaced with EAF steel slag hence, it is more important to review the studies already conducted for judging the use of steel slag in bituminous mixes. Review of studies carried by various researchers to evaluate the feasibility of steel slag in bituminous mixes are presented next.

Coomarasamy and Walzak (1995) evaluated the effect of moisture on surface chemistry and morphology of steel slags and asphalt mixes containing steel slag. BOF and EAF steel slags were used in this investigation. Mixes with BOF steel slag showed reduced expansivity compared to the EAF steel slag mixes. The failure mechanism observed in steel slag aggregate mixtures was attributed mainly to the excessive expansivity of steel slags due to reaction with moisture. This reactivity could be the cause of long-term degradation of the asphalt-aggregate interface in the presence of moisture. Mineralogical characterization indicated that steel slags exhibited similar bulk phase composition, but the distribution (microstructure) of the slags was very different. In most cases, outer surface regions of the slag were of different composition from the slag interior. The main phases present were oxide phases based on FeO, MnO, MgO, and CaO, and calcium silicate phases. The most likely source for the calcium-rich deposits formed during humidity exposures were calcium silicate phases present in the slags.

Stock *et al*. (1996) evaluated the frictional characteristics of pavement surfaces incorporating EAF steel slag aggregates. They selected 10-mm surface dressings and 14-mm close-graded wearing course surfaces using both steel slag and natural aggregate, laid on a stretch of road in Rotherham, England during the early 1980s. The skidding resistance data of these road surfaces were available for the year 1990, 1992 and 1994, which were measured using Sideways-Force Coefficient Routine Investigation Machine (SCRIM). From the results, it was observed that steel slag road surfaces had 10 to 15% higher long-term skidding resistance properties compared to natural aggregate road surfaces, under the same traffic density.

Kandhal and Hoffman (1997) examined the viability of steel slag as a replacement of fine limestone aggregates in HMA mixture. An excellent correlation was found between the average total expansion of fine aggregate fraction and the coarse aggregate fraction, which indicated that the expansion of the coarse aggregate could be used to predict the expansion potential of the fine aggregate. Mixes with steel slag showed high resistance to moisture damage, found through modified Lottman test and retained Marshall Stability test. Mixtures with steel slag as fine aggregate had 20 to 35% higher stability compared to control mixes. There was no relationship observed between the percentage aggregate expansion (passing 4.75 mm sieve fraction) and the increase in volume of mixture from freeze-and-thaw conditioning and hot water bath conditioning. This result was attributed to an effective asphalt coating around the fine aggregate particles that prevented any significant ingress of water into the aggregate. It was also reported that the utilisation of steel slag in bituminous mixes should be limited to substitute either the fine or the coarse fraction, but not both.

Bagampadde *et al*. (1999) analysed the feasibility of steel slag in bituminous mixtures as a replacement for limestone aggregates. It was found that mixes with only coarse aggregate replacement showed high fatigue life and high resistance to permanent deformation as compared to other combinations of mixes. These results were accredited to the high stiffness and the presence of high angular and hard steel slag aggregates as coarse particles that increased the shear strength of the mixtures.

Asi *et al*. (2007) evaluated the feasibility of using steel slag aggregates (SSA) in asphalt concrete mixtures through determination of indirect tensile strength, rutting resistance, resilient modulus and fatigue life. Dense graded bituminous mixes were designed with different percentage replacement (0%, 25%, 50%, 75% and 100%) of coarse limestone aggregates with SSA aggregates. Mixes incorporating SSA showed improved resistance to moisture compared to mixes with limestone. The improvement was attributed to the better aggregate structure of the SSA. Mixes with 25% replacement showed better resistance to permanent deformation followed by 50%, 75% and 0% replacement with SSA aggregates. However, mixes with 100% replacement didn't show any improved resistance to permanent deformation due to the presence of higher binder content. Mixes up to 75% replacement of limestone aggregate with SSA showed higher resilient modulus due to the angularity of the SSA. Mixes with 25% replacement with SSA showed the highest fatigue life followed by 50%, 75%, 100% and 0% replacement. It was concluded that a replacement up to 75% of the limestone coarse aggregate by steel slag aggregate, improved the overall mechanical properties of the asphalt concrete mixes.

Asi (2007) conducted a laboratory study for comparing skid resistance of different asphalt concrete mixes. The different mixes studied were: a Marshall mix with natural aggregate at its optimum binder content (OBC); Marshall mixes with 0.5% and 1% bitumen content higher than the OBC; a mix designed using Superpave design procedure; a mix with 30% steel slag as replacement to limestone aggregate; and a mix with stone matrix asphalt (SMA) aggregate gradation. Asphalt concrete mixes containing 30% slag had the highest skid number followed by Superpave, SMA and Marshall mixes respectively (Figure 2.12). Skid resistance of the bituminous mixes decreased with increase in bitumen content above the OBC. Mixes designed as per the Superpave method showed high skid number in terms of BPN as compared to the mixes designed according to the Marshall method. The combination of steel slag and SMA gradation was finally recommended for high skid resistance of road surface.

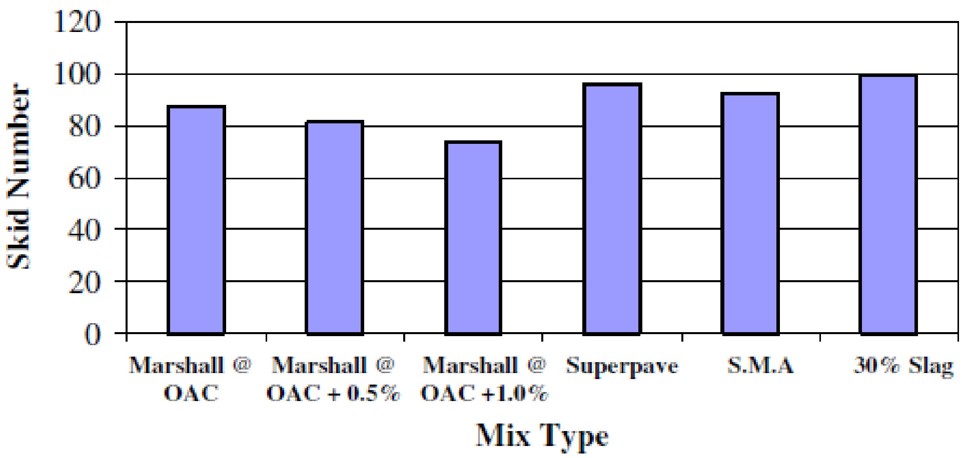


Figure 2.12: Skid numbers for the different asphalt concrete mixes (Asi, 2007)

Wu *et al.* (2007) explored the use of BOF steel slag aggregate in SMA mixture (9.5 mm NMAS) by replacing approximately 80% of basalt coarse aggregate with steel slag. The steel slag selected used hot-sprinkling method of cooling, and was then air aged for 3 years before use. The surface texture of the steel slag was observed using a scanning electron microscope (SEM) (Figure 2.13). The SEM images showed that the porosity of steel slag was 24 times higher than the basalt (5.76% and 0.24% respectively), when determined through mercury intrusion porosimeter. The optimum binder content of mixes with steel slag was slightly higher than the mixes with basalt, as steel slag was reported to consume larger quantity of asphalt binder during mixing due to its porous structure. The SMA mixtures with steel slag aggregate showed acceptable results in expansion rate (with no significant increase and below 1% after 7 days), which indicated that the stability of steel slag can be enhanced by proper processing technology and a long aging time. The high-temperature property of SMA mixes with steel slag improved with an increase in percentage replacement of basalt coarse aggregates with steel slag. The improved physical properties of steel slag enhanced rutting resistance at high temperature as compared to the control mixes. An excellent performance with good abrasion resistance and coefficient of friction were found for the mixes with steel slag after 2 years of service from the inspection of road sections.

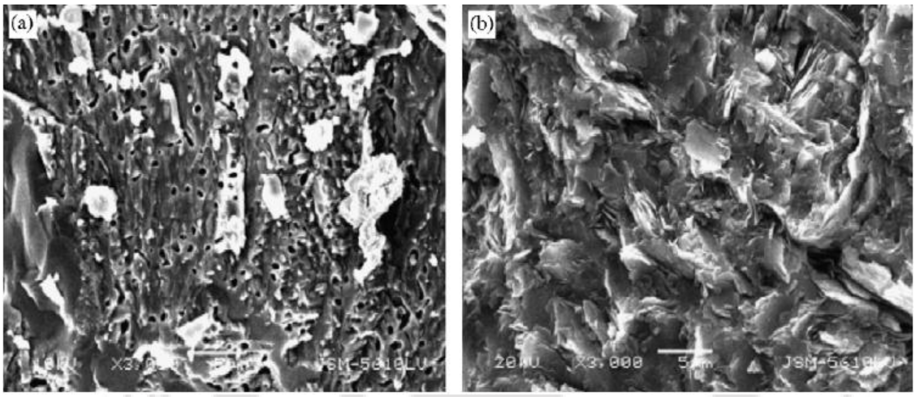


Figure 2.13: SEM images of steel slag and basalt (Wu *et al.*, 2007)

Shatnawi *et al.* (2008) evaluated the performance of different types and contents of aggregates in dense graded asphalt mixes of 12.5 mm NMAS. It included 100% of limestone (natural aggregate); 100% steel slag aggregates; coarse natural aggregates with fines and filler from steel slag; and steel slag as coarse aggregate with natural aggregates as fine and filler. Mixes with 100% of steel slag aggregate led to a reduction in OBC to 4.8% from a value of 5.3% in case of mixes prepared with 100% limestone. This was attributed to the low absorption value of the steel slag aggregates (1.7%) as compared to natural aggregates (3.2%) used. It was also found that the mixes with 100% steel slag aggregates had high stability and improved density compared to the other combination of mixes, due to their high crushing and abrasion resistance compared to the natural limestone aggregates.

Ahmedzade and Sengoz (2009) also checked the viability of steel slag coarse aggregates as a substitute for limestone in dense graded bituminous mixes (12.5 mm NMAS) with two binders (AC-10 and AC-5). Higher Marshall quotient and creep stiffness values of steel slag mixtures indicated their better resistance to permanent deformation compared to the control mixes (without steel slag). Mixes with steel slag showed higher resistance to moisture induced damage, in terms of indirect tensile strength ratios, when compared to the control mixes (Figure 2.14). Stiffness modulus values of steel slag mixes were higher than the control mixes at all test temperatures. Higher indirect tensile strength values of steel slag mixes indicated better cracking resistance as compared to control mixes.

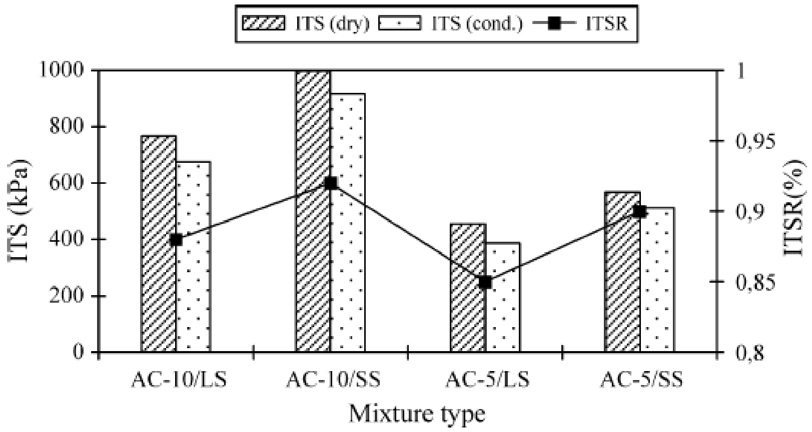


Figure 2.14: ITS and ITSR values of asphalt mixtures (Ahmedzade and Sengoz, 2009)

Shen *et al.* (2009) studied the viability of using basic oxygen furnace (BOF) steel slag in porous asphalt mixes by replacing 0%, 25%, 50%, 75% and 100% of coarse natural aggregates. From chemical composition analysis using inductively coupled plasma (ICP) spectrometer, it was found that the steel slag had high CaO content. This indicated the possibility that steel slag has a higher affinity for binder than for water and can therefore improve the adhesion between the aggregate and asphalt binder. The frictional resistance of porous mixes was improved with an increase in percentage replacement by BOF steel slag (Figure 2.15). This was attributed to the angular shape and rough surface texture of BOF steel slag. TSR values increased with the increase in BOF slag substitution percentage when measured through the modified Lottman test. The improvement in stripping resistance was attributed to slag’s hydrophobic nature and rough surface texture, which allowed deeper penetration of the asphalt binder to form a strong bond.

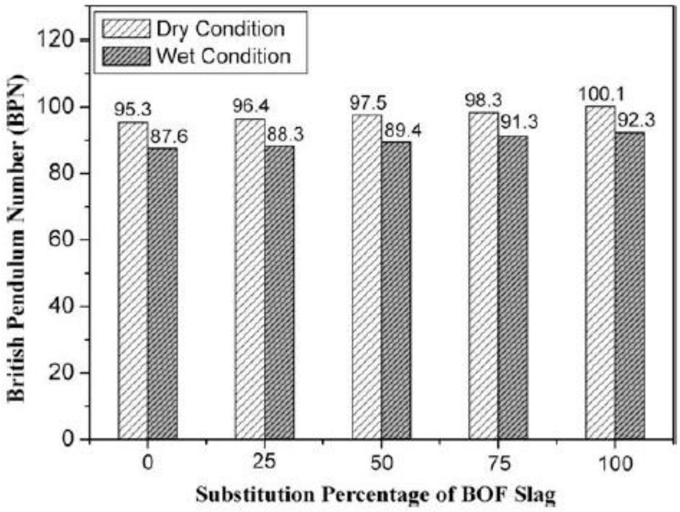


Figure 2.15: Skid resistance test results for the porous asphalt mixtures (Shen *et al.*, 2009)

Hamburg wheel tracking test results showed that the mixes containing steel slag aggregates demonstrated high resistance to rutting compared to the mixes prepared with natural aggregates. High angularity and friction angle of the BOF steel slag enhanced the shearing resistance due to improved interlocking mechanism of the aggregate skeleton. Overall, it was reported that mixtures with steel slag improved skid resistance, rutting resistance, moisture susceptibility and sound absorption as compared to the control mixes.

Pasetto and Baldo (2010) did a laboratory study to evaluate the performance of EAF slag as a replacement of natural aggregates in asphalt concrete wearing course for flexible pavement with NMAS of 20 mm. The study included a preliminary study of the chemical, physical, and leaching properties of EAF steel slag followed by the performance characteristics in terms of permanent deformation, stiffness modulus and resistance to moisture damage of the bituminous mixes. EAF steel slags satisfied all physical-mechanical requirements. EAF steel slag did not show any hazardous leaching behavior. Mixes with EAF steel slag showed better resistance to permanent deformation, measured at 40 °C temperature, as compared to mixes with natural aggregates. This behaviour was attributed to the polyhydric shape, high angularity and rough surface texture of EAF steel slag. Mixes with EAF steel slag showed higher (40-60%) stiffness modulus values than those with natural aggregate. The results of stiffness modulus test at 20 °C were coherent with those of fatigue life at the same temperature, where mixes with higher stiffness modulus showed higher resistance to fatigue. Mixes containing steel slag had 7-10% higher resistance to moisture compared to the mixes containing natural aggregates due to the presence of high binder content, which provided a thicker film of bitumen around the aggregates.

Pasetto and Baldo (2011) investigated the feasibility of using EAF steel slag in dense graded bituminous mixes with NMAS of 10 mm. EAF steel slags were found to have better adhesion properties with weakly acidic bitumen due to the alkaline nature of EAF steel slag (higher value of CaO/SiO_2 for EAF steel slag than the natural aggregates). EAF steel slags demonstrated improved physical properties as compared to natural aggregates. Mixes incorporating EAF steel slag coarse aggregates showed better performance in terms of permanent deformation, stiffness modulus, fatigue tests and indirect tensile strength tests compared to the mixes with natural aggregates.

Wang and Wang (2011) studied the feasibility of utilisation of EAF steel slag in porous asphalt mixes with NMAS of 12.5 mm. Two different type of mixes were prepared and evaluated: one consisted of EAF steel slag (100% aggregates were EAF slag) and another consisted of granite aggregate with modified PG76-22 binder. The asphalt pavement analyser test results showed that mixes with steel slag demonstrated high resistance to rutting (rut depth of 2 mm at 8,000 load cycles) than the mixes with granitic aggregates (rut depth of 6 mm at 8,000 load cycles). Based on AASHTO T283 stripping test it was stated that moisture damage in steel slag mixes is more related to hydration of free lime, whereas the loss of bond between the aggregate and asphalt binder is the main cause for stripping in mixes with conventional aggregates. Mixes with steel slag aggregates were more flexible at 40 °C than the mixes made with granite aggregates, but this flexibility was similar at relatively high temperature of 45 °C.

Liapis and Likoydis (2012) conducted a field study on a thin (25 mm) skid-resistant wearing course containing EAF steel slag and mixes containing natural aggregates. The skid performance was measured after 30 and 41 months of opening to traffic, and were found to be satisfy the requirements as per Greek specifications. Mixes with EAF steel slags were found to have improved skid resistance value and macro-texture depth as compared to mixes containing natural aggregates. EAF steel slag mixes showed good skid resistance with the passage of time, probably due to removal of thin film of bitumen resulting in a higher micro-texture.

Behnood and Ameri (2012) carried out an experimental study on stone matrix asphalt mixtures containing steel slag. It was also observed that mixes with coarse steel slag aggregate had higher ITS value (833 kPa) than the mixes with natural aggregates (690 kPa). This was attributed to the relatively high air void content of limestone mixes, which resulted in higher deformation and lower strength. The resilient modulus test results showed that mixes with steel slag increased the resilient modulus by around 30% as compared to the control mixes with natural aggregates, probably due to higher bitumen content and rough surface texture in case of steel slag aggregates. High resistance to permanent deformation of steel slag mixes was attributed to higher hardness, bearing strength and roughness of steel slag aggregates. Overall, the results indicated that the mixes with steel slag as a coarse portion showed better performance in terms of Marshall stability, tensile strength, resilient modulus, moisture susceptibility and permanent deformation as compared to the mixes with natural aggregates.

Xie *et al.* (2012) analysed BOF steel slag as a replacement of coarse basalt aggregates in asphalt mixtures with 60/80 penetration grade bitumen. X-ray fluorescence

(XRF) and scanning electron microscopy (SEM) were used to determine the chemical composition and microscopic morphology characteristics of BOF steel slag. It was observed that greater CaO/SiO_2 ratio in BOF steel slag compared to basalt aggregates resulted in higher alkalinity and thus led to stronger and improved cohesive bond of BOF steel slag with bitumen. Micro pores on the surface of BOF slag resulted in longer heating time to ensure complete drying of retained water in the pores. Mixes with BOF steel slag were superior than control mixes even after several freeze-thaw cycles (1, 2, 3 and 5) in terms of moisture resistance evaluated through resilient modulus, TSR and dissipated creep strain energy (DCSE) parameters. These enhancements were attributed to the better physical and chemical properties of BOF steel slag. The higher stiffening effect of BOF steel slag on the binder compared to basalt aggregates, resulted in a higher resistance to moisture.

Arabani and Azarhoosh (2012) evaluated the effect of recycled concrete and steel slag aggregate on the dynamic properties of bituminous mixtures. Six different combinations of asphalt mixtures containing three types of aggregates (dacite as natural aggregates and recycled concrete and steel slag as a secondary aggregate) were evaluated. The combinations were formed with replacement of steel slag and recycled concrete aggregate as replacement of coarse aggregate or fine aggregate or filler. The mix with steel slag as coarse aggregate, recycled concrete aggregate (RCA) as a fine aggregate and dacite as filler (designated as ‘CA: SS+FA: RCA’ mix) showed the highest Marshall quotient (MQ), which is a measure of a material’s resistance to permanent deformation, shear stress and rutting. It was also reported that CA: SS+FA: RCA mixtures showed the highest resilient modulus due to the excellent angularity of steel slag and RCA aggregates. From the indirect tensile fatigue test, it was observed that the fatigue life of the CA: SS+FA: RCA mixes was significantly better than that of the control mixes. The results were ascribed to the following effects: (1) due to the increase in filler content with increase in the percentage of RCA in the mix as RCA aggregate comprises of cement dust, (2) higher OBC of the modified mixes. The results indicated that the combinations of steel slag as a coarse aggregate, recycled concrete as a fine aggregate and dacite natural aggregate as filler provided the best performance.

Sorlini *et al.* (2012) studied the physical, geometrical, mechanical and chemical properties of dense graded bituminous paving mixtures containing 40% EAF steel slag. Volumetric expansion was measured at 15, 30, 60, 120 and 190 days. Free lime (16–22%) and magnesium oxide concentrations (2–3%) were said to be responsible for the expansive phenomena. Based on the volumetric analysis it was suggested that an aging period of 2 to 3 months is required to minimise the effects of oxides on hydration. Mixes with EAF steel slag had higher air void content (4.4 to 5.6%) and lower percentage of void filled with bitumen (62-71%) when compared to those (2.9 % and 77% respectively) in control mixes. The performance of bituminous mixes with EAF slag were comparable to the performance of mixtures containing natural aggregates (Marshall stability and flow value of slag modified mixes were 16.8 kN and 2.8 mm respectively compared to 14.9 kN and 2.7 mm for control mixes).

Pasetto and Baldo (2013) studied the performance characteristics of stone matrix asphalt and dense graded bituminous mixes prepared with EAF steel slag and binders modified with crumb rubber and SBS. Four-point bending test, tensile strength ratio (TSR) test, and wheel tracking test were employed in the study respectively for fatigue, moisture damage and rutting evaluation. Mixes with CRMB showed superior performance when compared to the mixes with SBS modified binder higher fatigue life, higher TSR and lower rut depth.

Haddock and O’Brien (2013) studied frictional characteristics of HMA pavements in Indiana, USA with steel slag as a replacement of dolomite aggregates. British pendulum number was measured using the British Pendulum Tester (BPT) before and after subjecting aggregates to polishing for 10 h using the accelerated polishing machine also known as British polishing wheel. The main aim of this polishing was to simulate polishing of coarse aggregate in HMA pavements by vehicular traffic, according to ASTM D3319. Mixes with steel slag aggregates showed high frictional resistance and polishing resistance in comparison to the natural (dolomite) stone aggregates. Thus, in places where the frictional resistance of pavement and its resistance to polishing are of prime importance, steel slag or natural aggregate- slag blend was recommended for use.

Ameri *et al.* (2013) conducted a laboratory study to check the feasibility of electric arc furnace steel slag as a replacement of natural limestone (LS) aggregates in warm mix asphalt (WMA) mixtures. SEM images revealed that the EAF steel slag aggregate had higher porosity and roughness than LS aggregate. Steel slag aggregates had higher bulk specific gravity, higher angularity, and high angle of internal friction than the LS aggregates. The higher angle of internal friction led to improved aggregate skeleton resulting in enhanced rutting resistance of mixes with EAF steel slag. These desirable characteristics of steel slag resulted in higher Marshall quotient value representing higher resistance to shear stress and permanent deformations. Mixes with limestone aggregates had higher indirect tensile strength and resilient modulus values. This was attributed to the better adhesion ability of LS to binder than the EAF steel slag due to higher CaO/SiO_2 ratio for LS aggregate. However, mixes with coarse EAF steel slag had higher TSR value than the control mixes with LS aggregate, due to their higher bitumen content and better coating of aggregates. Mixes with steel slag as fine portion had higher TSR values than the mixes with steel slag as a coarse fraction. The result was attributed to the low air void content and high OBC content for this type of mixes. The lower air void content in that particular mixes decreased the water penetration into the mixture. At the same time, the higher bitumen content resulted in better coating of aggregates in this type of mixtures.

Pandey and Jain (2013) evaluated the feasibility of using EAF steel slag in dense graded bituminous mixes (13.2 mm NMAS) compared to the mixes with containing natural aggregates (control mixes). It was found that OBC of the mixes with steel slag decreased slightly as compared to control mixes due to the higher specific gravity of the steel slag aggregates. The rutting test result showed that the final rut depth in the steel slag mixes was about 24% less as compared to the control mixes. This trend was attributed to the higher specific gravity and improved interlocking of steel slag aggregates. It was observed that mixes containing steel slag showed higher resistance to fatigue cracking; higher tensile strength ratio; and higher retained Marshall Stability and resilient modulus.

Fwa *et al.* (2013) evaluated steel slag as complete replacement of coarse granite aggregates in porous asphalt surface course. Porous asphalt mixes using steel slag aggregates with two gradations (*i.e.* the maximum aggregate size of 13.2 mm and 16 mm) and two types of binder (*i.e.* normal penetration graded and polymer modified binder) were fabricated and tested. From the results obtained from on-board sound intensity (OBSI) test, it was observed that the noise level of steel slag mixes was lower than the control mixes by approximately by 2 dBA. Steel slag aggregates improved frictional resistance compared to the granite aggregates by 12% when measured through British pendulum tester. Asphalt mixes with steel slag aggregates provided higher resistance to rutting and moisture compared to the mixes with natural granite aggregates, when evaluated through wheel tracking and water immersion test respectively.

Ziaee *et al.* (2015) evaluated the long term aging properties of asphalt mixtures containing EAF and BOF steel slags as a replacement of coarse natural aggregates. Five replacement percentages were considered: 0, 25, 50, 75 and 100% replacement of natural coarse aggregates by EAF and BOF steel slag. In order to evaluate long term performance of mixtures, samples were subjected to aging as per AASHTO PP2 standard. Results showed that mixes with EAF steel slag shower higher resistance to aging as compared to the mixes with natural aggregates and BOF steel slags. It was also observed that the peak tensile strength area up to peak tensile strength and total dissipated energy density of the mixes containing EAF steel slag were higher than the other mixtures, i.e. mixes with EAF steel slag had higher resistance to moisture damage as compared to the mixes with BOF steel slag. The results were attributed to the improved adhesion between binder and EAF steel slag. Mixes with EAF steel slag also showed higher resistance to fatigue as compared to mixes with BOF steel slags. Overall, the mixes with EAF steel slag showed enhanced performance as compared to the mixes containing BOF steel slag due to improved physical properties (higher specific gravity and lower flakiness and elongated index) of EAF steel slag.

Kavussi and Qazizadeh (2014) studied the fatigue characteristics of asphalt mixes containing EAF steel slag as replacement of coarse aggregates in both aged and unaged conditions using four-point bending beam fatigue test. Based on stiffness and dissipated energy criterion, different methods were adopted to analyse the fatigue test data. Furthermore, to simulate the long-term performance of EAF steel slag mixes, the samples were subjected to aging (5 days at 85 °C) according to the procedures stipulated in the AASHTO PP2 standard. EAF steel slag mixes were found to have higher fatigue life compared to the mixes with limestone aggergate. High angularity of EAF steel slag increased the internal friction angle of the mixture and thus improved the interlocking mechanism of mixes. Furthermore, no significant changes in fatigue life were observed for aged specimens. Mixes with a higher percentage of steel slags resulted in decreased susceptibility to aging.

Hainin *et al.* (2014) investigated EAF steel slag as a complete replacement of coarse natural aggregates in porous asphalt mixtures containing polymer modified binder (PG 76). Porous mixes were compacted by means of Marshall hammer by applying 50 blows on each side of the specimen. Mixes with steel slag showed higher resilient modulus, almost twice as compared to the control mixes when tested at 25 °C and 40 °C temperatures, since steel slag was found to be hard, dense, rough and possessed high abrasion resistance along with the presence of higher bitumen content. Steel slag mixes had high resistance to rutting as compared to the control mixes (Figure 2.16). This was through better binding properties, low flakiness index, high angularity, high angle of internal friction and rough surface texture of steel slag that resulted in high resistance to deformation and shear. Permeability of slag modified mixes were lower than control mixes because of higher asphalt content for EAF steel slag mixtures, which caused obstruction in the interconnected voids.

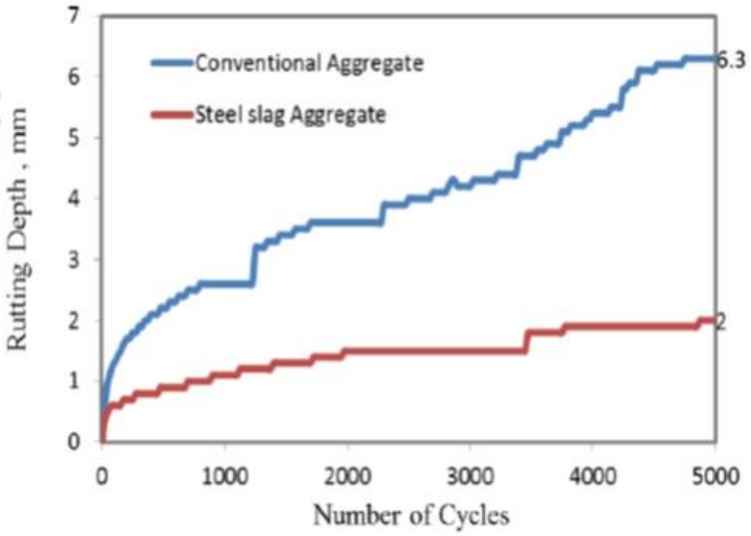


Figure 2.16: Rutting depth (mm) of porous mixes (Hainin *et al.*, 2014)

Bessa *et al.* (2014) studied polishing and degradation resistance of three types of natural aggregates (granite, gneiss and phonolite) and steel slag using the Aggregate Image

Measurement System (AIMS). In addition, Los Angeles abrasion equipment was used to measure the resistance to polishing and degradation of aggregates. In order to determine the aggregates properties before and after the abrasion process, digital image processing (DIP) technique was employed, using AIMS. The results suggested that steel slag aggregate was the most resistant to polishing. The steel slag aggregate offered lower loss of surface texture (15 to 45%) as compared to the natural ones.

Oluwasola *et al.* (2016) conducted a comparative study of dense graded and gap graded asphalt (SMA) mixes using EAF steel slag and copper mine tailings (CMT) as alternative paving materials. Feasibility of waste materials were evaluated through various performance tests by preparing different combination of bituminous mixes that included the following: Mix 1 comprised of 100% granite; Mix 2 comprised of 80% granite, 20% CMT; Mix 3 was with 80% EAF steel slag and 20% CMT; and Mix 4 comprised of 40% EAF steel slag, 40% granite, and 20% CMT. The tensile strength of the SMA mixes was slightly lower than the dense graded mixes due to relatively high air voids content of SMA mixes. Higher air void content resulted high deformation and lower tensile strength. Mixes with EAF steel slag and CMT showed higher tensile strength as compared to the control mixes (100% granite). Mixes incorporating EAF steel slag and CMT also showed high resistance to rutting compared to the control mix. Based on results obtained in the study, the EAF steel slag was recommended as a suitable candidate for replacement of natural aggregates.

Fakhri and Ahmadi (2017) studied the feasibility of using EAF steel slag and reclaimed asphalt pavement (RAP) in warm mix asphalt (WMA) mixes by evaluating moisture resistance, resilient modulus, dynamic creep and fatigue behavior. Six different types of WMA mixes comprising of two contents of coarse steel slag (0% and 40%) and three contents of fine RAP (0%, 20% and 40%) were fabricated for evaluation. WMA mixes with RAP improved the resilient modulus at all test temperatures, whereas mixes with steel slag improved the resilient modulus at intermediate and high temperatures only. Furthermore, it was observed that WMA mixes containing RAP and/or steel slag significantly improved the performance evaluated through dynamic creep and indirect tensile fatigue tests (ITFT). Overall, a combination of both EAF steel slag and RAP materials into the WMA demonstrated to be an economic and environment-friendly option compared to the control mixes.

Masoudi *et al.* (2017) studied the feasibility of use of EAF steel slag in warm mix asphalt when subjected to long term aging. Samples prepared by replacing the coarse limestone aggregates with EAF steel slag were compared with the control mix (prepared with limestone only) in terms of Marshall stability, indirect tensile strength, moisture susceptibility and resilient modulus. All the parameters were evaluated after subjecting the mixes to both short term and long-term aging. WMA mixes with EAF steel slag showed improved performance in terms of Marshall stability, resilient modulus and indirect tensile strength compared to the control mix under both short term and long term aged conditions. WMA mixes demonstrated lower resistance to moisture as compared to the hot mix asphalt (HMA). However, WMA mixes containing steel slag showed similar results to HMA mixes with limestone aggregates, which indicated that both aggregate type and production temperature played an important role in moisture damage resistance.

2.7 SUMMARY

This chapter presented a review of research studies performed on the use of open graded friction course (OGFC) mixes and steel slag aggregates in bituminous mixes.

The chapter began with an outline of historical development of OGFC and benefits associated with its use. Studies conducted globally on OGFC mixes were then reviewed and presented. Also research efforts on the feasibility of use of steel slag as a replacement of natural aggregates in various kinds of bituminous mixes such as dense graded bituminous mixes (DGBM), stone matrix asphalt (SMA) and OGFC mixes were reviewed and presented.

OGFC mixes showed to improve road safety as they help to minimise hydroplaning, reduce splash and spray, improve surface frictional resistance and enhance the pavement visibility. These mixes exhibit higher texture depth as compared to conventional dense graded mixes. Higher texture depth of OGFC mixes allows water to escape faster from the tyre-pavement interface and thus increase the skid resistance especially at higher speeds. Studies are conducted to check functional performance, i.e. permeability and clogging characteristics of OGFC mixes in relation to the effect of aggregate gradation and aggregate size. However studies lacked to study the role of aggregate type/source in clogging of OGFC mixes. Use of modified binders in OGFC mixes was recommended in majority of the studies to improve resistance to abrasion, moisture and permanent deformation. Fibres were also recommended in OGFC mixes to overcome the problem of binder draindown during production, storage and haulage of the mix.

Various studies analyzed the performance of steel slag in dense graded bituminous mixes as a replacement of coarse aggregates, fine aggregates and even as a filler, after crushing. Most of the studies reported that mixes with steel slag as coarse aggregate showed better performance as compared to the mixes with steel slag as fine aggregates. In several studies, both indirect tensile strength and resistance to moisture damage were higher when EAF slag was used as a replacement of coarse as well as fine aggregates. Mechanical performance of dense graded asphalt mixes containing steel slag in terms of Marshall stability, stiffness modulus, indirect tensile strength and resilient modulus was enhanced. In many studies, dense graded mixes containing steel slag even showed better performance compared to the mixes with conventional aggregates in terms of permanent deformation and fatigue. Dense graded mixes with significantly higher slag replacement percentages (up to 90% of the natural aggregate in asphalt mixture) showed high resistance to rutting and fatigue. Many authors defend high percentage replacement of coarse natural aggregate with steel slag. Based on some performance tests, up to 100% steel slag coarse aggregate was suitable, however optimum percentage replacement was low. Incorporation of steel slag has been studied in different kinds of asphalt mixtures including dense graded asphalt concrete, stone matrix asphalt and warm mix asphalt. However only few studies are found on use of steel slag in OGFC mixes (Fwa *et al.*, 2013; Hainin *et al.*, 2014; Li *et al.*, 2015; Pasetto and Baldo, 2006). Moreover, in these studies only a single replacement percentage of steel slag was employed.

In India, the wearing course of HMA pavements are mainly constructed using dense graded bituminous mixes. One main functional problem with conventional dense graded bituminous mixes when being used as wearing course is hydroplaning due to the standing water film on the road surface, and it constitutes a major road safety hazard. Hence, it is quite beneficial and useful from the point of road safety, especially for high speed roads in high rainfall and hilly regions, to construct wearing courses that have high permeability and allow quick drainage of surface water. OGFC is an alternative and potential candidate, due to its benefits in terms of improved skid resistance, higher visibility, lower noise production and enhanced safety. OGFCs have been in use in various parts of the United States and European countries, but in India its use is still not established. Unlike other developed countries, there are also no well-formulated guidelines for implementing the OGFC technology in India.

The demand for natural aggregates is increasing rapidly, and in response, it has become highly essential to explore waste materials or industrial by-products such as steel slag to achieve sustainability in road construction and relieve the pressure on natural aggregates. India being the third largest steel producer in the world, generates enormous quantities of steel slag, which need to be explored for possible bulk use. Steel slag has shown to improve the performance of dense graded asphalt mixes and thus can be a viable alternative to the natural aggregates in OGFC mixes also. A huge quantity of EAF steel slag is getting accumulated in landfills every year in India and has now become a serious environmental concern. Performance parameters of OGFC mixes need to be studied at different replacement percentages of natural aggregates by the EAF steel slag. Use of EAF steel slag, an industrial waste, will further help in reduction in the demand for natural aggregates in road construction; reduction in the environmental pollution due to large-scale mining and quarrying for natural aggregates; and reduction in environmental pollution due to the large scale dumping of steel slag in open landfills. OGFC mixes will help to improve the hydraulic and acoustic properties of asphalt pavements while contributing towards improved road safety aspects, especially for high speed corridors in heavy rainfall regions of India and similar parts of the world. Utilisation of EAF steel slag in OGFC mixes need to be explored for reduction in the consumption of natural aggregates without compromising the desired performance and benefits of OGFC mixes.

Chapter 3
MATERIALS AND EXPERIMENTAL PROGRAMME

3.1 INTRODUCTION

This chapter provides the description of raw materials used in the study, comprising the natural aggregates, bituminous binders, electric arc furnace (EAF) steel slag and cellulose fibres. This is followed by a discussion of the experimental programme formulated to accomplish the objectives framed for this research study. The chapter discusses in detail, the steps related to preparation of specimens and evaluation of various volumetric and design parameters of OGFC mixes with natural aggregates (control mixes) and with different replacement percentages (25, 50, 75 and 100%) of EAF steel slag as the coarse aggregate. The objectives of this study are grouped into five tasks. The task 1 includes the mix design characteristics of OGFC mixes with natural and EAF steel slag aggregates. Task 2 comprises of permeability and clogging characteristics of OGFC mixes with various percentage replacements of coarse natural aggregate with EAF steel slag. Task 3 includes frictional characteristics of OGFC mixes with and without EAF steel slags. Task 4 includes moisture susceptibility characteristics of OGFC mixes with various percentages of EAF steel slag. Task 5 includes performance characteristics (rutting, stiffness and fatigue) of OGFC mixes with various replacement percentages of EAF steel slag.

3.2 MATERIALS

3.2.1 Bitumen

Bitumen is one of the vital materials used in the production of bituminous mixes. As a glue or binding agent, bitumen has a key role in the performance of the pavement (Hunter, 2000). Majority of the highways constructed in India are flexible pavements, which utilise bituminous mixes mainly in binder course and wearing course. Bituminous layers are the key contributors to the structural capacity of the pavement. Growing axle loads, adverse climatic conditions, urge of low maintenance and longer service life, have raised the demand for use of modified bitumen in construction of bituminous mixes especially for national highways and expressways in India. Modified bitumen is the bituminous binder whose properties have been modified through incorporation of different additives/modifiers like polymers, crumb rubber, *etc*. Use of modifiers helps to enhance the performance of bituminous binders in terms of resistance against permanent deformation, moisture damage, thermal and fatigue cracking. More so, for OGFC mixes, the use of modified bitumen helps to: produce a thicker film over the aggregate particles; increase the resistance to abrasion/ravelling; and reduce the binder draindown (Fitts, 2002; Nielsen, 2007). In last two decades, use of modified bitumen, especially the use of crumb rubber modified bitumen (CRMB) and polymer modified bitumen (PMB), has increased significantly on Indian national highways and expressways. Polymer modified bitumen grade 40 (PMB-40) and crumb rubber modified bitumen grade 60 (CRMB-60) were selected for the present study. Both PMB-40 and CRMB-60 binders were obtained from Tiki Tar Industries India Limited in the state of Gujarat and were manufactured through wet process by modifying the base bitumen (viscosity grade 30 (VG30)) with ethylene terpolymer (ETP) and crumb rubber particles respectively. Physical properties of the modified bituminous binders were tested as per IS 15462 (2004) specifications and are presented in Table 3.1. Mixing and compaction temperatures used in this study were 170 °C and 160 °C for the PMB-40 binder and 175 °C and 165 °C for the CRMB-60 binder. These temperatures were used as per the recommendations of the manufacturer.

3.2.2 Aggregates

Aggregate is a key ingredient of bituminous mixes used mainly in construction of binder and wearing course of flexible pavements in India. The mineral aggregate, including coarse and fine particles in bituminous mixes, encompass approximately 90% of total volume. High air void content in OGFC mixes are achieved by adopting a uniform gradation with low fine content. In OGFC mixes, a coarse granular skeleton with proper stone-on-stone contact is necessary for the adequate distribution of traffic loads. Thus, OGFC mixes demand good quality aggregates that are angular and possess high resistance to abrasion, crushing, and polishing in order to achieve the desired performance and service life (Kandhal, 2002).

3.2.2.1 Natural Aggregates

For this study, natural aggregates were initially collected from different stone crushers located in the Indian state of Assam. The various physical properties such as Los Angeles abrasion, aggregate impact value, flakiness and elongation indices, percentage fractured faces, angularity number, water absorption, and hardness of these aggregates were then determined. Aggregate source located in Shillong, Meghalaya, about 100 km from IIT Guwahati, was finally chosen as a source of natural aggregates. The photographic view of the stone crusher selected for the study at Shillong is shown in Figure 3.1. The results of physical tests on this selected source of natural aggregate are presented in Table 3.2.

Table 3.1: Physical properties of PMB 40 and CRMB 60 binders

Property	**Test method**	**Requirements as per IS 15462**		**Results**	
		PMB 40	**CRMB60**	**PMB 40**	**CRMB 60**
Penetration at 25 °C, 0.1 mm, 100g, 5 s	IS 1203	30-50	<50	42	30.88
Softening point (R&B), °C	IS 1205	Min. 60	Min. 60	70.95	70.65
Flash point by COC, °C	IS 1209	Min. 220	Min. 220	320	340
Elastic recovery in ductilometer at 15 °C, %	IS15462 Annex A	Min. 70	Min.50	76.5	72.5
Separation difference in softening point (R&B), °C	IS 15462 Annex B	Max. 3	Max. 4	1.9	2.5
Viscosity at 150 °C, Poise	IS 1206 Part1	3-9	3-9	7.78	8.12
Thin Film Oven Test (TFOT) residue					
Loss in weight, %	IS 9382	Max. 1	Max. 1	0.2	0.4
Increase in softening point, °C	IS 1205	Max. 5	Max. 5	2.8	3.65
Reduction in penetration of residue at 25 °C, %	IS 1203	Max. 35	Max. 40	34	31.32
Elastic recovery in ductilometer at 25 °C, %	IS 15462 Annex A	Min. 50	Min. 35	74.5	68.5

Figure 3.1: Stone crusher (Shillong, Meghalaya)

Table 3.2: Physical properties of natural aggregates

Property	**Test method**	**General requirement**	**Result**
Specific gravity	ASTM C127	NA	2.96
Angularity number (%)	IS 2386 P1	NA	9
Combined elongation and flakiness (%)	IS 2386 P1	Max 20%$^{\Psi}$	18.5
Abrasion Value (%)	ASTM C131	Max 30%*	19.5
Water absorption (%)	ASTM C127	Max 2%$^{\Psi}$	0.45
Aggregate impact value (%)	IS 2386 P4	NA	15.8
Aggregate crushing value (%)	IS 2386 P4	NA	19.8
Percent fracture face			
(i) One face	ASTM D5821	95%*	98%
(ii) Two faces		90%*	95.7%
VCA$_{drc}$	ASTM C29	NA	44.23

Notes: NA: Not applicable; * Requirement as per ASTM D7064 (2013); $^{\Psi}$Requirement as per NAPA IS 115 (Kandhal, 2002); VCA$_{drc}$: voids in coarse aggregates (dry rodded condition)

3.2.2.2 EAF Steel Slag Aggregates

Steel slag is a type of ferrous slag and is a by-product of steel making industries, generated during the conversion of iron to steel. Based on the steel manufacturing process, steel slag is categorised mainly in two types: electric arc furnace (EAF) and basic oxygen furnace (BOF) steel slag. The EAF and BOF steel making processes occupy a share of about 56.8% and 43.2%, respectively, in India (World Steel, 2018).

The usage of steel slag, mainly lying unutilised as an industrial waste, as an aggregate can be a promising solution to overcome the scarcity of natural aggregates. Its usage will also help to reduce the high disposal cost and landfill space requirement for steel slag. For this study, EAF steel slag was selected and collected from the Jindal Steel and Power Plant at Angul in the state of Odisha, India. This plant makes use of Electric Arc Furnace process to produce steel and has an annual capacity of 1.67 million ton.

Figure 3.2 shows the photographs of the steel slag crusher plant and the steel slag dumped in open landfills. EAF steel slag collected from the plant was examined for the physical characteristics and the results are presented in Table 3.3. OGFC mixes mainly consist (> 90%) of coarse aggregates (sizes greater than 2.36 mm) with a very low filler content (1-3%). In order to evaluate the feasibility of EAF steel slag as a coarse aggregate in OGFC mixes, mixes were prepared, designed and evaluated at five replacement percentages (*i.e.* 0%, 25%, 50%, 75% and 100%) of natural coarse aggregates by EAF steel slag. OGFC mixes with 0 % EAF steel slag (or 100% natural aggregates) as coarse aggregate are also referred as control mixes in the study.

(a) (b)

Figure 3.2: Photographs (a) steel slag crusher (b) slag dump area

Table 3.3: Physical properties of EAF steel slag aggregates

Property	**Test method**	**General Requirement**	**Result**
Specific gravity	ASTM-C127	NA	3.26
Angularity number (%)	IS 2386 P1	NA	10.9
Combined elongation and flakiness (%)	IS 2386 P1	Max 20%$^{\psi}$	9.3
Abrasion value (%)	ASTM-C131	Max 30%*	13.3
Water absorption (%)	ASTM-C127	Max 2%$^{\psi}$	0.51
Aggregate impact value (%)	IS 2386 P1	NA	14.6
Aggregate crushing value (%)	IS 2386 P1	NA	14.7
Percent fractured face			
(i) One face	ASTM D5821	95%*	100%
(ii) Two faces		90%*	98%
VCA_{drc}	ASTM C29	NA	45.07

Notes: NA: Not applicable; * Requirement as per ASTM D7064 (2013); $^{\psi}$ Requirement as per NAPA IS 115 (Kandhal, 2002); VCA_{drc} : voids in coarse aggregates (dry rodded condition)

Volumetric expansion of EAF steel slag aggregate

The feasibility and performance of steel slag as an aggregate in a pavement will depend on its physical and mechanical properties as well as on its volumetric expansion potential (Juckes, 2003; Wang and Yan, 2010). Calcium oxide (CaO), iron oxide (FeO), alumina (Al_2O_3), silica (SiO_2) and magnesium oxide (MgO) are the major chemical constituents in EAF steel slag. Due to the presence of unstable phases in its mineralogy, steel slag may show volumetric instability, caused mainly by the presence of free CaO. In the presence of water, free CaO hydrates and forms portlandite (naturally occurring form of calcium hydroxide $Ca(OH)_2$). Portlandite has a lower density than CaO and hence, hydration of free CaO results in volume increase. High levels of free lime or magnesia may have adverse effect on the performance of the materials made up of slag (Shen *et al.*, 2009).

In order to reduce the expansibility of steel slag aggregates, three aging methods are usually employed before putting them to use in pavement construction: air aging; hot water aging; and steam aging. In the air aging method, steel slag is left out in the air in open for about a month to allow weathering through air. In the hot water aging, steel slag is immersed in hot water at about 80 °C temperature for 1 to 3 days. In the steam aging method, steel slag is exposed to steam at 100 °C for over 3 days.

The EAF steel slag used in this study had undergone air aging for about one month in the manufacturer’s landfill facility, as per the information gathered from the plant engineers. In addition, prior to its use in OGFC mixes, EAF steel slag was tested for volumetric stability as per the guidelines stipulated in ASTM D4792 (2013). Figure 3.3 illustrates the results of volumetric expansion of EAF steel slag aggregate with time. Wu *et al.* (2007) recommended a maximum expansion of 1% after 7 days for steel slag. It was found that the expansion is below 0.1% even after 7 days, and thus makes the collected EAF steel slag a suitable candidate for further use and evaluation as a replacement of natural aggregates.

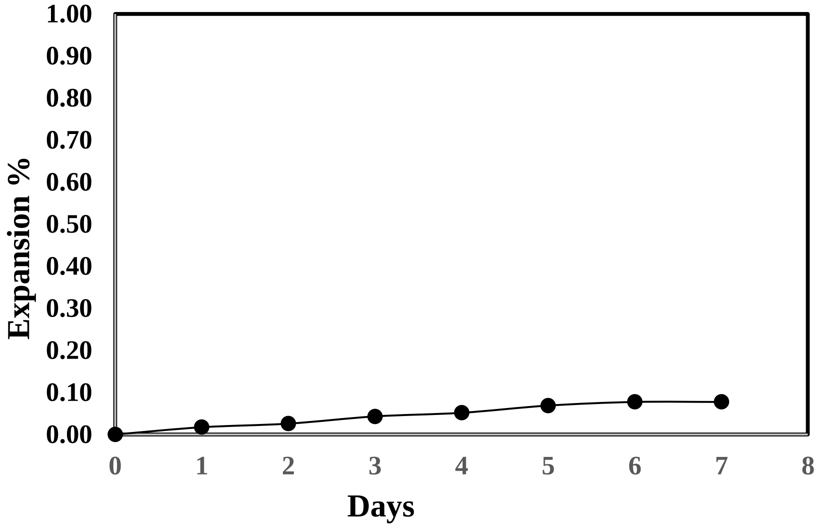


Figure 3.3: Expansion rate of electric arc furnace (EAF) slag aggregate

Toxicity characteristics leaching procedure test on EAF steel slag aggregate

Toxicity and leaching characteristics of EAF steel slag are of prime concern before its reuse for civil engineering purposes. The leaching potential of EAF steel slag was examined as per the toxicity characteristics leaching procedure (TCLP) test in accordance with US-EPA Method-1311 (USEPA, 2008). The test is important to ascertain the suitability of industrial by-product materials for potential use as aggregates (Onuaguluchi and Eren, 2012). This test method evaluates the mobility of both organic and inorganic compounds present in a material. The test was carried out on EAF steel slag aggregates alone as well as on EAF steel slag aggregates coated with bituminous binder. The aggregates were passed through a 200 micron IS sieve, and while in case when they were coated by bitumen as a part of the bituminous mix, they were sieved through a 1.18 mm sieve, in order to remove large particles. The residue was extracted using a solvent having a pH of 4.93 prepared by adding 64.3 mL 1 N NaOH and glacial acetic acid (CH_3COOH), and diluted to a final volume of 1 L by adding distilled water. 5 g of dried EAF steel slag sample with and without bitumen coating was taken in a conical flask and then 100 mL of prepared solution was added to obtain a proportion of 20:1 (liquid/solid). The solution was then set onto a horizontal shaker, which was rotated at a speed of 30±2 rpm for 18 h. Thereafter, the solution was centrifuged at a speed of 10,000 rpm for 5 min. The solution was filtered using Whatman 42 number filter paper and stored at 4 °C for heavy metals concentration evaluation through Atomic Absorption Spectroscopy (AAS).

Atomic absorption spectrometry (AAS) is a popular analytical technique used for measurement of concentrations of elements. This method is very sensitive to measures up to parts of a billion. Different elements absorb wavelengths that are characteristic to that element. During this test procedure, the test sample is first converted from ground state to free atom in the vapour state and then a beam of electromagnetic radiation is passed through the sample. This electromagnetic beam is produced by a lamp, which produces a mix of wavelengths that can be absorbed by any atom in the sample. When the beam is passed through the vaporised sample, atoms in the sample absorb some of the radiation. The amount of absorption is proportional to the concentration of the element. By this principle, the concentration of a particular metal present in EAF steel slag aggregates samples was measured. Table 3.4 shows the results of the leaching test conducted on the EAF steel slag alone and EAF steel slag coated with the bituminous binder.

Table 3.4: Results of TCLP analysis

Element	**Permissible limit (mg/L)**	**TCLP leaching concentration (mg/L)**	
		EAF-Powder	**EAF-Bitumen Mix**
Magnesium (Mg)	100	13.5	1.7
Aluminium (Al)	0.2	0.015	0
Silica (Si)		0.89	0.23
Calcium (Ca)	200	93.2	13.4
Vanadium (V)	0.25	0.093	0
Chromium - total (Cr)	0.05	0.009	0
Manganese (Mn)	0.3	0.207	0.157
Iron (Fe)	0.3	0	0
Cobalt (Co)	0.05	0	0
Nickel (Ni)	0.02	0.007	0
Copper (Cu)	1.5	0.082	0
Zinc (Zn)	15	0.168	0.034
Selenium (Se)	0.01	0	0
Cadmium (Cd)	0.003	0.001	0
Mercury (Hg)	0.001	0	0
Lead (Pb)	0.01	0.008	0.001

It was observed from the concentrations of heavy metals tested, that the leaching concentration is well below the permissible limits given by IS: 10500 (2012) aggregates had no significant effect on leaching characteristics of heavy metals. This shows that the usage of EAF steel slag as a replacement of natural aggregate with bituminous binders would generate no immediate or long-term hazard to the environment in terms of leaching and this allows a positive judgment for their use as an aggregate in the present study. Similar findings were also made in other studies conducted by Oluwasola *et al.* (2016), Nikolic *et al.* (2016) and Chiu *et al.* (2009).

Chemical Composition of Aggregates

Chemical composition of aggregates is helpful in understanding the behaviour of aggregates in bituminous mixes. X-ray fluorescence (XRF) is an analytical technique used for quantitative and qualitative determination of the oxides present in an aggregate material. X-ray fluorescence is the phenomenon that occurs when a primary X-ray excites a material causing emissions of secondary X-ray, called fluorescence. The emission of secondary X-ray is a characteristic of chemical compound present in material and is evaluated by the detector. XRF analysis is used extensively for detection of oxides and for research in biomaterial science, archaeology and geochemistry (Kennedy, 1990). In XRF analysis, an aggregate is exposed to primary (short wavelength) X-rays that cause ionisation of component atoms. As the electrons are removed due to ionisation, the atom becomes unstable and the electrons from higher orbital fall to the lower orbital. This movement of electrons results in release of energy that is equivalent to the energy difference of the two orbitals. The energy emitted or radiated has the characteristics of the component atoms (Jenkins and Snyder, 1996). Both natural aggregates and EAF steel slag have different origin and XRF may be a useful tool to quantitatively determine the chemical composition of the two types of aggregates. XRF analysis was carried out on natural aggregates as well as EAF steel slag aggregates and the results are presented in Table 3.5.

A higher iron content observed for EAF steel slag is the reason for its higher specific gravity (3.26) compared to natural aggregates (2.96). XRF results also show a higher calcium and low silica content for EAF steel slag compared to the natural aggregates. The natural aggregate on the basis its chemical composition is identified as a metamorphic form of gabbro.

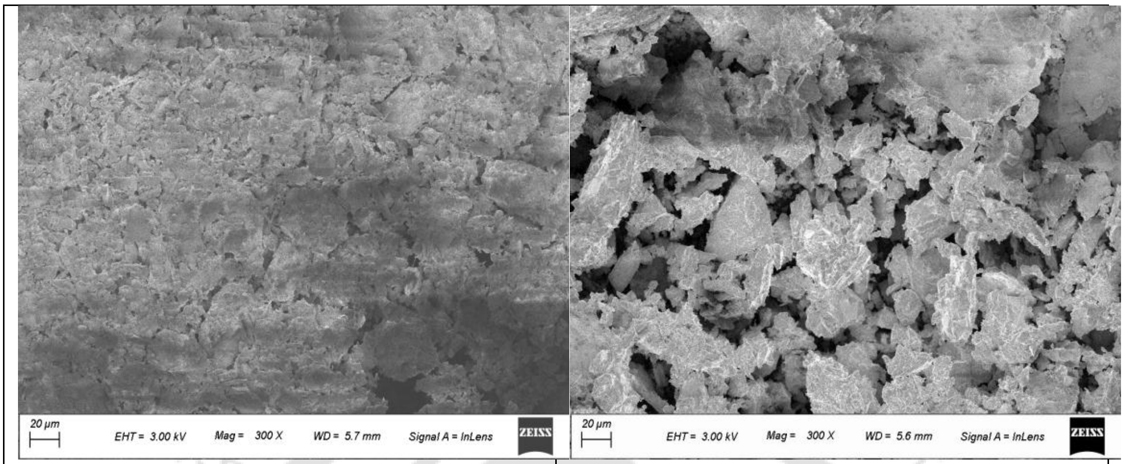
Table 3.5: Chemical composition of aggregates by XRF

Type of oxide	**Oxide content, percent**	
	EAF steel slag	**Natural aggregate**
Calcium - CaO	30.70	8.10
Iron - FeO	31.05	11.63
Silica - SiO_2	12.77	50.01
Aluminium - Al_2O_3	12	16.03
Magnesium - MgO	7.72	2.35
Manganese - MnO	0.48	0.16
Titanium - TiO_2	-	1.72
Phosphorous - P_2O_5	0.42	0.76
Potassium - K_2O	0.08	4.25
Sodium - Na_2O	0.09	2.69

Morphological Characteristics of Aggregates

Field emision scanning electron microscope (FESEM) was used to observe the shape and surface texture of both EAF steel slag and natural aggregates. The FESEM consists of an electron optical column that generates and focuses an electron beam over the aggregate surface. The beam strikes on the specimen and produces signals that can be detected as backscattered electrons (BE or BSE), secondary electrons (SE) and X-rays. These electrons are measured by electron detectors and converted into images. The instrument used in this study is Gemini 300 operated at 3 kV voltage. The captured

SEM micrographs and as well as the naked-eye view of EAF steel slag and natural aggregates are shown in Figures 3.4 and 3.5, respectively.



(a) (b)

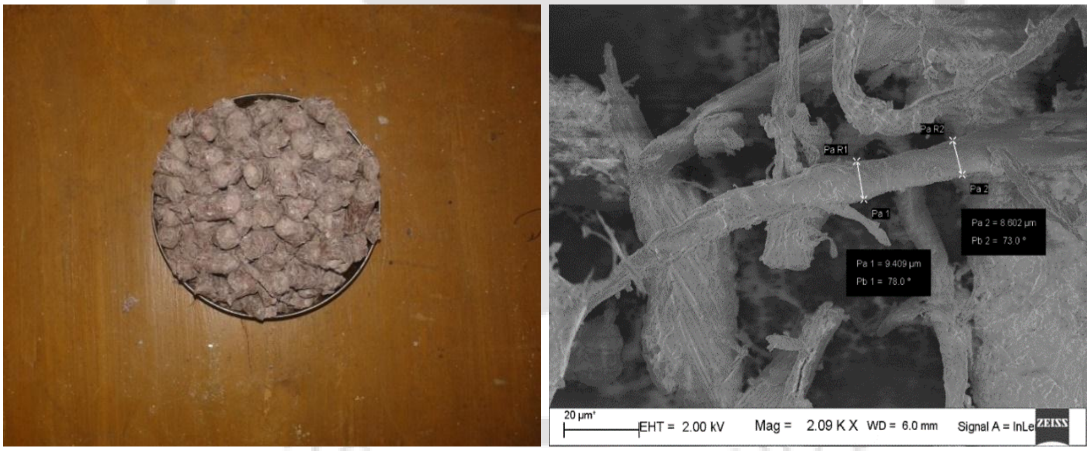
Figure 3.4: Scanning electron micrographs (SEM) of (a) natural stone aggregates and (b) EAF steel slag

Figure 3.5: Naked-eye view of natural stone (left) and EAF steel slag (right)

The SEM and naked-eye images of EAF steel slag and natural aggregates show higher angularity and rough surface texture of EAF steel slag aggregates. Moreover presence of many surface pores indicates a porous morphology of EAF steel slag as compared to the natural aggregate, which will also affect the absorption and adhesion ability of EAF steel slag with asphalt binder.

3.2.3 Stabilising Additive

OGFC mixes have a relatively coarser and uniform gradation than the conventional dense graded mixes. Coarser gradation along with low filler content may lead to draining of the binder in the OGFC mixes under gravity. To prevent the binder draindown as well as to form a thicker film over the aggregates, stabilising additives such as fibres, are usually added in OGFC mixes. Addition of fibres helps to minimise binder draindown by absorbing and stiffening the bituminous binder. Cellulose TOPCEL fibre (a type of organic fibre) obtained from pulp of natural wood was used in this study and was supplied by Organo Chemical Industries, Mumbai, India. The naked-eye view and FESEM images of fibres are presented in Figure 3.6. The cellulose fibre was added to all mix types in this study at a dosage rate of 0.3 percent by weight of the mix, as per the manufacturer recommendation for modified bituminous binders.



(a) (b)

Figure 3.6: (a) Naked eye view of cellulose fibre; and (b) FESEM micrograph of cellulose fibre

3.3 EXPERIMENTAL PLAN

The objectives of this study were divided into five independent tasks for proper execution. Each task was carried out separately to fulfil the specific objectives framed for the study. The five tasks formulated are discussed in the successive sections.

3.3.1 Task 1: Design of Open Graded Friction Course (OGFC) Mixes with and without EAF Steel Slag

Task 1 of this research was aimed to evaluate the effect of replacement of natural aggregate with different percentages of EAF steel slag, on the mix design characteristics of OGFC mixes prepared with both PMB and CRMB binders. Five replacement percentages are considered: 0, 25, 50, 75 and 100% replacement (by weight) of natural coarse aggregates by EAF steel slag, along with two modified binders (PMB and CRMB). Ten combinations of OGFC mixes were tested for the following OGFC design parameters: bulk density, air voids, stone-on-stone contact, unaged abrasion loss, aged abrasion loss, and binder draindown. Based on the above design parameters optimum binder content (OBC) was determined for OGFC mixes. The OGFC mix design was carried out as per the guidelines of ASTM D7064 (2013). Mix design helps to determine the OBC for OGFC mixes to ensure an adequate performance in terms of: proper stone-to-stone contact for gradation selection, requisite air void content, good abrasion resistance under unaged and aged conditions, and low a binder draindown. The experimental flow chart to achieve this task is presented in Figure 3.7.

3.3.1.1 Aggregate gradation for preparation of OGFC mixes

An aggregate gradation for use in OGFC mixes is to be selected based on the results of stone-on-stone contact criterion. This criterion is quite important in order to ensure adequate stability of the OGFC mixes. The criterion is verified by comparing the air voids in the coarse aggregate skeleton in the OGFC mix after compaction, with the voids between the same coarse aggregates on compacting coarse aggregates blend alone through dry rodded technique as per ASTM C29 (2007) guidelines. In order to ensure stone-on-stone contact in an OGFC mix, voids in the coarse aggregate fraction of the compacted OGFC mix (VCA_{mix}) should be equal to or less than the voids in the coarse aggregate alone in the dry-rodded condition (VCA_{drc}).

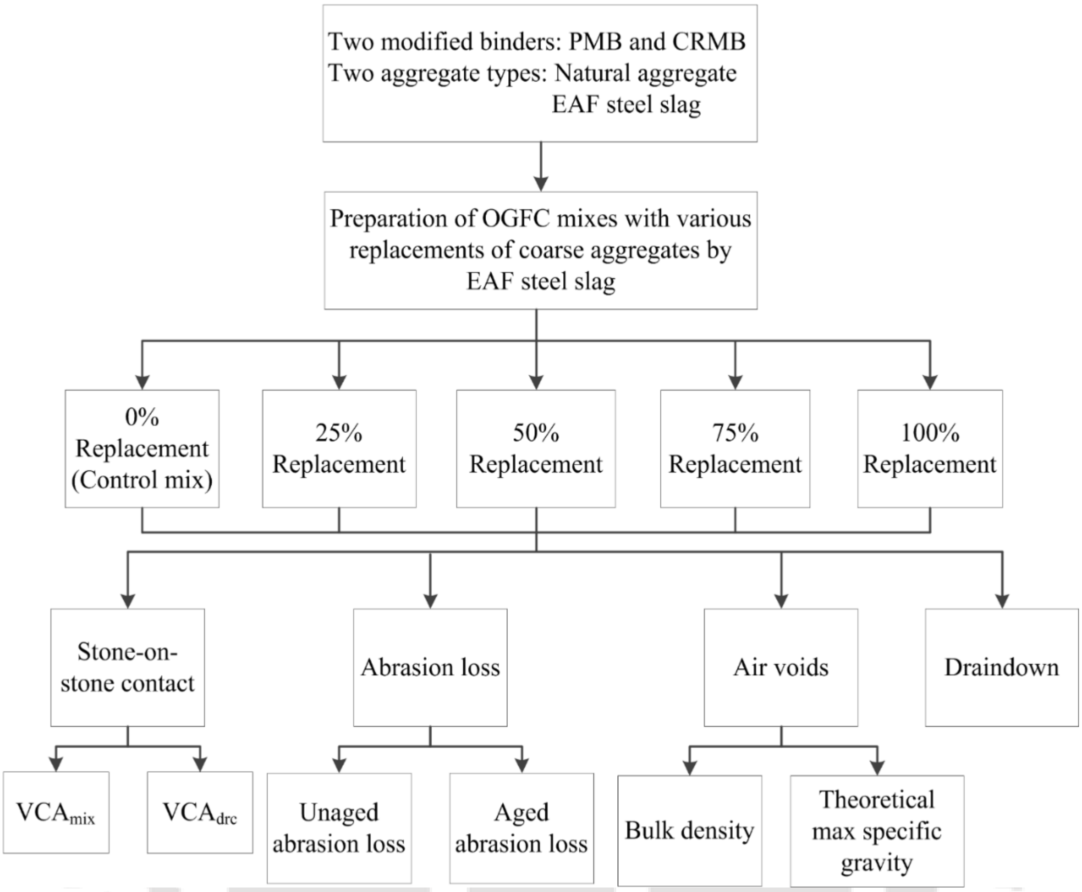


Figure 3.7: Experimental Plan for Task 1

In this study, aggregate gradation selected and the specified gradation limits conforming to ASTM D7064 specifications are shown in Figure 3.8. The selected gradation was found to meet the criterion, and the results are discussed in detail in Section 4.2.3 of Chapter 4. VCA_{mix} and VCA_{drc} are discussed further in the following sections.

3.3.1.2 Voids in coarse aggregate in dry rodded condition (VCA_{drc})

VCA_{drc} is the voids in the coarse aggregates after compacting the coarse aggregates alone through dry-rodded technique as specified in ASTM C29 (2007). In this test procedure, a cylindrical test measure is filled one-third with the coarse aggregate fraction (defined as the fraction retained on 4.75 mm sieve for this test method) and 25 evenly distributed strokes of a tamping rod are imparted to the aggregate sample.

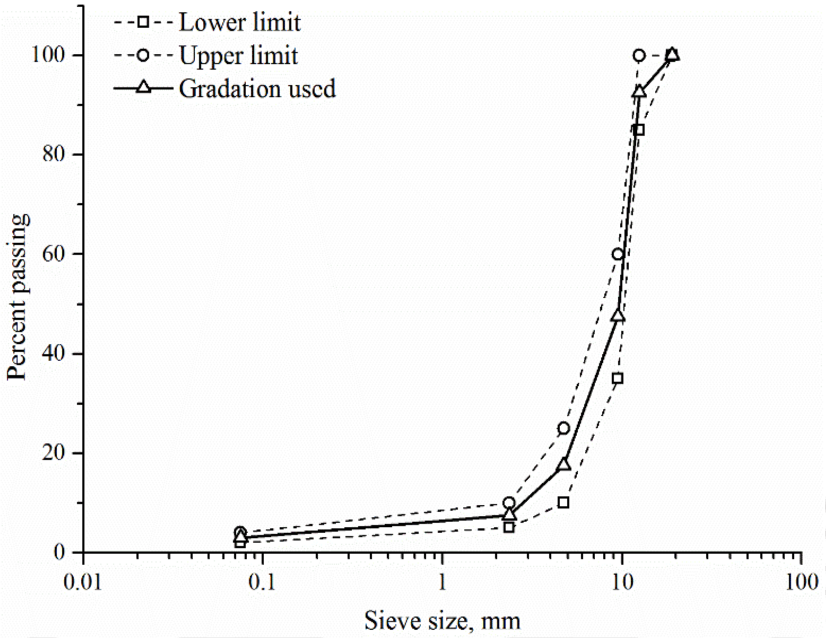


Figure 3.8: Aggregate gradation for OGFC

The measure is then filled up two-thirds of the volume and the aggregate is rodded again. Lastly the measure is filled completely with aggregate and is rodded again using the tamping rod for same number of blows. The excess aggregate is levelled off. The weight of the measure with the aggregates in dry-rodded condition is recorded. The dry-rodded density of the aggregates is determined by using the weight of the aggregates and the volume of the measure. After determining the dry-rodded density, the VCA_{drc} is calculated using Equation 3.1:

$$VCA_{drc} = \frac{G_{CA}\gamma_w - \gamma_s}{G_{CA}\gamma_w} \times 100 \tag{3.1}$$

where, G_{CA} = bulk specific gravity of the coarse aggregate, γ_s = bulk density of the coarse aggregate fraction in the dry-rodded condition and γ_w = density of water.

3.3.1.3 Voids in coarse aggregate of the compacted bituminous mix (VCA_{mix})

VCA_{mix} is the voids within the coarse aggregate structure in the OGFC mix achieved after compaction. It includes the volume of air voids, filler, fine aggregate, fibre and bitumen. For VCA_{mix} determination, the OGFC samples were compacted at 6.0 percent trial binder content and then allowed to cool. On reaching the room temperature they are removed from the mould and tested to determine their bulk specific gravity using geometrical measurements. The VCA_{mix} is then calculated using Equation 3.2:

$$VCA_{mix} = 100 - \frac{G_{mb}}{G_{CA}} \times P_{CA} \tag{3.2}$$

where, P_{CA}= percent coarse aggregate in the total mixture, G_{mb} = bulk specific gravity of the compacted mixture and G_{CA} = bulk specific gravity of the coarse aggregate fraction (fraction retained on 4.75 mm sieve for this test method).

3.3.1.4 Selection of Optimum Binder Content (OBC)

Preparation of OGFC specimens

Mix design was carried out to determine the optimum binder content (OBC) of OGFC mixes with all replacement percentages (0, 25, 50, 75 and 100%) of EAF steel slag with both binder types (PMB and CRMB). For preparing the OGFC mixes, Marshall method of compaction was adopted by giving 50 blows on both sides of the OGFC sample. For compaction of OGFC mixes in the laboratory, ASTM D7064 recommends the use of 50 number of gyrations of Superpave gyratory compactor, or a compaction method providing equivalent compacted density. Several studies have used 50 Marshall impact compactor blows for fabrication of compacted OGFC mixes. Further, it has been reported that a good agreement exists between compaction achieved through 50 gyrations of gyratory compactor and 50 blows of the Marshall compactor (Alvarez *et* *al.*, 2006; Watson *et al.*, 2003; Mallick *et al.*, 2000). In this study, compaction of OGFC mixes was performed through 50 blows of the Marshall hammer. The OGFC samples were prepared using Marshall moulds of 4 inch diameter and 2.5 inch height. Aggregates were batched according to the selected gradation. Table 3.6 presents the estimates for the aggregate type and quantity used for fabrication of OGFC specimens. The aggregate batches were kept in an oven at a temperature 10-15 °C higher than the mixing temperature for a minimum of 4 h for drying and heating. The modified binders were also heated in an oven to attain the desired mixing temperature. On reaching the desired temperature the batched heated aggregate and the specified content/amount of binder were mixed in a temperature controlled mixer at the mixing temperature. After mixing, the loose mixes were transferred into a rectangular tray and placed inside a forced air draft oven at the compaction temperature for 2 h ± 5 min to allow short term conditioning. The conditioned mass was then compacted in a Marshall mould by application of 50 blows on both sides using an automatic Marshall impact compactor having a weight of 4.54 kg and free fall of 457.2 mm. OGFC mix specimens were prepared at three trial binder contents: 5.5, 6.0 and 6.5% (by weight of the total mixture) for the ten different mix types/combinations (five EAF slag replacement percentages and two modified bituminous binder types). Cellulose fibre at a dosage of 0.3% by weight of the mix was used for each of the combination of mixes.

Twelve samples were prepared at each bitumen content an OGFC mix type. Out of the twelve samples, six were compacted for abrasion loss (three for unaged and three for aged) and the remaining six were kept uncompacted (three used to determine draindown and three for theoretical maximum density). The compacted samples were also used to examine the volumetric properties in addition to the abrasion characteristics.

Table 3.6: Estimate of aggregate quantity required for fabrication of OGFC mixes

IS sieve passing (mm)	**IS sieve retained (mm)**	**Percent (%) reqd.**	**Weight taken for 1 Marshall specimen in 'g'**									
			Mix 1		**Mix 2**		**Mix 3**		**Mix 4**		**Mix 5**	
			NA (100% of CA)	**EAF slag (0% of CA)**	**NA (75% of CA)**	**EAF slag (25% of CA)**	**NA (50% of CA)**	**EAF slag (50% of CA)**	**NA (25% of CA)**	**EAF slag (75% of CA)**	**NA (0% of CA)**	**EAF slag (100% of CA)**
19	12.5	7.5	75	0	56.3	18.8	37.5	37.5	18.8	56.3	0	75.0
12.5	9.5	45	450	0	337.5	112.5	225.0	225.0	112.5	337.5	0	450.0
9.5	4.75	30	300	0	225.0	75.0	150.0	150.0	75.0	225.0	0	300.0
4.75	2.36	10	100	0	75.0	25.0	50.0	50.0	25.0	75.0	0	100.0
2.36	0.075	4.5	45	0	45.0	0	45.0	0	45.0	0	45.0	0
0.075	Pan	3	30	0	30.0	0	30.0	0	30.0	0	30.0	0

Selection of OBC for OGFC mixes is based on the requirements of the following mix design parameters: air voids content, abrasion loss and binder draindown. Each of these design parameter is discussed in the successive sections.

Air voids

Air voids content (V_a) is the total volume of the small pockets of air in a compacted bituminous mix, expressed as a percent of the total volume of the compacted mix. It is calculated based on the bulk specific gravity (G_{mb}) and theoretical maximum specific gravity (G_{mm}) using Equation 3.3:

$$V_a = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100 \tag{3.3}$$

where, G_{mb} = bulk specific gravity of the compacted specimen; G_{mm} = theoretical maximum specific gravity of the loose mixes. Bulk specific gravity of the compacted sample was determined using the geometric measures of height and diameter and mass of the specimen in air (ASTM D3203, 2000). For OGFC mixes, it is difficult to correctly measure the weight of mix in saturated surface dry (SSD) condition due to its high air void content. Water can easily drain off from the samples and the SSD condition will not be maintained (King *et al.*, 2009; Buchanan and White, 2005). Most OGFC the researchers have therefore employed as well as recommended the use of geometric measurement for determining the bulk specific gravity of OGFC specimens. The theoretical maximum specific gravity (G_{mm}) of the loose mix was determined in accordance with ASTM D6857 (2018) by using CoreLok TM equipment (manufactured by InstroTek Inc.). As per ASTM D7064, the minimum requirement of air void content is 18% for an OGFC mix.

Cantabro abrasion loss

Cantabro abrasion test was conducted to estimate the abrasion and ravelling resistance of the OGFC mix under the action of traffic. In this test procedure, a compacted OGFC sample is rotated in a Los Angeles abrasion machine drum without the abrasive charge at 30 to 33 revolutions per minute for 300 revolutions at a test temperature of 25 °C. The initial weight of the specimen, before commencement of the test and final weight after completion of the test is recorded, and the weight loss is found as a percentage of the original weight and reported as percentage abrasion loss. A comparison of the OGFC samples before and after Cantabro testing is shown in Figure 3.9. The test was performed on both unaged and aged OGFC specimens. The durability of the OGFC mixes against long-term aging was evaluated in terms of the aged abrasion loss. Aging was done by keeping compacted OGFC specimens in an oven at 60^{o}C for a period of 168 h (7 days). After aging, the samples were cooled down to the room temperature for a minimum of 4 h before being subjected to the usual Cantabro testing. The percentage abrasion loss in both unaged and aged condition was found using Equation 3.4:

$$P = \frac{P_1 - P_2}{P_1} \times 100 \tag{3.4}$$

where, P = abrasion loss (%); P_1 = weight of the compacted sample before test (g); P_2 = weight of the sample after completion of test (g). The unaged and aged abrasion loss of OGFC samples should not exceed 20% and 30% respectively as per ASTM D7064 specifications.

Figure 3.9: Comparison of the specimen before (left) and after (right) Cantabro testing

Binder draindown

The binder draindown test determines the separation potential of the bituminous binder from the coarse aggregate structure during production and while storage in silos as well as during mix transportation in trucks to the construction site. Due to the low fine content of OGFC mixes, the binder tends to draindown under gravity during mixing, storage, and hauling leading to inadequate binder film thickness over the coarse aggregate, consequently impairing durability of the mix. Binder draindown was measured as per ASTM D6390 (2011) guidelines to ensure that it is below the specified limit of 0.3%. This test is performed on loose OGFC mixes at temperatures 15 °C higher than the production temperatures. Immediately after mixing, a loose mix is transferred into a wire basket with 6.3 mm sieve size. The wire basket with the loose mix is placed on a plate of known mass and the entire assembly is placed in a forced draft oven set at a temperature 15 ^{o}C higher than the mixing temperature for 1 h. After the test period, the assembly is removed from the oven and allowed to cool down. The weight of the plate with the drained material is measured and the weight of drained mastic to the original sample weight in percentage is reported as the percent draindown. The draindown is calculated using Equation 3.5:

$$\text{Draindown} = \frac{D - C}{B - A} \times 100 \tag{3.5}$$

where, *D* is the mass of the plate and drained material after 1 h; *C* is the mass of plate before placing the assembly in oven; *B* is the mass of the sample and wire basket before placing the assembly in the oven and *A* is the mass of the empty wire basket.

3.3.2 Task 2: Permeability Characteristics of OGFC Mixes with and without EAF Steel Slag

Task 2 was aimed to determine the permeability characteristics of OGFC mixes fabricated at different contents of EAF steel slag (0, 25, 50, 75 and 100%) with both CRMB and PMB binders. The porous structure of OGFC mixes with high air void content helps in quick and effective removal of surface water laterally through the mixture, to the edges of the pavement. A laboratory permeability value of at least 100 m/day (300 ft/day) is recommended for OGFC mixes in the ASTM D7064 guidelines. As pavement life progresses, entry of dirt and debris may clog the OGFC layer and eventually reduce its permeability. The deposition of dirt and debris may be from wind, stormwater, and vehicles. When the pores get partially clogged, it may affect the drainage capability of OGFC mixes. De-clogging operations constitute an essential component of general maintenance activities for OGFCs. Cleaning/de-clogging of OGFC can be performed with a fire hose, high pressure cleaner, or a specially manufactured equipment vehicle (Kandhal, 2002; Kumar *et al.*, 2018). Under this task, in addition to permeability characteristics, the clogging and de-clogging characteristics of OGFC mixes with EAF steel slag were also investigated. The experimental plan followed to achieve this task is shown in Figure 3.10.

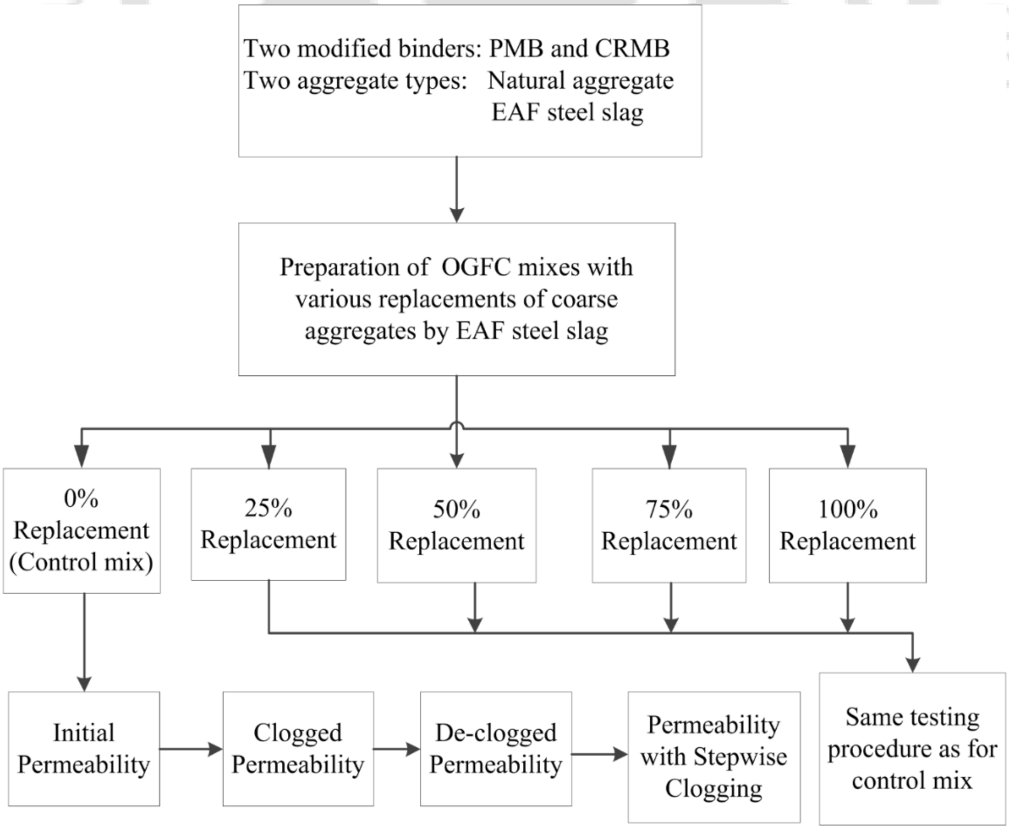


Figure 3.10: Experimental Plan for Task 2

All combinations of OGFC mixes under different clogging conditions were tested for permeability using a falling head permeability apparatus. The details of clogging and de-clogging procedures as well as permeability measurement of OGFC mixes are presented in the following sections.

3.3.2.1 Permeability Measurement

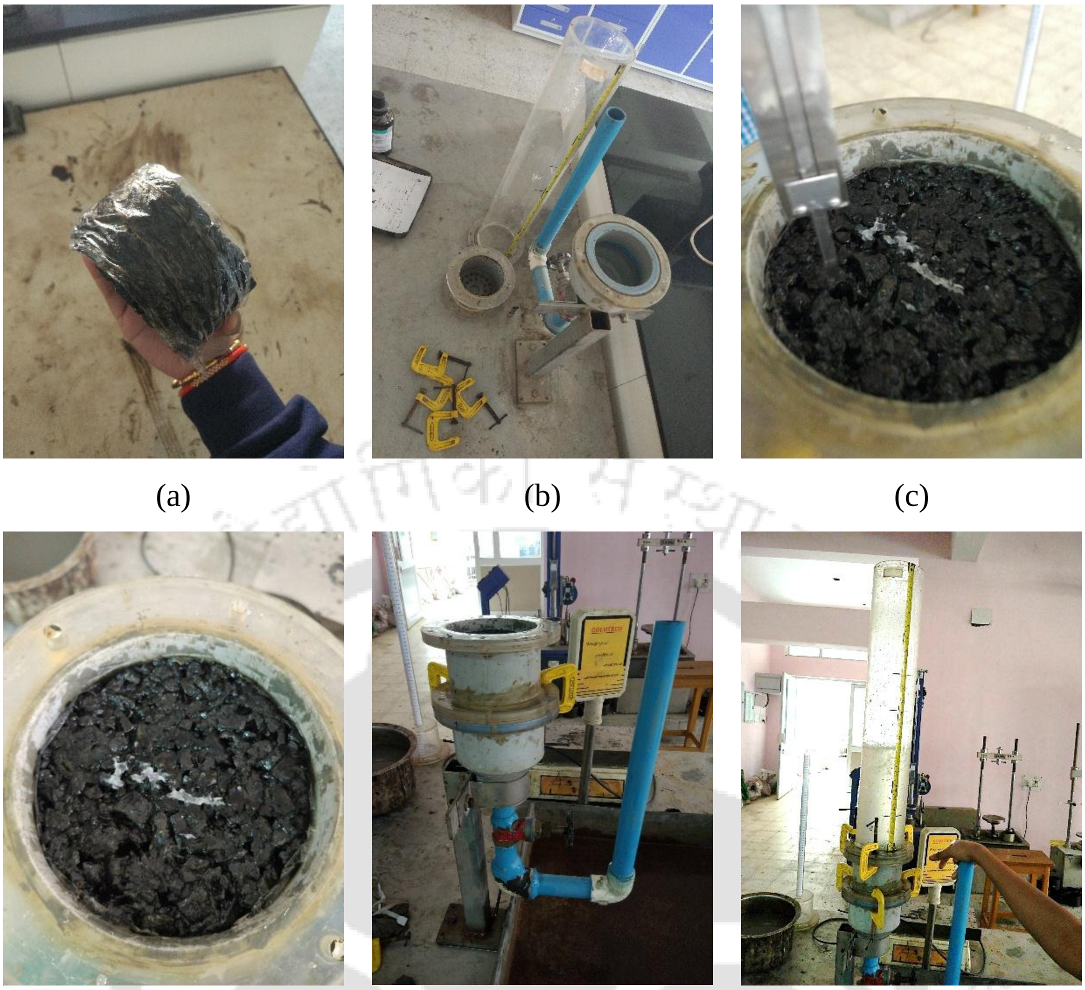
In this study a falling head permeameter was used to measure the laboratory permeability of OGFC mixes. Permeability measurements were done on compacted OGFC specimens of 101 mm diameter, prepared at their respective OBC and compacted by giving 50 blows on both sides using the standard Marshall compaction hammer. Three specimens for each EAF slag content and binder type were fabricated for permeability evaluation. The air voids content of prepared OGFC mixes was determined from bulk density and theoretical maximum specific gravity measure using geometrical measurements and CoreLok respectively, as explained before under the Task 1. The porosity of each compacted specimen was also determined using the vacuum sealing method as per ASTM D7063 (2017) specifications. The permeability measurement were done using a falling head permeameter/apparatus shown in Figure 3.11. Similar set up has been used by other researchers also (Wurst and Putman, 2013; Martin *et al.*, 2013) for permeability determination at laboratory scale. The OGFC specimens were first wrapped with plastic film to seal the edges to ensure/force the exit of the water from the bottom of the sample. Also for easy insertion and extraction of the sample from the standpipe, the plastic film wrapped side of samples were coated with grease. After positioning sample inside the permeameter, plumber putty was applied on the outer edges to stop any leakage between the edges and the standpipe. Figure 3.12 shows the different steps involved in measurement of permeability through the laboratory set up.

Figure 3.11: Permeability apparatus

After fitting and sealing of the OGFC specimens in the permeameter, water was made to flow in reverse direction though the bottom of specimen until it rose above the specimen top, to ensure saturation of the specimen. Then the valve was tightened and held for half an hour and then additional water was poured from top until the level of water was near the brim of standpipe. Thereafter, water was allowed to flow by opening the valve. The time for water level to drop from an initial head h_1 (375 mm) to final head h_2 (75 mm) was recorded using a stopwatch. This test was repeated thrice for each specimen and the permeability (k) was calculated using the following equation:

$$k = \frac{aL}{At} \ln\left(\frac{h_1}{h_2}\right) \tag{3.6}$$

where, a = cross-sectional area of standpipe (m^2); L = specimen height (mm); A = cross-sectional area of the specimen (m^2); t = the time required to drop of water from h_1 to h_2 (s). As per ASTM D7064, the minimum permeability requirement for an OGFC mix is 100 m/day.



(a) (b) (c)

(d) (e) (f)

Figure 3.12: Steps involved in permeability measurement: (a) sample sealing with plastic film, (b) different parts of permeameter (c) insertion of sample in sample holder (d) application of plumber putty on side of sample to prevent any side leakage (e) sample holder attachment (f) permeability measurement

3.3.2.2 Effect of Clogging on Permeability Characteristics

Clogging and de-clogging procedures were attempted on OGFC mixes to understand the effect of clogging of pores/voids on permeability characteristics of OGFC mixes. In field OGFC mixes may get clogged due to deposition of dirt and debris from wind, stormwater and vehicles. A clogged surface was attained by spreading a graded sand (passing 425 µm sieve and retained on 150 µm sieve) to completely flush the surface voids with surrounding aggregate tips. For clogging the specimen, the perimeter of the specimen was wrapped with a clear tape with a hard sheet of paper, leaving approximately 20 to 30 mm height of paper above the top surface of the specimen to avoid loss of material during the clogging procedure (Figure 3.13). The clogged specimen was then evaluated for permeability. After attempting clogging for different OGFC mix types, the permeability was measured. The permeability measured after clogging is termed as 'clogged permeability' ($K_{Clogged}$) as the surface pores of the compacted specimen are fully clogged. Once the clogged permeability was measured, the specimens were allowed to dry at room temperature for 24 h. The samples were then de-clogged by first vacuum suction using a household vacuum cleaner (standard pressure of the cleaner 22 kPa) for 5 min and then by reverse flushing using normal tap water (water head of about 10 m with 0.5 inch opening) for 5 more minutes as an effort to remove the clogging sand from the OGFC samples (Figure 3.14).

Figure 3.13: Clogging of OGFC sample

Figure 3.14: De-clogging of OGFC samples by (a) vacuum cleaner (b) Tap water

After de-clogging, the samples were inserted in the permeameter and then permeability was measured again, which is termed as ‘de-clogged permeability’. The de-clogged OGFC specimens further went for stepwise clogging by evenly spreading 14 g of graded sand in each step on top of the compacted OGFC specimen, in order to evaluate the effect of secondary stepwise clogging. The permeability of each specimen was measured per increment of sand and continued until the mass of sand was greater than the mass used in the macro-texture evaluation of the specimen. Graded sand was used for clogging evaluation of OGFC mixes throughout this study.

3.3.3 Task 3: Frictional Characteristics of OGFC Mixes with and without Steel Slag

Task 3 of this study was performed to evaluate the frictional characteristics of the different OGFC mixes in terms of British pendulum number (BPN) and texture depth (TD). OGFC mixes were prepared with five percentage replacements (0%, 25%, 50%, 75% and 100%) of natural coarse aggregates with EAF steel slag and two modified binders (PMB and CRMB). All combinations were tested for frictional characteristics and texture depth using British pendulum tester and sand patch method respectively. In addition, the effect of water film on frictional characteristics was also evaluated by considering different depths of the water film onto the specimen surface. The experimental plan shown in Figure 3.15 was used to accomplish this task. The detailed procedures followed for these tests are presented in the subsequent sections.

3.3.3.1 Frictional Evaluation (British Pendulum Tester)

In the present study, frictional evaluation was carried out in accordance with ASTM E303 (2013) using a British Pendulum Tester shown in Figure 3.16 under both dry (BPN_{dry}) and wet (BPN_{wet}) conditions.

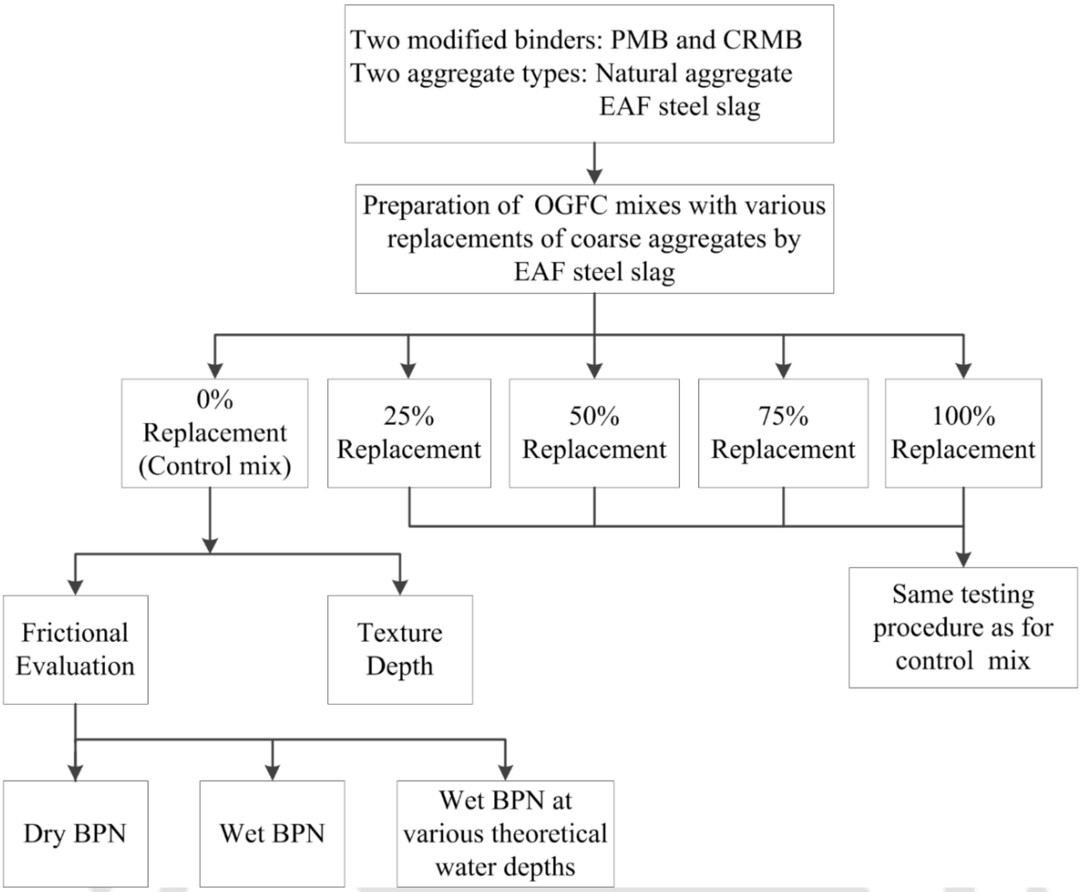
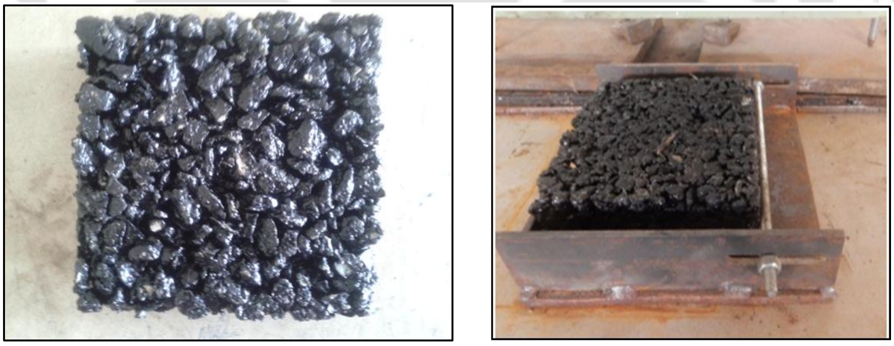


Figure 3.15: Experimental Plan for Task 3

Figure 3.16: British Pendulum Tester

British pendulum tester: The instrument provides a simple method of assessing friction of any surface and also provides a highly consistent reading. The main advantage of this instrument is its insensitivity to operator efforts (Dillard and Mahone, 1964; Giles *et al.* 1962). It consists of a pendulum that rotates about a spindle attached to a vertical pillar. At the end of the pendulum, a head of known mass is fitted with a rubber slider. The pendulum is released from a horizontal position so that it strikes the sample surface with a constant velocity. The energy lost when the rubber slider grazes over the test surface provides a measure of friction offered by the surface. The measurement of friction is indicated by a pointer on an engraved scale.

Prior to frictional measurement, the test instrument is leveled accurately with the help of spirit level. As the recommended contact path for the British Pendulum shoe on the asphalt concrete surface is 124 to 127 mm, slabs of OGFC mixes of size 152×152×50 mm were fabricated for all combinations of OGFC mixes. The slabs were compacted in a square mould of internal dimensions 152×152 mm. The slab specimens are shown in the Figure 3.17a. In order to ensure that the slab didn't get displaced during testing, an assembly was fabricated to hold the slab specimen in place as shown in the Figure 3.17b. Once the specimen was fixed on the assembly, a zero check was made for the apparatus.



(a) (b)

Figure 3.17: (a) OGFC slab specimen (b) finished slab specimen attached with test assembly

This was done by raising the pendulum so that the slider did not touch the test surface during its swing. The pendulum was then released from a horizontal position and the reading indicated by the pointer noted. If reading was not zero, friction ring on bearing spindle was slightly rotated. The test was repeated and friction ring adjusted until the pendulum swing carried the pointer to zero. The instrument was now considered ready for testing. The pendulum was then lowered to touch the test specimen. The slider was lifted using the lifting handle and the pendulum was moved to the left and brought back to touch the surface while coming from left to right. The point where the slider made contact was marked. This point gave the length of the contact path that was indicated on the scale. Once the required contact length was set, an initial swing was made for conditioning followed by four more swings and each result was recorded. These readings were recorded as the BPN. The frictional characteristics in terms of BPN were measured both in dry and wet conditions for all combinations of mixes. For evaluation of frictional characteristics under wet conditions, a suitable wetting protocol was adopted to achieve different levels of wetting of the specimen surface (discussed next).

3.3.3.2 Wetting Protocol

The specimen surface was wetted with different amounts of water in increments to produce a known theoretical water depth (calculated from the volume of water sprayed and the area of the slab specimen). The friction test was conducted at each water depth increment. Friction was measured for water depths ranging from 0 to 1 mm in the increments of 0.1 mm. The amount of water sprayed on the test surface was ensured by weighing the sample before and after spraying of water. An average theoretical water depth is calculated by dividing the volume of water by the wetted area. To avoid water flowing from the test area, the edge of the test area was filled with a sealant, and the slab was covered, except on its upper face, by a waterproof sheet, as shown in Figure 3.18. As soon as the surface got wetted, friction test was performed. The amount of water to be sprayed onto the surface of the specimen was found out as follows.

Thickness of water required = 0.1 mm = 0.01 cm

Volume of water required = 15.2×15.2×0.01 = 2.3 cm^3= 2.3 g (density of water: 1 g/cm^3).

Figure 3.18: OGFC mix slab wetting protocol

Therefore, 2.3 g of water was sprayed onto the test surface to achieve an average theoretical depth of water equal to 0.1 mm. This process was repeated with an increment of 0.1 mm thick water film.

3.3.3.3 Frictional Evaluation (Texture Depth Evaluation)

After frictional measurement in both dry and wet conditions on OGFC specimen, the samples were allowed to dry completely for a minimum of 48 h. Texture depth of the HMA slab was determined by the volumetric method as per ASTM E965 (2015). It involves spreading a known volume of sand (passing 250 µm sieve and retained on 180 µm sieve) on a clean and dry test surface in the form of a circle with the help of a spreading tool which is a flat, hard disc approximately 25 mm thick and 60 to 75 mm in diameter, shown in Figure 3.19. The spreading is done till the surface voids are filled flush with the highest aggregate tip. This is followed by measuring the area covered, and subsequently calculating the average depth between the bottom of the pavement surface voids and the top surface of aggregate particles by dividing the volume of sand by the area of the sand patch. The expression for the evaluation of texture depth (TD) is given in Equation 3.7.

$$TD = \frac{4V}{\pi D^{2}} \qquad (3.7)$$

where, *TD* = texture depth (mm); *V* = sample volume (mm^3); *D* = average diameter of the area covered by the material (mm). In a similar way the texture depth for all combinations of mixes with different percentage of steel slag and modified binders were measured.

Figure 3.19: Texture depth evaluation

3.3.4 Task 4: Moisture Susceptibility Characteristics of OGFC Mixes with and without EAF Steel Slag

Task 4 included determination of the moisture susceptibility characteristics of OGFC mixes. It is important to evaluate moisture damage properties of OGFC mixes as they are designed for hydraulic function and remain in prolonged contact with water. The experimental plan followed to achieve this task is shown in Figure 3.20. OGFC mixes were prepared with five percentage replacements by EAF steel slag (0%, 25%, 50%, 75% and 100%) and two modified binders to evaluate the effect of EAF steel slag replacement on moisture damage resistance. Intrusion of moisture weakens the adhesion bond between the binder and aggregate surface and accelerates the initiation and propagation of distresses such as cracking, ravelling and potholes. Currently, there are no widely accepted procedures for evaluation of moisture susceptibility of OGFC mixtures due to its high air void content (greater than 18%). In this study, moisture susceptibility characteristics of OGFC mixes were evaluated using four approaches: (1) retained tensile strength or tensile strength ratio (TSR) test, (2) wet abrasion loss (WAL) test, (3) static immersion test, and (4) modified boiling water test. The detailed procedures followed for these tests are presented in the succeeding sections.

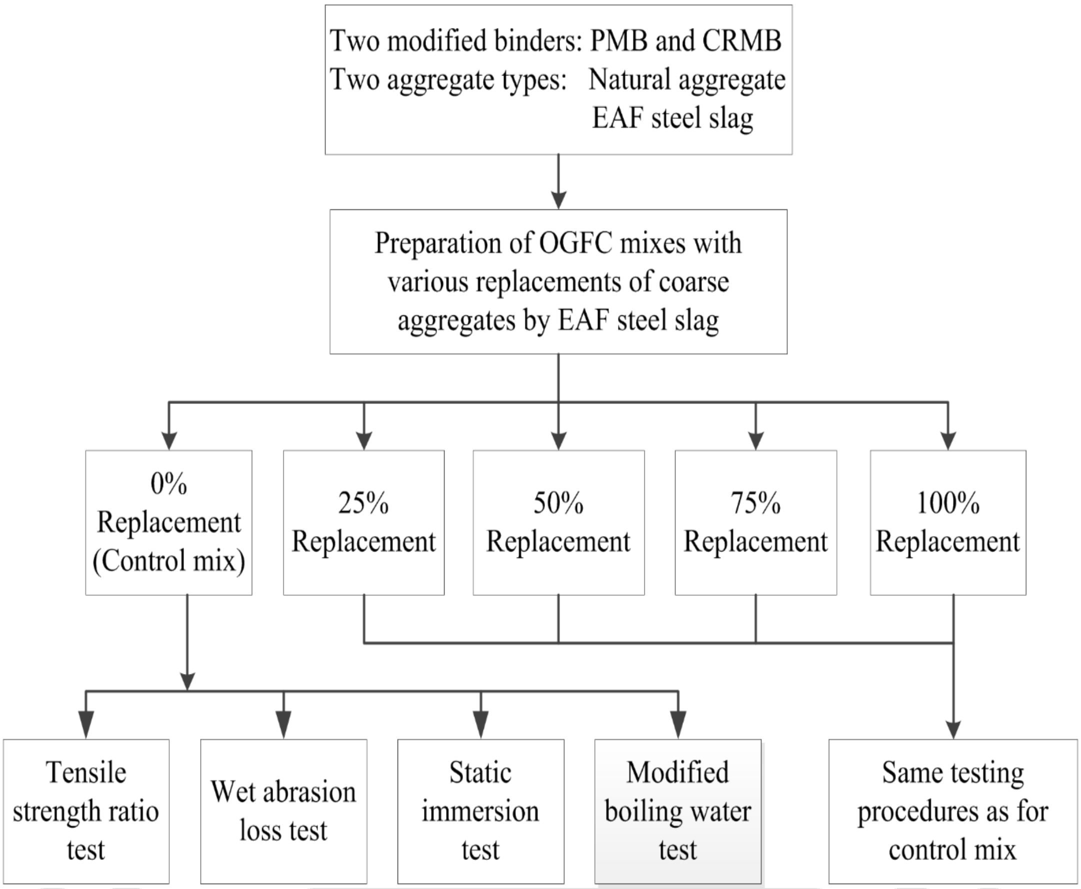


Figure 3.20: Experimental Plan for Task 4

3.3.4.1 Retained Tensile Strength or Tensile Strength Ratio Test

In the present study, Modified Lottman test with few modifications was carried out as per test procedure stipulated in AASHTO T283 (2003), to determine indirect tensile strength (ITS) and tensile strength ratio (TSR) of OGFC mixes. In this test procedure, OGFC samples compacted at the respective OBC for each combination were first divided into two groups (with at least three samples in each group), namely dry set and wet set. Samples in the dry set were cured in a water bath at 25 °C for 2 h and then tested for ITS at 25 °C. The specimens the wet set were subjected to a moisture conditioning procedure by subjecting them to a vacuum of 87.8 kPa (660 mm of Hg) for 10 min to soak the compacted OGFC specimens for whatever degree of saturation achieved. Saturated samples were then subjected to a freeze-thaw cycle. Freezing was done at -18 ± 3 °C for 16 h followed by immediate thawing in a water bath at 60 ± 1 °C for 24 h. Specimens were kept submerged during the freeze-thaw cycle to maintain the saturation and were cured in a water bath for 2 h at 25 °C and then finally subjected to ITS testing. The ITS tests were performed on the dry and wet subsets. The mean ITS values were used to determine the TSR of the mix. The ratio of average ITS of the wet conditioned subset to the average ITS of the dry conditioned subset, tested at 25 °C is termed as tensile strength ratio (TSR). The ITS and TSR values were determined by as per Equations 3.8 and 3.9:

$$ITS = \frac{2000P}{\pi d t} \tag{3.8}$$

$$TSR = \frac{ITS_{wet}}{ITS_{dry}} \tag{3.9}$$

where, ITS = indirect tensile strength (kPa); P is the maximum load (N); d is the diameter of the compacted OGFC sample (mm); t is the height of the compacted OGFC specimen (mm); ITS_{wet} is the mean indirect tensile strength (kPa) of the wet conditioned subset; ITS_{dry} is the mean indirect tensile strength (kPa) of the dry subsets.

Stripping is one of the major problems associated with the OGFC mixes, especially resulting from freeze and thaw cycles. To simulate the complete saturation of OGFC mixes that may occur in the real scenario, especially in cold weather conditions, multiple freeze-thaw (FT) cycles, were considered during the tests: 1 and 5 freeze-thaw cycles. Five freeze-thaw cycles were incorporated in compliance with the guidelines of ASTM D7064 standard. One freeze-thaw cycle was also incorporated in compliance with the proposal of Watson *et al.* (2004) where it was reported that only one freeze-thaw cycle is satisfactory for the wet conditioning of porous asphalt mixtures. As per ASTM D7064 specifications, the minimum requirement of TSR value for OGFC mix after 5 FT cycle is 80%. Conditioning procedure and ITS testing are shown in a pictorial form in Figure 3.21.

Figure 3.21: (A) OGFC samples of dry and wet subsets (B) samples at vacuum saturated condition (C) Samples inside a freezer at test temperature (D) Samples in freezing conditions (E) Samples at 60 °C (F) Samples at test temperature of 25 °C (G) Sample arrangement for testing (H) samples after testing

3.3.4.2 Wet Abrasion Loss (WAL) Method

The wet abrasion loss (WAL) test is another approach to assess the resistance of OGFC mixes to moisture damage. This test was conducted as per South African Code (Sabita Manual, 1995). To estimate the WAL of the OGFC mixes, the compacted specimens/mixes were exposed to moisture conditioning process done in the same manner as for TSR test. Six samples were prepared at OBC for each combination of mixes and were divided in two groups: wetset-1 and wetset-2. Samples in wetset-1 and wetset-2 were subjected to one and five freeze-thaw cycles, respectively. In order to assess the moisture resistance of the OGFC mixes after the freeze-thaw conditioning, Cantabro abrasion test was conducted. This test uses a Los Angeles abrasion drum without abrasive charges. Laboratory compacted wet conditioned OGFC specimens were placed in the Los Angeles abrasion drum and subjected to 300 revolutions at a rate of 30 to 33 revolutions per minute. The test was performed for both sets of OGFC specimens. The abrasion loss was determined using Equation 3.10:

$$WAL = \frac{W_1 - W_2}{W_1} \tag{3.10}$$

where, WAL is the abrasion loss (%); W_1 is the initial weight of specimen (g); W_2 is the final weight of specimen after testing (g). The wet abrasion loss should not exceed 50% and 30% respectively for the single and average values of samples as suggested in the Sabita Manual (1995). OGFC samples before and after WAL testing are shown in Figure 3.22.

Figure 3.22: Comparison of the specimen before (left) and after (right) wet abrasion loss testing

3.3.4.3 Static Immersion Test

It is another approach used to evaluate the adhesion properties or extent of stripping of aggregates. The stripping of bitumen coating from the aggregate occurs in the presence of water, making the asphalt mixture permeable to water. The water can then further pass on to various pavement layers resulting in pavement deterioration. Therefore, it is necessary to determine the effect of the presence of water on adhesion between binder and aggregates. The static immersion test is a simple test and was carried out as per IS 6241 (2000).

In this test approach, about 200 g of the mix was first prepared with the bituminous binder (5% by weight of aggregates) at mixing temperature. After reaching the ambient temperature the mix was transferred to a 500 mL beaker and then filled with distilled water. The beaker was then transferred to a water bath maintained at 40 °C, taking care that the level of water in the water bath came up to at least half the height of the beaker. After 24 h the beaker was taken out, cooled to room temperature and the extent of stripping was estimated visually while the specimen was still in the water. The ratio of the uncovered area observed visually to the total area of aggregates, expressed as a percentage is termed as stripping value of the aggregate. Indian Roads Congress (IRC) has specified that the stripping value of aggregates should not exceed 5%. Three loose mixes were prepared and tested for each combination of mixes. The photographs of (a) loose mixes inside the beaker, (b) samples in water bath (c) sample arrangement for determining the percentage of stripping is presented in Figure 3.23.

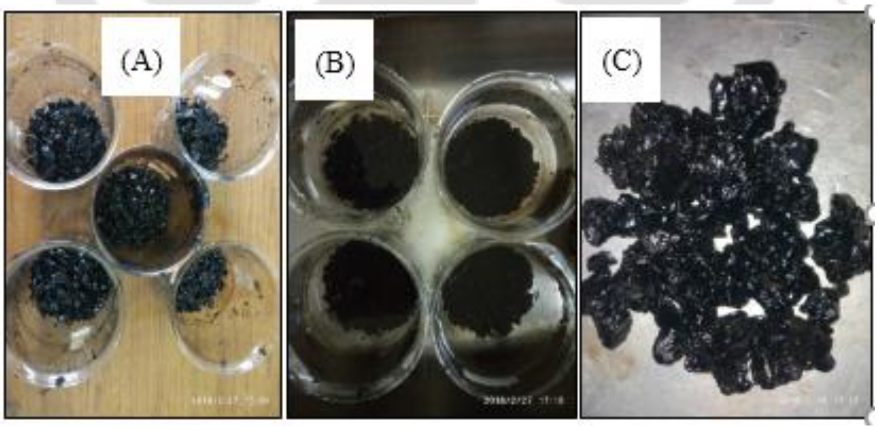


Figure 3.23: (A) mixes kept for cooling (B) samples inside water bath at 40 °C (C) stripping determination

3.3.4.4 Modified Boiling Water Test

The modified boiling water test is also used to evaluate the sensitivity of the different combination of OGFC mixtures to moisture induced damage. The conventional boiling water test (ASTM D3625, 2012) for asphalt mixtures, is a quick and easy visual indication of chemical incompatibility between the aggregate and asphalt binder. As per the specification of ASTM D3625 (2012), the bonding behaviour between aggregate and asphalt binder is examined by visual observations to estimate the degree of stripping of bitumen from aggregate surface. The obtained results by visual observation may not be quantified correctly and are also highly dependent on the operator's judgment. Hence a modified boiling test was conducted with following steps (Chen *et al.*, 2014): (1) oven dried aggregate was preheated at a temperature 10 °C higher than the mixing temperature for a minimum of 4 h, (2) the mixes were prepared at the mixing temperature and then allowed to cool down to 80-100 °C, (3) after reaching the test temperature, the mixes were poured in boiling water for 10 min and then allowed to cool to room temperature, and (4) samples were transferred on a paper and then allowed to dry properly in the air for enough time. The adhesive damage between the asphalt binder and aggregate was estimated by Equation 3.11:

$$AD = \frac{W_{cab} - \left(W_{caa} + W_{fp}\right)}{W_{cab} - W_{a}} \tag{3.11}$$

where, AD is adhesive damage (%), W_a is the dry weight of the virgin aggregate, W_{cab} is the weight of the coated aggregate before test, W_{caa} is the dry mass of the coated aggregate after test. The introduction of boiling water may lead to detachment of loose parts from the surface of aggregate and the corresponding dry mass is reported as W_{fp}. $W_{cab}-(W_{caa}+W_{fp})$ equals the mass of asphalt binder stripped from the aggregate surface. Hence, AD can represent the bonding between aggregate and asphalt binder, a lower value of AD

representing a better bonding. The testing was also conducted for each combination of the OGFC mixes. The photographs of (a) loose OGFC mixes (b) samples at the time of boiling (c) samples allowed to cool to its room temperature, and (d) samples allowed to dry completely after boiling test are presented in Figure 3.24.

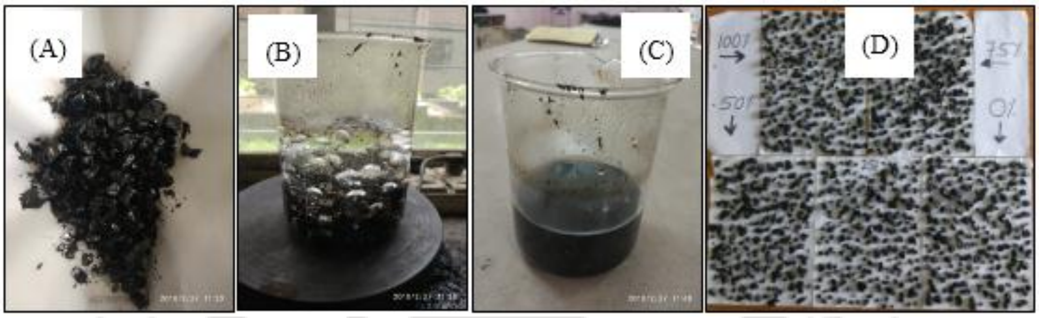


Figure 3.24: (A) loose mixes for boiling test (B) samples in boiling condition (C) samples kept for cooling (D) determination of percentage stripped off.

3.3.5 Task 5: Performance Characteristics of OGFC Mixes with and without EAF Steel Slag

Task 5 of the study was conducted to evaluate performance characteristics of the different OGFC mixes in terms of stiffness modulus, permanent deformation and fatigue life. OGFC mixes with the two modified binders and varying EAF steel slag substitution percentages were prepared and evaluated for the performance characteristics. Though OGFC layer is not considered a structural pavement layer, but the different performance parameters related to static creep, dynamic creep, stiffness modulus, Hamburg wheel tracking, and fatigue are evaluated in this study to compare performance of OGFC mixes at different contents of EAF steel slag as a coarse aggregate. Experimental plan used to accomplish this task is shown in Figure 3.25.

Static creep test, dynamic creep test, stiffness modulus test, Hamburg wheel tracking device (HWTD) test and indirect tensile fatigue test (ITFT) were performed according to BS 598-111 (1995), BS DD 226 (1996), EN 12697-26 (2012), AASHTO T324

(2016) and EN 12697-24 (2012) respectively to evaluate the performance of EAF slag modified OGFC mixes. Static creep test, dynamic creep test, stiffness modulus test and ITFT were performed using a Cooper 14 kN universal testing machine (UTM). HWTD test was performed on a Hamburg wheel tracking machine. The experimental test procedures of these tests are explained in detail in the subsequent sections.

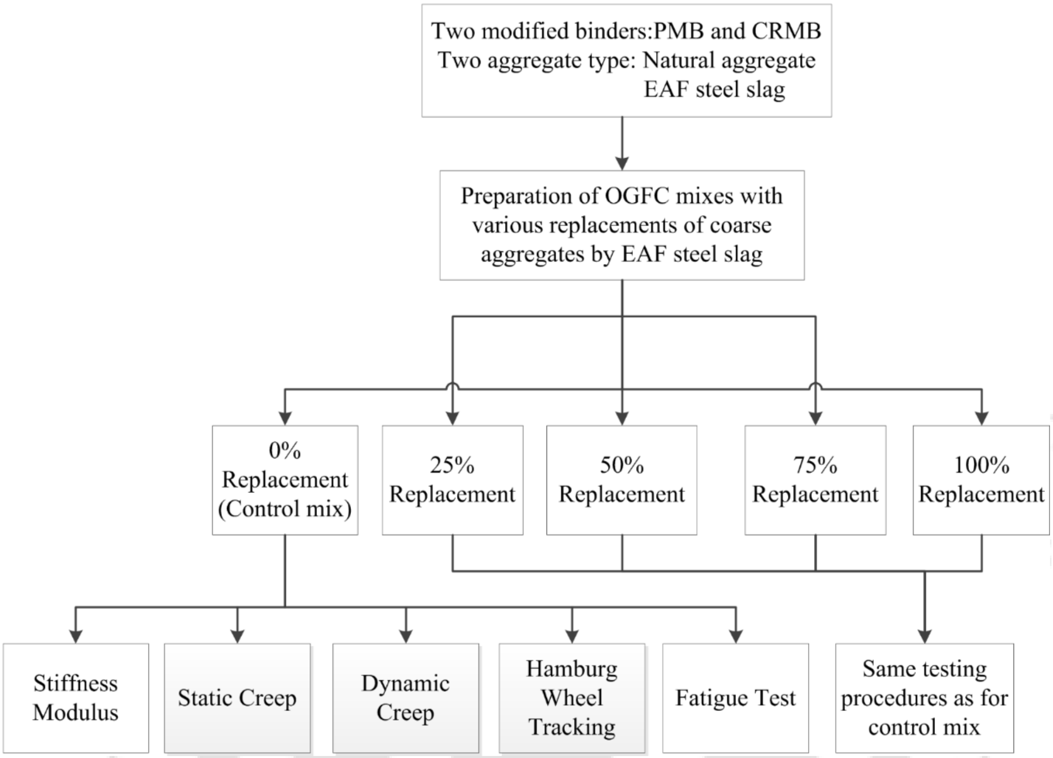
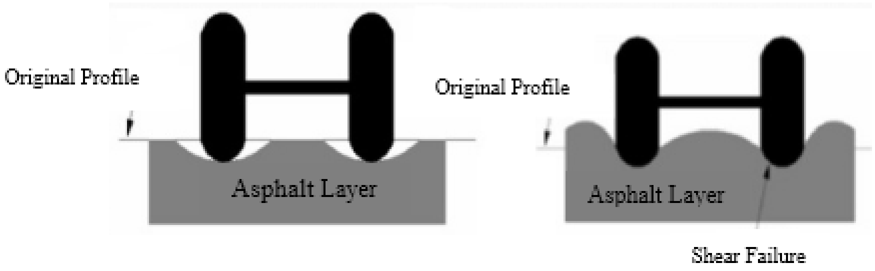


Figure 3.25: Experimental Plan for Task 5

3.3.5.1 Rutting

Rutting, also known as channeling or grooving is a longitudinal surface depression along the wheel path. It is a major type of failure in flexible pavements and it influences both functional and structural properties of the pavement structure and layer, which are directly related to the performance of road surface. There are two modes of deformation, *i.e.* compaction deformation (consolidation of layers) and plastic deformation (asphalt shear flow) (Huang and White, 1997; Gokhale *et al.*, 2005). The difference between these two failures is presented in Figure 3.26.



(a) (b)

Figure 3.26: (a) Compaction deformation and (b) Plastic deformation of asphalt layer

In the first mode, the deformed surface is lower than the initial pavement surface whereas, in the second mode, the deformed surface is higher than the initial pavement surface. The first mode generally occurs along the wheel path whereas the second mode deformation occurs between and outside the wheel path. The second mode is attributed to shear flow of bituminous materials under traffic loads, and is frequently referred as ‘heave’.

There are various test methods used to determine the permanent deformation characteristics of bituminous mixtures, such as Marshall stability test, static creep test, dynamic creep test, wheel tracking test and asphalt pavement analyser test. In this study, both static creep and dynamic creep along with Hamburg wheel tracking tests were performed to assess the permanent deformation characteristics of the OGFC mixes.

Static creep test

Static creep test is a simple and low cost test, and is used by researchers that do not necessitate use of more sophisticated and costly equipment (Fortes and Merighi, 2004). This test was performed as per BS 598-111 (1995) on a universal testing machine (UTM) to determine the permanent deformation or rutting characteristics of OGFC mixes subjected to a constant load. The test set assembly for the test is shown in Figure 3.27. Three Marshall OGFC samples were prepared at OBC content for each combination of EAF slag content and binder type. The end of the specimens was smoothened by applying flakes to minimise the friction between the load platen and specimen surface.

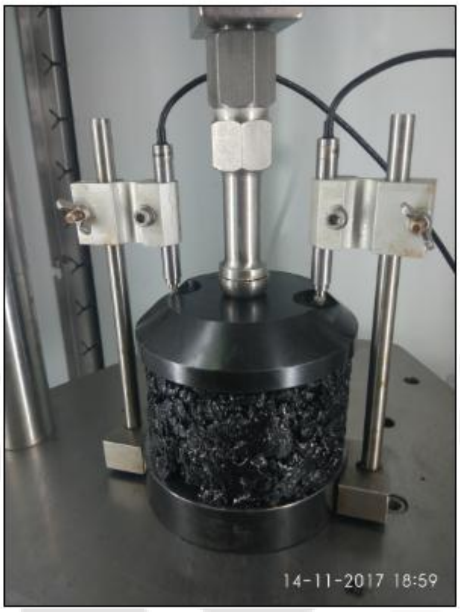


Figure 3.27: Creep test assembly

The main aim of doing this was to prevent variations in the specimen stiffness due to end restraints. As the permanent deformation distress is mobilised under the high service temperatures, test was carried out at 40 °C temperature. Prior to the test, the OGFC specimens and test setup along with accessories were kept inside the temperature-controlled chamber at the test temperature for 4 h. During the test, the specimen was subjected to a pre-conditioning load of 10 kPa for 10 min and then to a constant axial stress of 100 ± 2 kPa for a period of 1 h. The deformation of the specimen was noted every 60 s. Linear variable displacement transducers (LVDTs) were mounted on both sides of the specimen to measure the deformation. After completion of the loading time, recovered strain was recorded for the next 1 h. Axial strain was measured as per Equation 3.12:

$$\varepsilon \quad t = \frac{\Delta h(t)}{h} \tag{3.12}$$

where, $\varepsilon(t)$ = axial strain of the specimen at loading time t; $\Delta h(t)$ = axial deformation (change in the height of the specimen) at time t; h = specimen height.

Dynamic creep

Dynamic creep test is an important test to evaluate the resistance to permanent deformation or rutting. The dynamic creep test has a high capability of assessing the rutting potential of bituminous layers as it has a very good correlation with measured rut depth (Kaloush *et al.*, 2002). In the present study, this test was performed as per BS DD 226 on a UTM to evaluate the permanent deformation characteristics of asphalt mixtures under dynamic loading conditions. Test equipment and accessories for dynamic creep test are the same as for the static creep test but with repeated loading. Three Marshall OGFC specimens were prepared at OBC content for each combination of mixes for dynamic creep evaluation. The ends of the samples were smoothened to minimise the friction between the load platens and the sample surface. Specimens were pre-conditioned in temperature-controlled chamber at the test temperature (40 °C) for 4 h. A load of 10 kPa was applied for a period of 600 ± 6 s to confirm that loading platen and samples surface are entirely in contact with each other. After the pre-conditioning period, the stress was removed and a stress of 100 kPa was applied on the horizontal diametral plane of the cylindrical specimen in a square waveform with a frequency of 0.5 Hz. The test was continued for 10,000 cycles with a loading period of 1 s and a rest period of 1 s. During the test, the axial deformation of the samples was recorded by LVDTs positioned at 180 °C. The axial strain of the test specimen was determined from the measured deformation at the end of the rest period immediately after application of load using Equation 3.12.

Hamburg Wheel Tracking Device Test

The Hamburg wheel tracking device (HWTD) was developed in Hamburg, Germany, to evaluate the combined effect of rutting and moisture susceptibility of bituminous mixtures. The test assembly for the test is shown in Figure 3.28. The device rolls a steel wheel of diameter 203 mm and width 47 mm across the surface of a slab specimen or two Superpave gyratory compactor (SGC) specimens. The reciprocating wheel carries a load of 705 N and travels 230 mm in a single pass before reversing its direction. HWTD test was performed as per AASHTO T324 test method. Two SGC OGFC mixes of 150 mm diameter and 60 mm height constituted one specimen for the HWTD test.

(a) (b)

Figure 3.28: (a) Hamburg wheel tracking test device, (b) Specimens prepared for the HWTD test

The SGC specimens prepared at the OBC were sawed along a secant line and then joined together for the test. Each set of specimens was submerged in water bath (in the HWTD) maintained at 40 °C and subjected to 20,000 passes (52 passes per minute) of a loaded wheel. Each set of specimen was preconditioned for 30 min at the test temperature before commencement of the test. Two replicates were tested at each combination of EAF steel slag content (0, 25, 50, 75 and 100%) and binder type (PMB and CRMB).

3.3.5.2 Stiffness Modulus Test

Stiffness modulus of the bituminous mixture is considered a vital performance characteristic, as it is directly associated with the ability of the material to distribute the loads. Stiffness modulus test is a non-destructive test and has been well-established as a method to measure the stiffness properties of bituminous mixtures. This test is employed to rank bituminous mixtures based on the stiffness as a guide to relative performance within the pavement, to get information for estimating the structural behaviour of the pavement, and to judge test data according to specifications for bituminous mixtures. The stiffness modulus of the mixture, which can be measured in indirect tensile mode is the most popular stress-strain indicator. Stiffness modulus of the material regulates the level of traffic-induced tensile strain along the underside of the road and compressive strains in the subgrade, which is responsible for fatigue cracking and rutting respectively (Kok and Yilmaz, 2009). The stiffness modulus values can be only considered important for the performance analysis to compare the different mixtures as it doesn’t have any indication in the regulations on the minimum threshold of suitability for the acceptance of the mixture (Pasetto and Baldo, 2010). The stiffness of the OGFC mixes is usually around one-half to two-third of dense graded mixes. The stiffness of the mixture mainly depends on the volume of air voids within the mixture, *i.e.* lower the void content, higher is the stiffness of the mixture.

The indirect tensile stiffness modulus (ITSM) test was performed in accordance with EN 12697-26 at an intermediate pavement service temperature of 20 °C to estimate the stiffness modulus of the cylindrical OGFC specimens. The test set up for determining the stiffness modulus is shown in Figure 3.29. In this study, for each combination of mixes, three Marshall samples were prepared for stiffness measurement. Prior to the stiffness modulus testing, the OGFC specimen and ITSM test accessories were pre-conditioned in temperature-controlled chamber at the test temperature for 4 h. During the test, a compressive repetitive load pulse was applied by means of the load actuator on vertical diameter of the cylindrical specimen. The load actuator applied a repeated haversine load pulse with a rise time of 124 ms (rise time is the time for the application of load from zero to the peak).

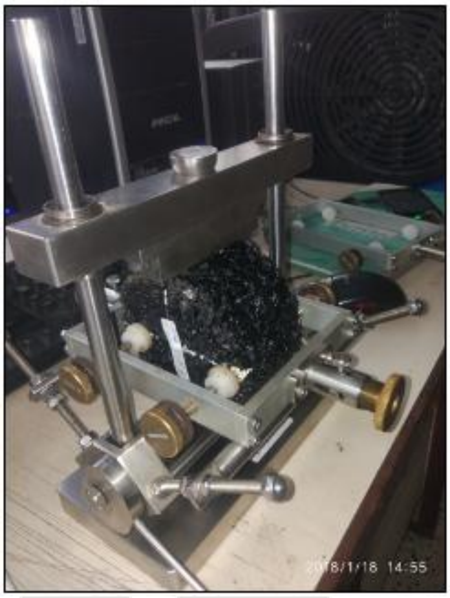


Figure 3.29: ITSM test assembly

The resultant peak transient deformation both in horizontal and vertical direction was measured with LVDTs. During the test, the specimen was subjected to 10 repetitive load pulses for conditioning and 5 repetitive load pulses for calculating the stiffness modulus. After completion of the test, the sample was rotated by 90° and then allowed to stabilise at the test temperature then the second load set was applied perpendicular to the direction of the first set. The average stiffness modulus obtained from the two specimen axis orientations was reported as the stiffness modulus of the specimen. The stiffness modulus of the specimen is determined from Equation 3.13:

$$S_m = \frac{F \times (\mu + 0.27)}{z \times h} \tag{3.13}$$

where, S_m = the stiffness modulus of the specimen, MPa; F = peak value of the applied vertical load, N; z = amplitude of the horizontal deformation for the duration of the load cycle, mm; h = specimen height, mm; μ = Poisson’s ratio (assumed 0.35).

3.3.5.3 Fatigue Test

Fatigue cracking is one of the major distresses on flexible pavements. Fatigue cracking is primarily caused by repeated traffic loading at medium-low temperatures, leading to the development of cracks that may cause the complete fracture of the road pavement, which in turn, results into a significant reduction in the serviceability of flexible pavements. Fatigue resistance is generally influenced by the density (compaction conditions) of the bituminous mixes and consequently by the morphological characteristics of the aggregates, properties of the binder, adhesion between the aggregate and bitumen, and mix compaction. Fatigue failure generally occurs in three stages. Initially, the failure and fatigue cracking begins and extends to other areas and reduces pavement resistance and finally, the sudden failure of pavement is observed (Marienfeld and Smiley, 1994). There are two modes of fatigue tests, namely, control stress mode and control strain mode. In controlled stress fatigue test mode, the stress is kept constant that causes the strain to increase within the bituminous sample whereas, in controlled strain mode, the strain is kept constant and the stress carried by the sample reduces with progress of the test (Arabani *et al.*, 2010).

In the present study, indirect tensile fatigue test (ITFT) was performed to evaluate the fatigue characteristics of OGFC mixes. The test was conducted as per EN 12697-Part 24 (2012) at test temperature of 20 °C. ITFT is a simple and economical test for evaluating fatigue performance of asphalt mixtures and can utilise cylindrical specimens prepared in the laboratory or cored samples from a pavement. To evaluate the fatigue life of OGFC mixes for each combination at respective OBC content, three Marshall samples were compacted. The sample was placed inside the temperature controlled environment for conditioning at a test temperature of 20 °C for a minimum period of 4 h prior to testing. The test specimen was subjected to a repetitive compressive load of 200 kPa with a haversine load signal through the vertical diametrical plane to achieve a strain in the range

100 με to 400 με. The test setup and the sample failure at the end of the test are shown in Figure 3.30. In this test procedure, the loading progressed as a relatively uniform tensile stress normal to the direction of the applied load and along the vertical diametral plane, which caused the specimen to completely fail by splitting along the central part of the vertical diameter as shown in Figure 3.31.

Figure 3.30: Test setup and failure of samples during ITFT test

Figure 3.31: Sample failure along the central part of the vertical diameter

The repetitive haversine load was applied at a frequency of 2 Hz with a loading time of 0.1 s and rest time of 0.4 s. In the ITFT, LVDTs were mounted horizontally to the test specimen to measure the deformations. Fracture life, defined as the total number of load applications for a complete fracture of the specimen, was used as the measure of fatigue resistance.

3.4 SUMMARY

This chapter presented the details of the selected materials for this study including bituminous binders, natural aggregates, electric arc furnace (EAF) steel slag, and fibres. The experimental programme to achieve the objectives of the study was presented and discussed in detail. Methodology for preparation of OGFC mixes with different percentage replacement of coarse natural aggregates with EAF steel slag and the evaluation of design parameters *i.e.* Cantabro abrasion loss, binder draindown, air voids, and performance parameters in terms of moisture susceptibility, permeability characteristics, frictional characteristics, stiffness modulus, permanent deformation and fatigue characteristics were also presented in this chapter.

Chapter 4
MIX DESIGN OF OGFC MIXES WITH EAF STEEL SLAG

4.1 INTRODUCTION

Open graded friction course (OGFC) mixes are asphalt mixes that help in quick and effective removal of water from the pavement surface, and enhance the skid resistance especially under wet weather conditions. OGFC mixes are designed to have high air voids content and a coarse granular skeleton with proper stone-on-stone contact, which is achieved through selection of a uniform gradation of aggregates. Due to quick removal of surface water through open granular structure, OGFC mixes offer several beneficial characteristics such as reduced hydroplaning, reduced splash and spray, improved frictional resistance, improved visibility, and reduced tyre-pavement noise. Due to the presence of high air void content, an OGFC mix also allows easy movement of air within the mixture that may result in enhanced aging of the bituminous binder film over aggregates, leading to loss of cohesion and bonding and subsequent ravelling problems. Cantabro abrasion test is conducted to estimate the short and long term abrasion/ravelling resistance of OGFC mixes under the action of traffic. OGFC specimens were tested under unaged and aged conditions. Due to the presence of low filler content and coarse aggregate skeleton of OGFC mixes, the bituminous binder may tend to draindown under gravity during mixing, storage, and hauling. This may lead to inadequate binder film thickness over the aggregates and hence impair the mix durability. To achieve a higher binder thickness over aggregates and to reduce the draindown potential, fibres are commonly used in OGFC mixes as stabilising agents. Binder draindown test is carried out to measure the draindown potential of OGFC mixes. In OGFC design, it is aimed to have: high amount of air voids to facilitate quick drainage of surface water along with a good stone-on-stone contact for mechanical stability; a high binder film thickness for a greater resistance towards ravelling/abrasion; and a low draindown potential to prevent binder loss during production, storage and transportation. OGFC mixes are evaluated for different parameters as per the requirements laid by ASTM D7064, given below, in order to determine the optimum binder content (OBC):

a. **Air voids** – An OGFC mix should have a minimum of 18 percent air voids.
b. **Abrasion loss on unaged samples** – The abrasion loss of the unaged OGFC mixes should not exceed 20 percent.
c. **Abrasion loss on aged samples** – The abrasion loss of the aged OGFC mixes should not exceed 30 percent.
d. **Binder draindown** – The draindown of the binder from the OGFC mix should not exceed 0.3 percent.

Mix design parameters of OGFC mixes with five natural coarse aggregate replacement percentages (0, 25, 50, 75 and 100%) with EAF steel slag and two modified bituminous binders, *viz.* polymer modified bitumen (PMB) and crumb rubber modified bitumen (CRMB) are presented in this chapter. Three trial binder contents (5.5, 6 and 6.5%) were used to determine the OBC of OGFC mixes with different contents of EAF slag and the two modified binder types. Cellulose fibre was used as stabilising additive at a dosage rate of 0.3% by weight of mix, as per the manufacturer’s guidelines. Three replicates were used for each test parameter at all combinations of EAF slag and binder type. The detailed experimental flow chart for this phase of the study was shown in Figure 3.7 of Chapter 3. The results of volumetric and mix design parameters in terms of stone-on-stone contact, bulk density, air voids, binder draindown, unaged abrasion loss and aged abrasion loss of EAF steel slag-OGFC mixes and control mixes (mixes without steel slag) are presented, analysed and discussed in this chapter. For unaged and aged abrasion loss tests, the same compacted OGFC specimens were utilized that were used for the calculation of air voids.

4.2 VOLUMETRIC AND MIX DESIGN PARAMETERS OF OGFC MIXES

4.2.1 Bulk Density of OGFC Mixes

Usually, bulk specific gravity of compacted dense graded bituminous mixes (G_{mb}) is determined using the water displacement method as stipulated in ASTM D2726 (2017). The water displacement method has advantages that it is quite inexpensive and simple to perform. Moreover, it is the traditional method on which design procedures and quality control (QC) and quality assurance (QA) specifications for most asphalt mixtures are based. However, this method is not accurate in case of coarse graded or open graded mixtures as it is quite difficult to measure the saturated surface dry (SSD) weight. OGFC mixes have larger and higher interconnected air voids. This interconnectivity permits water to easily flow through the interior of the mix sample, thus undervaluing the sample volume, particularly if this water drains out from the sample during the SSD weight measurement. As the volume is undervalued, the G_{mb} is overvalued, and in turn, air voids determined for the OGFC sample are undervalued (King *et al.*, 2009; Buchanan and White, 2005). Therefore, geometric method was adopted to measure the G_{mb} of compacted OGFC mixes as stipulated in ASTM D3203 (2003). In this test procedure, the bulk specific gravity of the compacted sample was determined using the geometric measures of height (as the average of three readings taken 120° apart) and diameter and the mass of the sample in air. The variation of bulk density of OGFC mixes with the increment of binder content and the percentage replacement of EAF slag for both PMB and CRMB binders is presented in Figures 4.1 and 4.2, respectively.

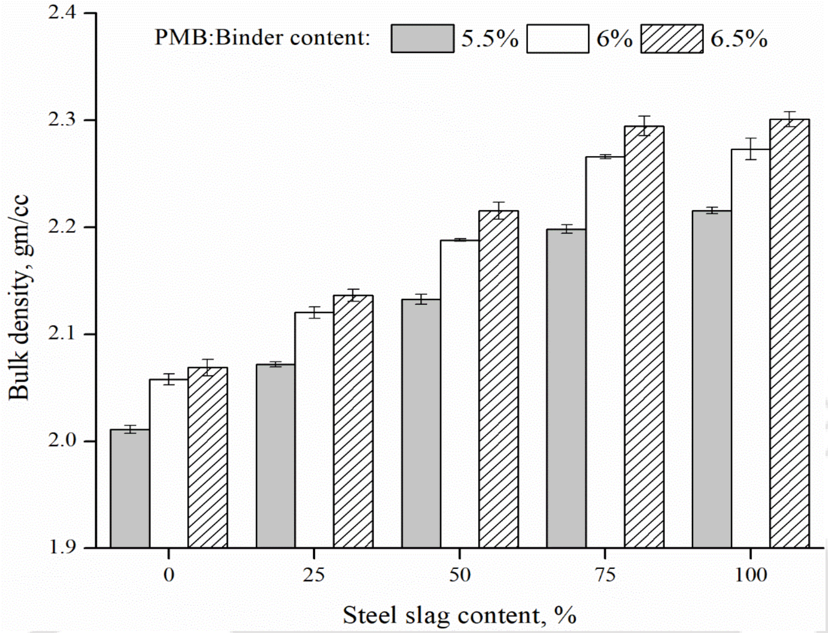


Figure 4.1: Bulk density of OGFC mixes with PMB binder

It is observed that with the increase in binder content the bulk density increases. An increase in binder content enhances the workability of the mix, which results in better compaction and thus a higher bulk density. For a particular binder content there is an increase in the bulk density with the increase in the EAF slag replacement percentage. This is due to the higher specific gravity of EAF steel slag (3.26) compared to the conventional natural aggregates (2.96). With the increase in the EAF steel slag replacement percentage in OGFC mixes, there is an overall decrease in the volume of the mix for a given weight due to the high specific gravity of EAF steel slag. Therefore, less binder is required to coat the aggregates for a particular binder content, which results in a higher residual binder. Higher residual binder enhances the workability and consequently leads to better compaction and higher bulk density. The G_{mb} values are found to be in the range of 2.011 to 2.301 and 2.006 to 2.299 for OGFC mixes with PMB and CRMB binders, respectively.

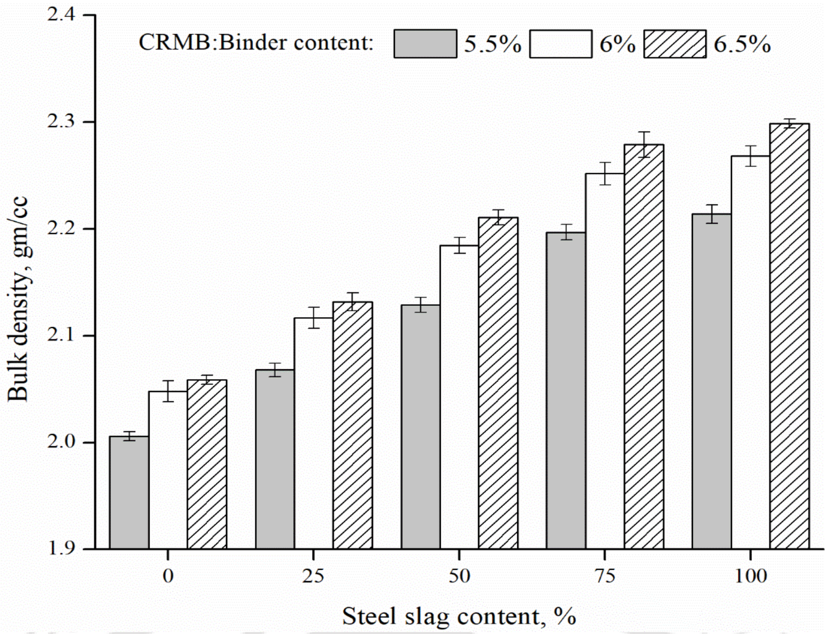


Figure 4.2: Bulk density of OGFC mixes with CRMB binder

4.2.2 Air Voids

The variation of air void content with binder content and EAF steel slag replacement percentage is presented in Figures 4.3 and 4.4 for PMB-OGFC and CRMB-OGFC mixes, respectively. For all EAF slag replacements, a reduction in the air void content is observed with the increase in the binder content for both PMB-OGFC and CRMB-OGFC mixes. Air void content in CRMB-OGFC mixes is slightly higher than the PMB-OGFC mixes, which may be due to the higher stiffness of CRMB binder compared to PMB binder as observed from the test results of the two binders in Table 3.1 of Chapter 3. For an OGFC mix, an increase in binder content improves workability and thus leads to better compaction and high bulk density with low air void contents. It is observed that at a particular binder content, increase in EAF steel slag content decreases the air voids. With increase in EAF percentage at a given binder content, two factors play a key role in the air void content achieved, namely: workability of the mix, and the angularity of the combined aggregates. With replacement of natural coarse aggregates with EAF slag, workability increases due to increase in the residual binder content resulting in better compaction and a low air void content.

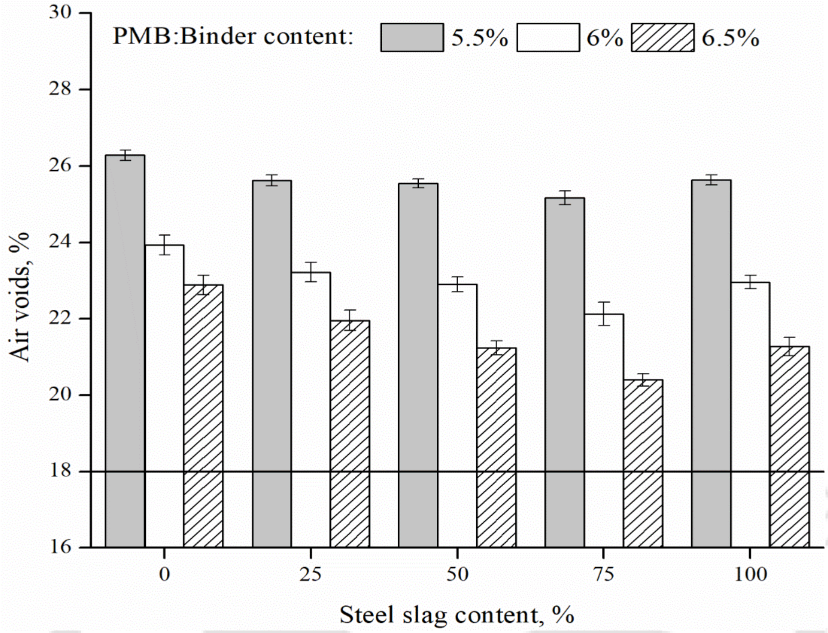


Figure 4.3: Variation of air voids in OGFC mixes with PMB binder

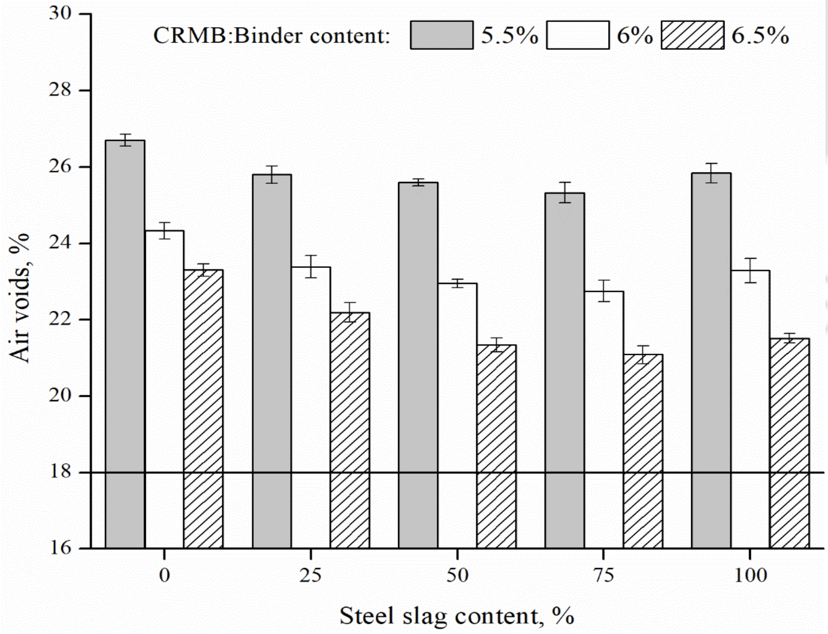


Figure 4.4: Variation of air voids in OGFC mixes with CRMB binder

However, the angularity of combined aggregates (containing EAF slag and natural aggregates) increases with the increase in EAF slag percentage. Higher angularity results in higher air void contents in OGFC mixes (Ziari and Khabiri, 2007; Bagampadde *et al.*, 1999; Skaf *et al.*, 2017). Air void content is found to decrease with the addition of steel slag up to 75% replacement of natural aggregates and then it slightly rises on further addition of EAF steel slag (at 100% replacement). It is surmised that the workability dominates over the combined aggregate angularity up to 75% replacement of steel slag but on further addition of EAF steel slag, the angularity becomes more prevailing. The air voids in all OGFC mixes are well above the minimum specified value of 18%. While high air voids are beneficial for hydraulic (permeability) and acoustic (noise-reduction) properties, it is important to study their effect on performance characteristics (resistance to permanent deformation, moisture-induced damage, and fatigue). Results of the performance characteristics will be presented in Chapters 5 and 6.

4.2.3 Stone-on-Stone Contact

For requisite performance, an OGFC mix must have a coarse aggregate skeleton with stone-on-stone contact, which is ensured if the voids in the coarse aggregate of the compacted bituminous mix (VCA_{mix}) are equal to or less than the voids in coarse aggregate in the dry rodded condition (VCA_{drc}), or the ratio of VCA_{mix} to VCA_{drc} is less than unity. VCA_{mix}/VCA_{drc} ratio gives a better representation of the effect of EAF steel slag replacement on the stone-on-stone contact criteria. The VCA_{mix} to VCA_{drc} ratio for all combination of mixes were found and are presented in Figure 4.5 and 4.6 for PMB-OGFC and CRMB-OGFC mixes, respectively. From Figures 4.5 and 4.6, it can be seen that the stone-on-stone contact shows an improvement with the increase in the substitution percentage of EAF steel slag up to 75% replacement. At 100% replacement, a decrease in stone-on-stone contact is observed (VCA_{mix}/VCA_{drc} ratio increases). However, the stone-on-stone contact criteria is fulfilled up to 100% replacement of EAF slag for both modified binders at all binder contents as the VCA_{mix}/VCA_{drc} ratio is always found less than 1.0. With increase in binder content VCA_{mix} decreases thus resulting in lower VCA_{mix}/VCA_{drc} ratios.

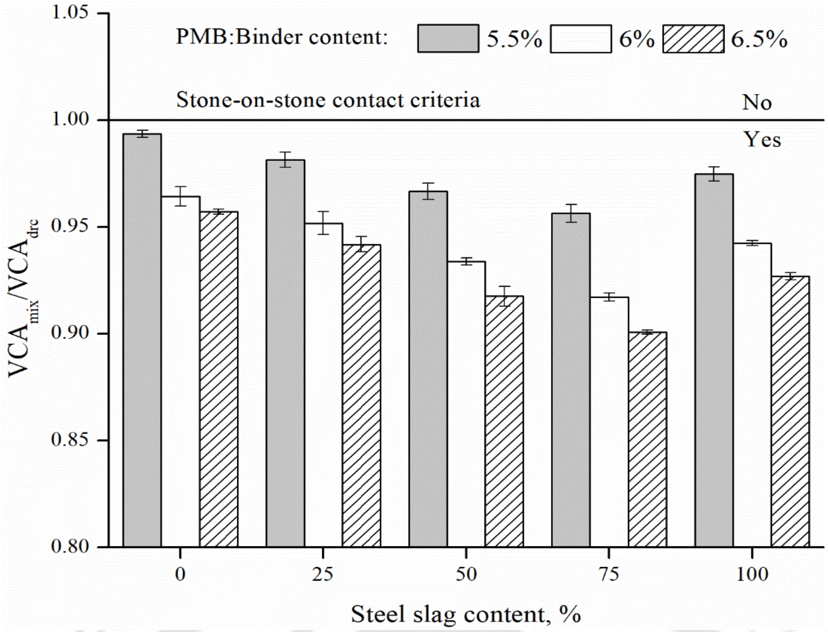


Figure 4.5: Stone-on-stone contact criteria for OGFC mixes with PMB binder

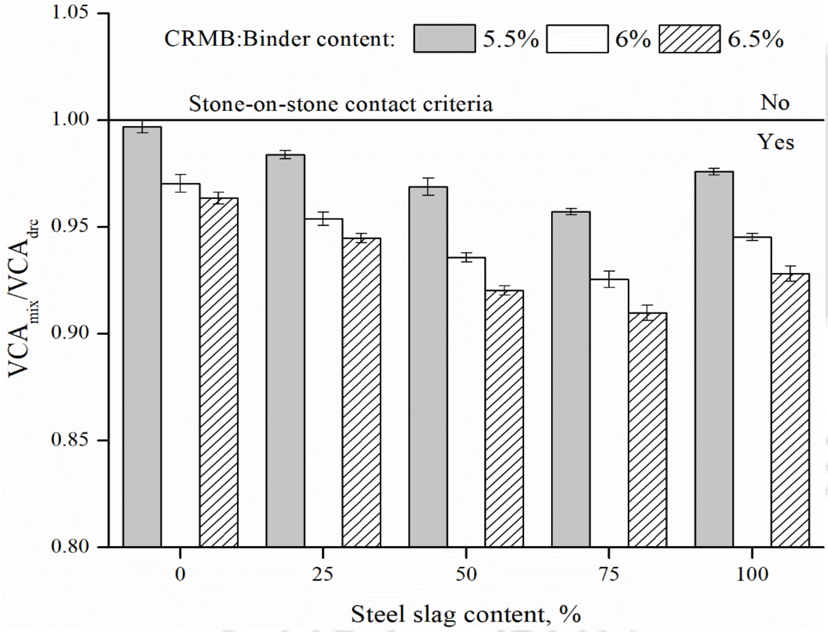


Figure 4.6: Stone-on-stone contact criteria for OGFC mixes with CRMB binder

4.2.4 Unaged Abrasion Loss (UAAL)

Cantabro abrasion loss test is conducted on OGFC mixes to ascertain their resistance to ravelling/degradation. The variation of unaged abrasion loss for OGFC mixes with binder content at different percentages of natural aggregate replacement by EAF steel slag with PMB and CRMB binders is presented in Figures 4.7 and 4.8, respectively.

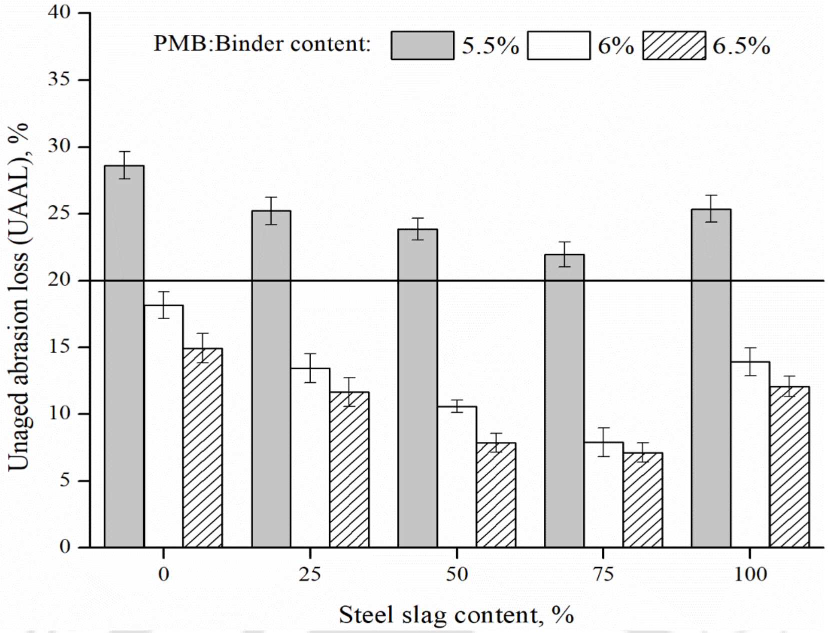


Figure 4.7: Unaged abrasion loss (UAAL) of OGFC mixes with PMB binder

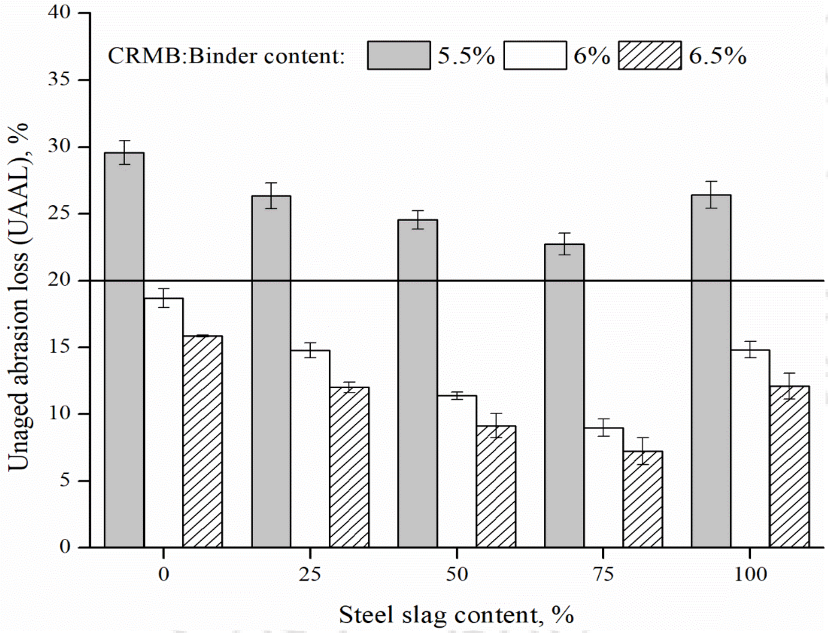


Figure 4.8: Unaged abrasion loss (UAAL) of OGFC mixes with CRMB binder

Abrasion loss decreases with the increase in binder content, as an increase in binder film thickness around the aggregates helps to enhance the cohesion and bonding, resulting in an improvement in the resistance towards abrasion/ravelling. The maximum UAAL requirement of 20% according to ASTM D7064 specifications (shown as a horizontal solid line in Figures 4.7 and 4.8) is met by OGFC mixes with all replacement percentages of

EAF slag at 6.0% and 6.5% binder contents. Control mixes (with 0% EAF slag content) show the highest percentage of abrasion loss at all binder contents ranging from 29 to 15% and 30 to 16% for PMB-OGFC and CRMB-OGFC mixes, respectively. OGFC mixes with 75% replacement of EAF steel slag show the lowest abrasion loss and hence highest abrasion resistance with both PMB and CRMB binders. This can be attributed to the improvement in stone-on-stone contact condition with the EAF steel slag replacement. OGFC mixes with lower VCA_{mix}/VCA_{drc} ratio are reported to show better performance compared to mixes with higher VCA_{mix}/VCA_{drc} ratio (Suresha *et al.*, 2009a).

Table 4.1: ANOVA results for unaged abrasion loss

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type (BT)	1	10.69	0.002	Yes
Slag content (SC)	4	54.59	<0.001	Yes
Binder content (BC)	2	742.86	<0.001	Yes
BT:SC	4	0.048	0.995	No
BT:BC	2	0.054	0.947	No
SC:BC	8	0.879	0.540	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	NS	S	S	S	NS	S

Note: 'S': Significant; 'NS': Not Significant; 'DF': Degree of Freedom

Analysis of variance (ANOVA) was performed on UAAL values of OGFC mixes (at 5% significance level) wherein slag content, binder type and binder content are the factors and UAAL is the response variable. Table 4.1 presents the results of ANOVA followed by Tukey's multiple comparisons at 5% level of significance. Steel slag content, binder type and binder content are found to have statistically significant effect on the UAAL values. Further, a higher F-value for binder content indicates that it has the highest influence on the UAAL values as compared to binder type and slag content. Non-significant interactions between the factors (binder type and slag content; binder type and binder content; binder content and slag content) indicates that the UAAL values follow a similar trend for varying slag contents for both binder types and binder content. Multiple comparison results show that substitution of natural aggregate by steel slag leads to significant changes in the UAAL values.

4.2.5 Aged Abrasion Loss (AAL)

AAL tests determines the long term ravelling resistance of OGFC mixes to traffic abrasion after subjecting them to an extended aging procedure (conditioning at 60 °C for 7 days). The variation of aged abrasion loss with binder content and EAF slag replacement percentage for PMB-OGFC and CRMB-OGFC mixes is presented in Figures 4.9 and 4.10, respectively. AAL values decrease with the increase in binder content. A high reduction in abrasion loss is observed for increase in binder content from 5.5% to 6.0% by weight of mix, compared to the further increase in binder content to 6.5%. Increase in binder content in the OGFC mixes allows a higher binder film thickness over the aggregates, thus resulting in improved durability and resistance of the mixes towards abrasion. Figures 4.9 and 4.10 show that for control mixes, abrasion loss ranges from 30 to 18% and 33 to 19% for PMB and CRMB binders, respectively, whereas mixtures with 75% replacement show aged abrasion loss in the range of 24 to 7% and 25 to 8% for PMB and CRMB binders, respectively. Both unaged and aged abrasion loss values show a similar trend with EAF slag replacement percentage at different binder contents. Better shape, angularity and FESEM test results of the EAF steel slag showed that it has rough surface texture and higher angularity than natural aggregates, which tends to provide high internal friction; better bitumen bonding; and an improved interlocking mechanism. The low percentage of flat and elongated particles in EAF steel slag materials makes it resistant towards fracture or breakage under heavy traffic.

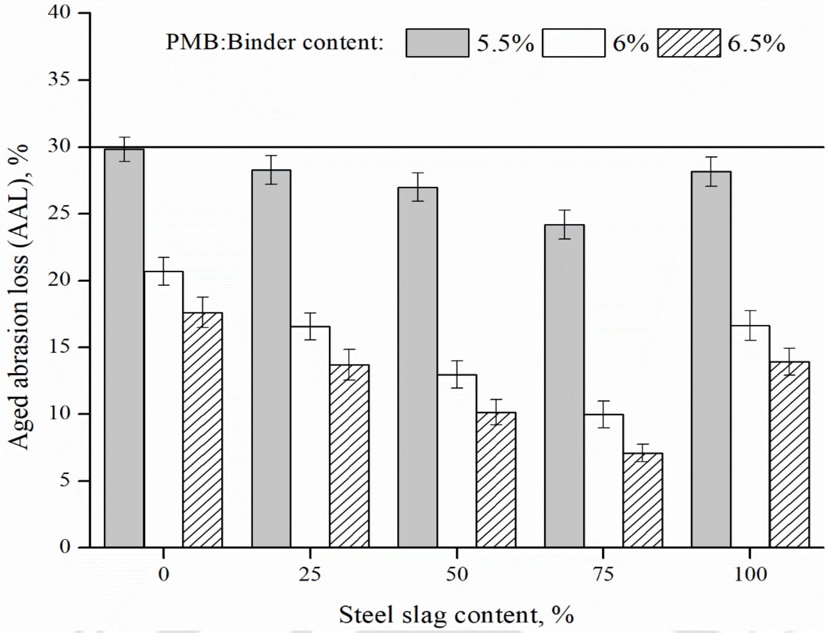


Figure 4.9: Aged abrasion loss (AAL) of OGFC mixes with PMB binder

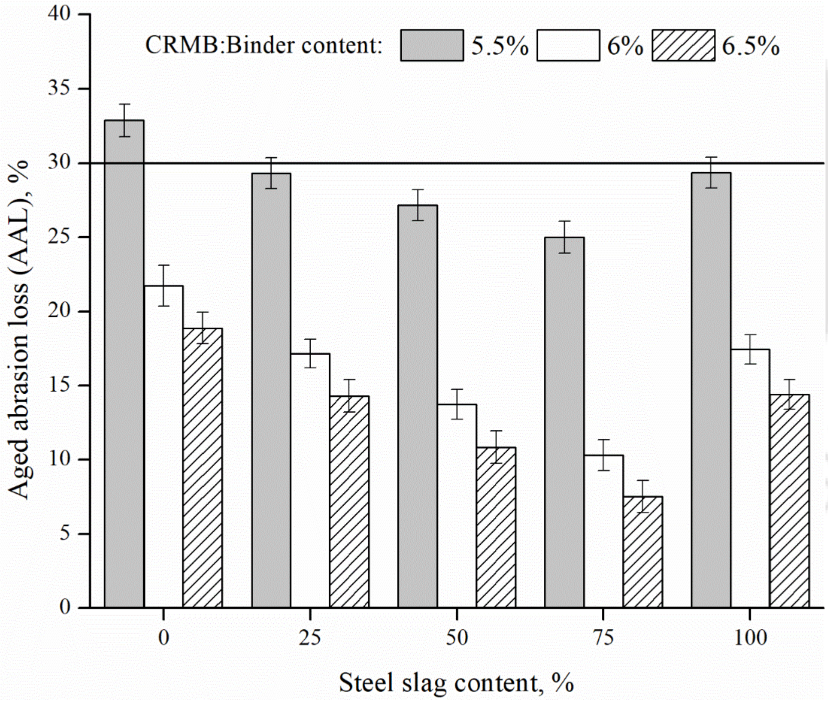


Figure 4.10: Aged abrasion loss (AAL) of OGFC mixes with CRMB binder

Improved abrasion resistance of OGFC mixes with EAF slag indicates that EAF slag aggregates have a good bonding with the asphalt binders. A similar observation has also been reported in other studies (Li *et al.*, 2015; Arabani and Azarhoosh, 2012). Further, a low silica content of EAF steel slag (generally less than 20%) makes it alkaline in nature with better adhesion capability (Zhou *et al.*, 2015), thus leading to improved resistance to ravelling/abrasion. From the comparison of abrasion loss results of both unaged and aged OGFC specimens as expected also, it is observed that the AAL results are higher than the UAAL results, which is likely due to higher brittleness in the binder after the extended aging procedure. The satisfying criteria for aged abrasion loss as per ASTM D7064 (horizontal solid line at the maximum of 30% abrasion loss in Figures 4.9 and 4.10) is met by all mixes with 0, 25, 50, 75 and 100% EAF slag replacement at 6.0% or higher bitumen content for both PMB and CRMB binders.

Table 4.2: ANOVA results for aged abrasion loss

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type (BT)	1	1.803	0.185	No
Slag content (SC)	4	22.033	<0.001	Yes
Binder content (BC)	2	224.07	<0.001	Yes
BT:SC	4	0.097	0.983	No
BT:BC	2	0.065	0.937	No
SC:BC	8	0.600	0.774	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	NS	S	S	S	NS	S	S

Note: 'S': Significant; 'NS': Not Significant; 'DF': Degree of Freedom

ANOVA was performed on aged abrasion loss values also to investigate the effect of three factors: slag content, binder type, and binder content and results are presented in Table 4.2. Further, a higher F-value for binder content indicates that it has the highest influence on the AAL values as compared to binder type and slag content. Non-significant interactions between the factors (binder type and slag content; binder type and binder content; binder content and slag content) indicates that the AAL values follow a similar trend for varying slag contents for both binder types and binder content. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the AAL values (in comparison to control mixes and mixes with various slag contents).

4.2.6 Binder Draindown

It is essential to determine binder draindown potential of OGFC mixes with EAF steel slag, to ensure that the binder does not get separated from the mix during its production, storage and transportation. At each binder content, three loose OGFC mixes with different EAF slag contents, were subjected to the draindown test. Figures 4.11 and 4.12 respectively show the average draindown results of OGFC mixes with PMB and CRMB binders.

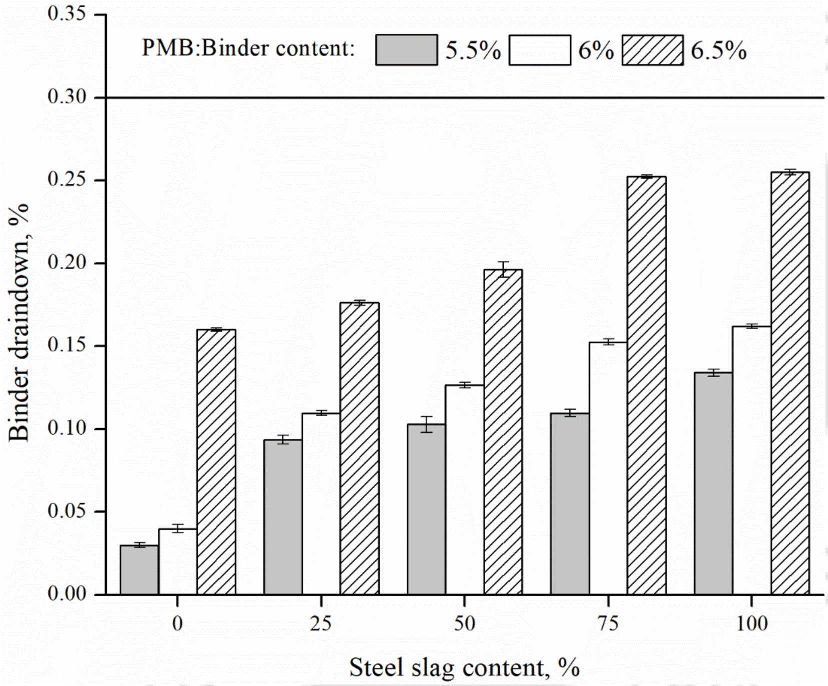


Figure 4.11: Draindown results of OGFC mixes with PMB binder

As expected, the draindown values show an increase with the increase in the binder content. Draindown also increases with increase in the EAF slag replacement percentage. This is explained by a higher specific gravity and therefore more residual binder in OGFC mixes with EAF steel slag. However, all combinations are able to meet the maximum limit of 0.3%. The use of cellulose fibre also helps to absorb and stiffen the binders and thus helps to provide a good binder film over the aggregates. Slightly lesser draindown values are observed for OGFC mixes with CRMB binder due to higher stiffness of CRMB binder compared to the PMB binder.

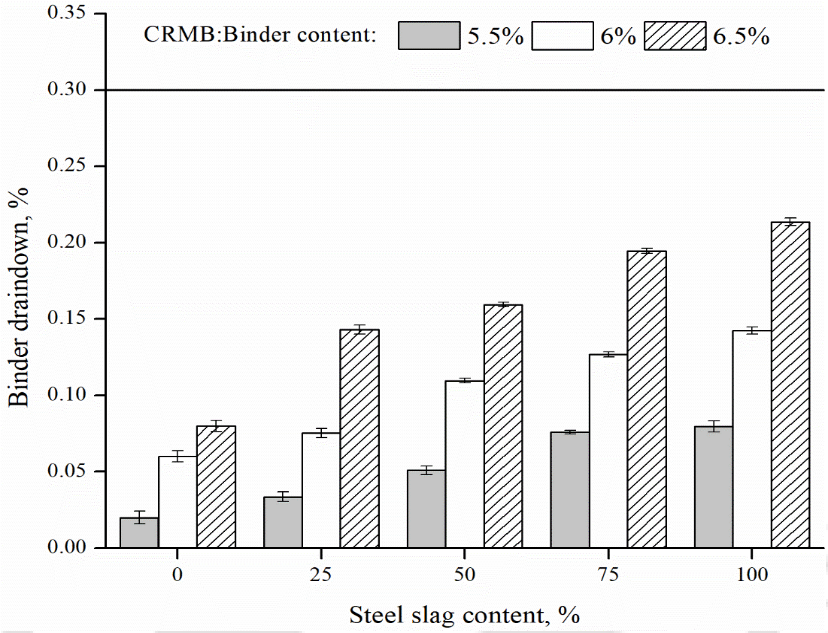


Figure 4.12: Draindown results of OGFC mixes with CRMB binder

4.3 OPTIMUM BINDER CONTENT (OBC)

OBC of an OGFC mix is the minimum binder content that provides the requisite amount of air voids to facilitate quick drainage of surface water, along with a good stone-on-stone contact for mechanical stability, a high binder film thickness for a greater resistance towards ravelling/abrasion and a low draindown potential to prevent binder loss during production, storage, transportation and construction. Based on the different parameters including air voids content, stone-on-stone contact, draindown, unaged and aged abrasion losses, the OBC of OGFC mixes with different replacement percentages of EAF slag is determined. All the mix volumetric and design parameters are checked for their fulfilment as per ASTM D7064 requirements as shown in Table 4.3. It can be seen that at lower binder content (5.5%), the UAAL criterion is not met for all combination of mixes and the AAL criterion is not met in case of control CRMB-OGFC mixes. OGFC mixes with all percentage replacements of EAF slag along with control mixes are able to satisfy the different design criteria at 6% binder content. Hence, the 6% binder content is selected as the OBC for all OGFC mixes containing different contents of EAF steel slag with both PMB and CRMB binders.

4.4 SUMMARY

This chapter presented the characterisation of mix design and volumetric properties of OGFC mixes with EAF steel slag (a by-product from steel industry), as partial replacement of coarse natural aggregates, with two types of modified binders, PMB and CRMB. The effect of EAF steel slag replacement percentage, binder type, and binder content on properties of OGFC mixes was investigated in terms of volumetric properties, stone-on-stone contact criterion, draindown and abrasion loss (unaged and aged). EAF steel slag aggregates were found to satisfy all the requirements of aggregates for being used in OGFC mixes. In comparison to OGFC mixes with natural aggregates, increase in EAF steel slag content up to 75% resulted in improvement in OGFC mix properties including bulk density, stone-on-stone contact condition, and abrasion loss in unaged and aged conditions for both PMB and CRMB binders. ANOVA results showed that the effect of substitution of natural aggregate by EAF steel slag on volumetric and mix design parameters of OGFC mixes was significant with both CRMB and PMB binders. Even after 100% replacement of natural aggregates by EAF steel slag, OGFC mixes met all the design requirements and showed a comparable performance to the OGFC mixes with natural aggregates. The OGFC mixes with PMB binder demonstrated higher density and resistance to abrasion compared to OGFC mix with CRMB binder. Finally, an OBC of 6% was determined and selected for all OGFC mixes at all EAF contents with both binders.

Table 4.3: Fulfilment of criteria for OBC selection of OGFC mixes

Slag (%)	**Binder type**	**Binder Content**	**Fulfilment of criteria**			
			Air Voids, %	**Draindown, %**	**Unaged Abrasion Loss, %**	**Aged Abrasion Loss, %**
			Min 18	**Max 0.3**	**Max 20**	**Max 30**
0%	PMB	5.5%	✓	✓	✗	✓
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓
25%		5.5%	✓	✓	✗	✓
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓
50%		5.5%	✓	✓	✗	✓
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓
75%		5.5%	✓	✓	✗	✓
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓
100%		5.5%	✓	✓	✗	✓
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓
0%	CRMB	5.5%	✓	✓	✗	✗
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓
25%		5.5%	✓	✓	✗	✓
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓
50%		5.5%	✓	✓	✗	✓
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓
75%		5.5%	✓	✓	✗	✓
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓
100%		5.5%	✓	✓	✗	✓
		6.0%	✓	✓	✓	✓
		6.5%	✓	✓	✓	✓

Chapter 5

PERMEABILITY AND FRICTIONAL CHARACTERISTICS OF OGFC MIXES WITH EAF STEEL SLAG

5.1 INTRODUCTION

Design of hot mix asphalt (HMA) is generally aimed to develop a structurally sound pavement system that can sustain repetitive traffic loading over its design life without excessive damage. The vital functions of a pavement from user perspective are mainly related to smoothness, high skid resistance, low tyre-pavement noise, and good visibility of road markings in night and during rain. Open graded friction course (OGFC) mixes have been in use since last few decades in many European countries (Belgium, Spain, Switzerland) and in countries like Japan, the United States, *etc*., to improve pavement surface drainage during wet weather conditions, to reduce the risk of hydroplaning, to enhance the skid resistance, and to reduce tyre-pavement interaction noise. OGFC mix is a special type of HMA, characterised by high interconnected air voids and a coarse granular skeleton with good stone-on-stone contact. The presence of high internal air voids leads to porous structure of OGFC mixes, which thus helps in quick and effective drainage of water through them to the pavement edges. Due to quick removal of surface water, OGFC mixes help to minimise hydroplaning, reduce splash and spray, and enhance the visibility of pavement marking during the rainy season (Nielsen, 2007). Many countries have reported a 90-95% reduction in splash and spray with OGFC mixes, when compared to the dense graded bituminous mixes. The coarse macro-texture of OGFC not only facilitates surface water drainage but also improves the frictional characteristics of the road surface.

Permeability or hydraulic conductivity is an important characteristic of OGFC mixes. Permeability is the ability of a material to transmit fluids through the interconnected voids under a hydraulic gradient. Permeability of an asphalt mix is a function of compaction, mix volumetrics, aggregate gradation, nominal maximum aggregate size (NMAS) and lift thickness (Vardanega, 2012). Functional performance and effectiveness of OGFC mixes highly depends on its permeability characteristics. The highly porous structure of OGFC mixes helps in quick and effective removal of surface water. However, as pavement life progresses, entry of dirt and debris may clog the voids of OGFC mix and eventually reduce its permeability. The deposition of dirt and debris may be from wind, stormwater, or vehicles. The higher air void content of OGFC mixes allows the movement of air within the mixture, which can result in enhanced aging of the binder film leading to weakening of the cohesive bond, thereby causing ravelling. The ravelled fine aggregate particles may also get deposited in the OGFC, causing a further reduction in the air voids content and drainage capacity (Nielsen, 2007). Hence, it is vital to evaluate the permeability and clogging characteristics of OGFC mixtures.

Skid resistance is the frictional force developed when a tyre is prevented from rotating, and slides along the pavement surface. This force is an important component of traffic safety as it helps to maintain the vehicle in control in order to stop under emergencies. Therefore, skid resistance quantifies the safety aspects of a road surface. Skid resistance has two major components: adhesion and hysteresis. Adhesion is the bonding/force between the vehicle rubber tyre and pavement surface when they come in contact with each other. The total force required to overcome this adhesive bond depends upon the contact area and the interface shear strength. On the other hand, the hysteresis component of frictional force results from the energy lost due to bulk deformation of the vehicle tyre. When the vehicle tyre compresses against the irregular texture of pavement surface, the tyre gets deformed and potential energy is stored within the deformed rubber. As the tyre regains its original form, part of the energy is recovered and part of it is dissipated in the form of heat, known as hysteresis. This loss leaves a net frictional force to help stop the forward motion. These two components of tyre friction are illustrated in Figure 5.1.

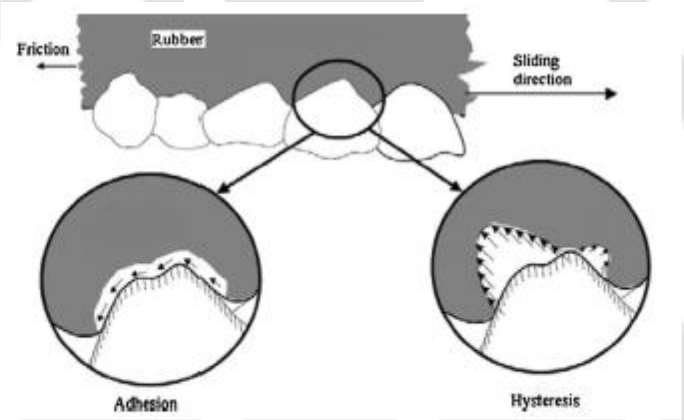


Figure 5.1: Key mechanisms of pavement–tyre friction (Hall *et al.*, 2009)

The surface texture characteristics of pavement play an important role in the skid resistance and the safe movement of vehicles under both wet and dry conditions. Surface texture comprises mainly of two components: micro-texture and macro-texture. Micro-texture refers to irregularities on the surface of the aggregate particles, measured at the micron scale of roughness and are known to be mainly a function of mineralogy of aggregate particles. Micro-texture is mainly responsible for pavement friction at low speeds. Micro asperities of size less than 0.5 mm play a key role in dispersing the thin water films formed during wet weather. Macro-texture refers to the larger irregularities on the road surface with a magnitude in the range of 0.5 to 50 mm, and is mainly associated with the voids between aggregate particles. The magnitude of this component will depend on the size; shape; aggregate gradation/distribution; nominal maximum aggregates size (NMAS); as well as on the construction technique used in the placement of the pavement layer (Hall *et al.*, 2009; Kogbara *et al.*, 2016). Adequate macro-texture is important for the quick dispersion of water accumulated on the pavement surface to prevent hydroplaning. A good correlation has been observed between pavement friction and texture (Kane *et al.*, 2015). Macro-texture promotes superior friction at higher speeds (Hall *et al.*, 2009). The surface texture of an HMA course is also controlled by the quality of aggregate used (Jayawickrama *et al.*, 1996; Skerritt, 1993; Haddock and O’Brien, 2013). Angular and rough textured aggregates can lead to enhancement of the frictional properties (Hall *et al.*, 2009). OGFC mixes are primarily used to enhance safety by increasing the frictional characteristics of pavement surface during the wet weather conditions (King *et al.*, 2013). Frictional resistance, especially in wet weather conditions, is an important functional requirement of road pavements. Wet roads are more prone to accidents than dry roads. Adequate friction between vehicle tyres and OGFC surface is desirable for safe driving.

This chapter presents the results and analyses of permeability characteristics, clogging characteristics, and frictional characteristics of OGFC mixes with EAF steel slag. OGFC mixes were prepared by replacing natural coarse aggregates with varying percentage of EAF steel slag (0, 25, 50, 75 and 100%) along with two types of modified binders: polymer modified binder (PMB) and crumb rubber modified binder (CRMB). These mixes were examined for permeability characteristics under different clogging conditions. Frictional characteristics of OGFC mixes were evaluated in terms of British pendulum number and texture depth. In addition, the effect of water film on frictional characteristics of OGFC mixes was also assessed.

5.2 PERMEABILITY CHARACTERISTICS OF OGFC MIXES WITH EAF STEEL SLAG AND MODIFIED BINDERS

5.2.1 Porosity and Air Voids

Prior to permeability measurement, the air voids content and porosity values for all combination of OGFC-EAF steel slag mixes were determined. The results of air voids (AV) content and porosity are presented in Figures 5.2 and 5.3 respectively. It is observed that air voids content decreases slightly with increase in EAF steel slag replacement up to 75% and then shows a small increase at 100% EAF steel slag replacement. This shows that improvement in workability due to increase in residual binder content is dominant over angularity up to 75% replacement of EAF steel slag, and on further increment, angularity of EAF slag becomes more dominant. These results were discussed in detail in Chapter 4.

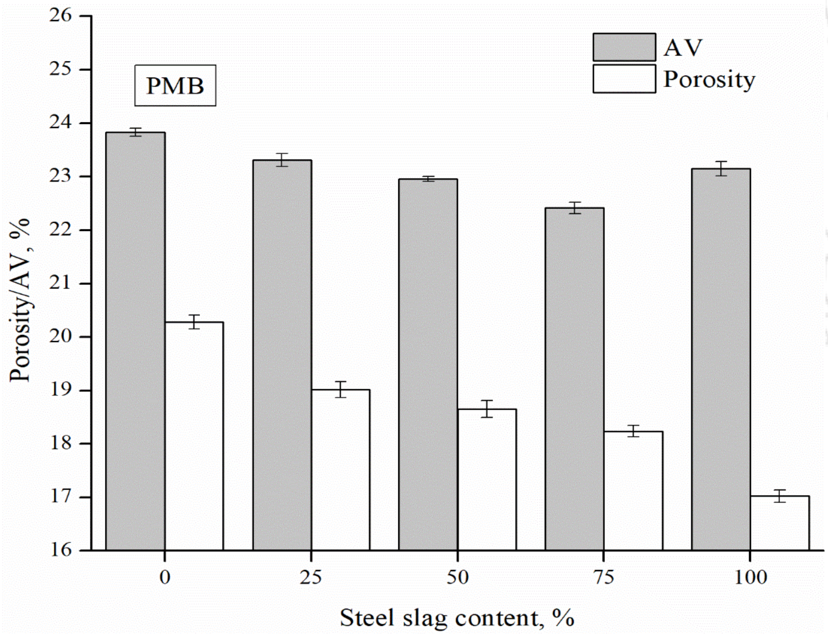


Figure 5.2: Average porosity/AV values for OGFC mixes with PMB binder

Air voids content is always higher than porosity in all the OGFC mixes. This is expected because porosity comprises of air voids that are accessible by water, and hence is less than the total air void content, which comprises of both accessible and non-accessible (isolated) air voids. Similar observation has also been reported by other researchers

(Mansour and Putman, 2012; Alvarez *et al.*, 2008; Kline and Putman, 2011). The average porosity varies from 20% to 17% and 22% to 17% for PMB and CRMB-OGFC mixes respectively, whereas the air voids content varies from 24 to 23% and 24 to 23% for PMB and CRMB mixes respectively.

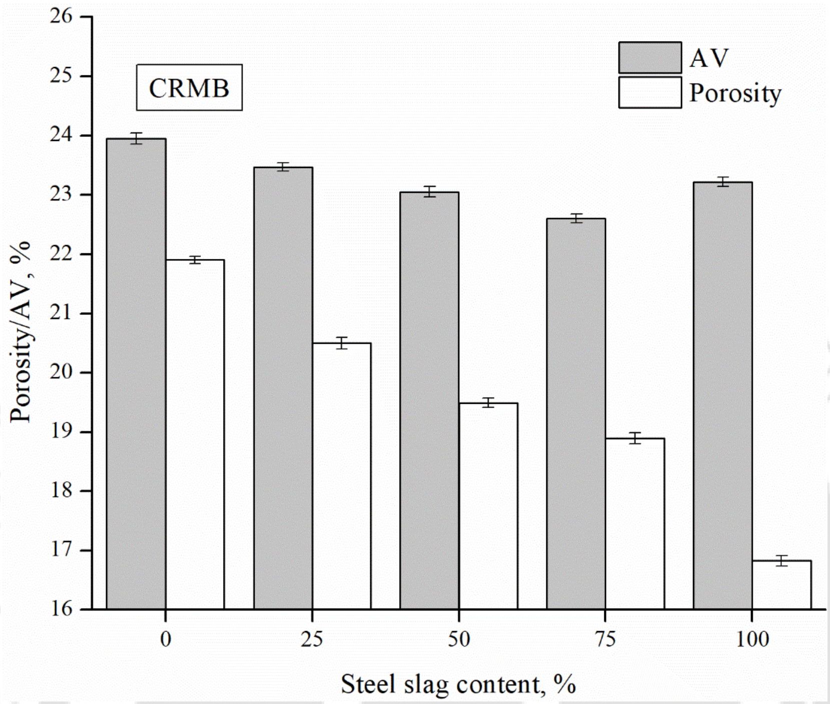


Figure 5.3: Average porosity/AV values for OGFC mixes with CRMB binder

5.2.2 Initial Permeability

For each combination of EAF steel slag and natural aggregates, the permeability values of OGFC specimens measured after the air voids content and porosity determination, is referred as 'initial' permeability (*i.e.* permeability of a fresh un-clogged OGFC specimen). The initial permeability results for OGFC mixes with both PMB and CRMB binders are presented in Figure 5.4. The average initial permeability values vary from 467 m/day to 293 m/day and 578 m/day to 291 m/day for PMB-OGFC and CRMB-OGFC mixes, respectively. The OGFC mixes with natural aggregates show higher permeability followed by mixes with 25%, 50%, 75% and 100% replacements of coarse natural aggregates with

EAF steel slag respectively. A similar trend is observed for porosity of the OGFC mixes with different EAF steel slag contents.

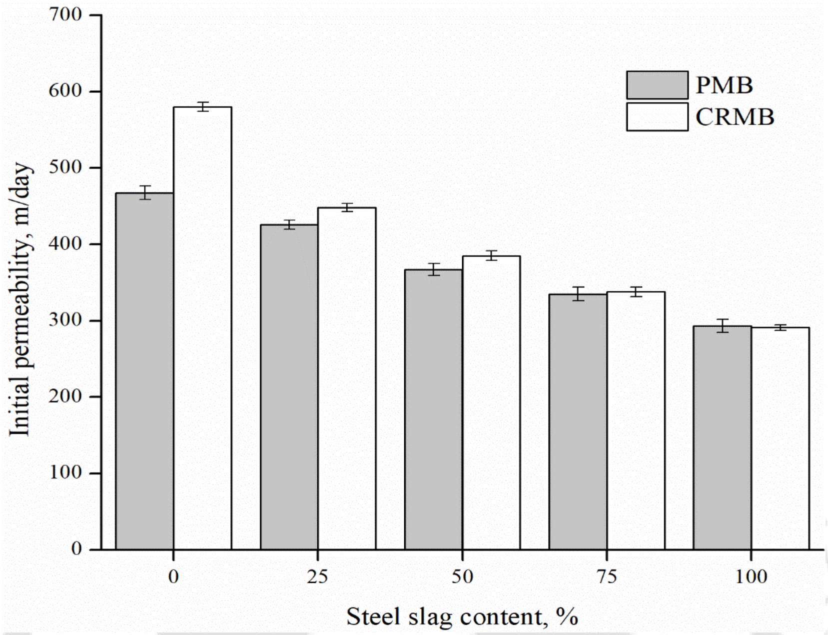


Figure 5.4: Initial permeability of OGFC mixes with various percentages of EAF slag

However, the initial permeability values of the mixes even up to 100% EAF steel slag content are much higher than the minimum requirement of 100 m/day for both PMB- and CRMB-OGFC mixes. Furthermore, it is observed that in general, mixes with CRMB binder have slightly higher initial permeability than the mixes with PMB binder. It is mainly due to the high porosity and air voids content of CRMB-OGFC mixes. The correlation observed between porosity and initial permeability for PMB-OGFC and CRMB-OGFC mixes is presented in Figures 5.5 and 5.6, respectively. The initial permeability shows a strong correlation with porosity, since porosity includes interconnected air voids only, that are accessible to water and hence is well correlated to permeability.

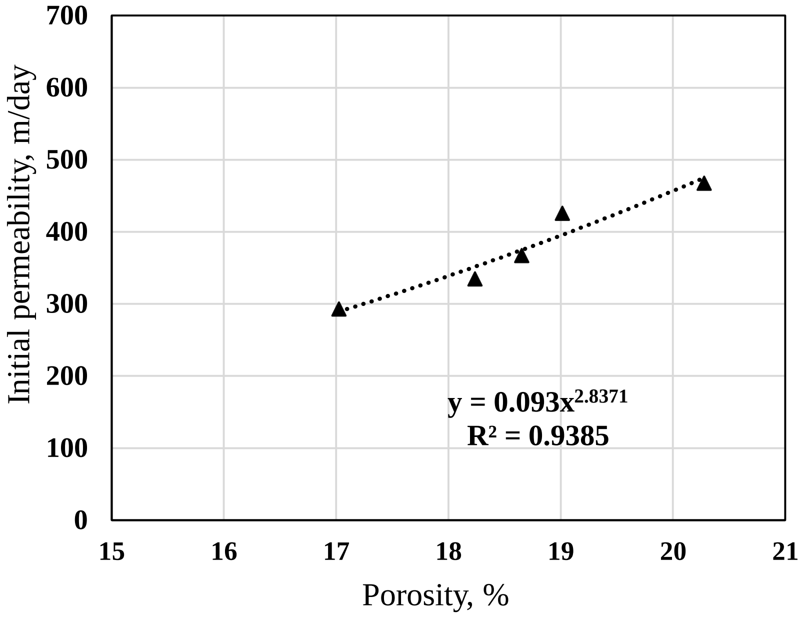


Figure 5.5: Correlation of initial permeability and porosity of PMB-OGFC mixes

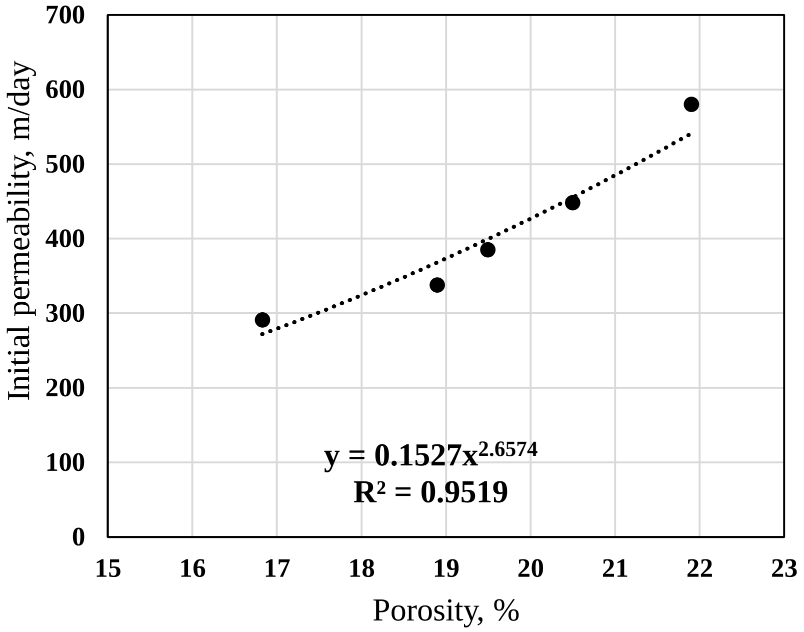


Figure 5.6: Correlation of initial permeability and porosity of CRMB-OGFC mixes

5.2.3 Clogged and De-clogged Permeability

After initial permeability measurement of OFGC mixes, fine graded sand was spread on the surface of OGFC specimens, as a clogging material, to measure the effect of clogging and the 'initial clogged' permeability was determined. This permeability is referred as 'initial clogged' because it differs from the clogged permeability obtained after the stepwise clogging (discussed in the next section), which is referred as ‘secondary clogged’ permeability. The sand was spread onto the specimen’s top face so that the surface voids were completely flush to the tips of surrounding aggregates. The variation of initial and clogged permeability with different contents of EAF steel slag in OGFC mixes for both PMB and CRMB binders is shown in Figures 5.7 and 5.8 respectively. To avoid ambiguity between the ‘initial’ and ‘initial clogged’ permeability, the latter is referred as ‘clogged’ permeability in the following discussions.

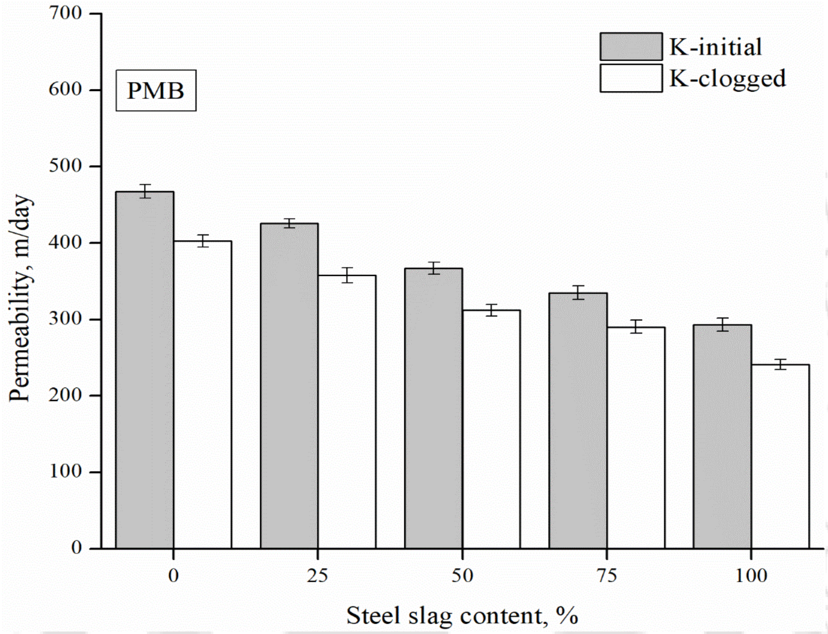


Figure 5.7: Initial and clogged permeability of OGFC mixes with PMB binder

The permeability of the OGFC mixes decreases due to clogging, which is expected as the surface voids are filled with clogging material. However, still the clogged permeability of the OGFC mixes is higher than the minimum requirement of 100 m/day as per ASTM D7064 guidelines. Even at 100% EAF steel slag content, the clogged permeability is found in the range of 241 to 236 m/day, which is quite higher than the minimum recommended value of 100 m/day for OGFC mixes. After evaluation of the initial and clogged permeabilities, de-clogging was attempted on all combinations of OGFC specimens for measurement of permeability called as ‘de-clogged permeability’, *i.e.* the permeability obtained after de-clogging. The detailed procedure for de-clogging was discussed in Section 3.3.2.2 of Chapter 3. After the de-clogging, the permeability was again determined for all OGFC mixes. Figures 5.9 and 5.10 compare the initial and de-clogged permeabilities for both PMB-OGFC and CRMB-OGFC mixes, respectively.

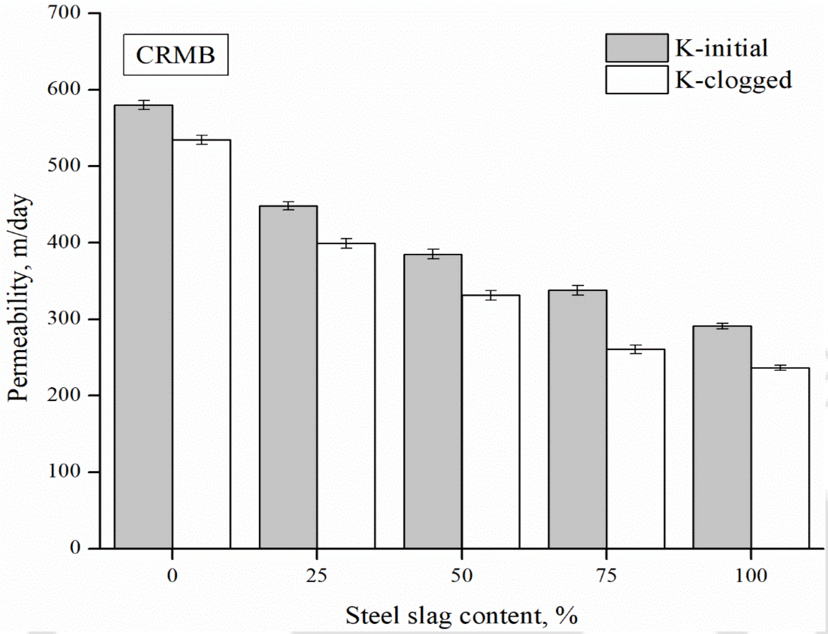


Figure 5.8: Initial and clogged permeability of OGFC mixes with CRMB binder

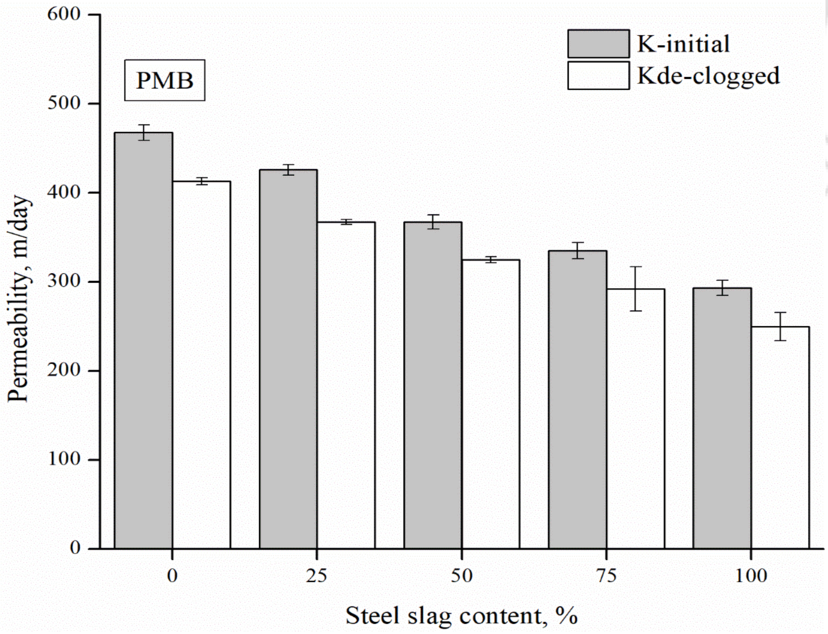


Figure 5.9: Initial and de-clogged permeability of PMB-OGFC mixes

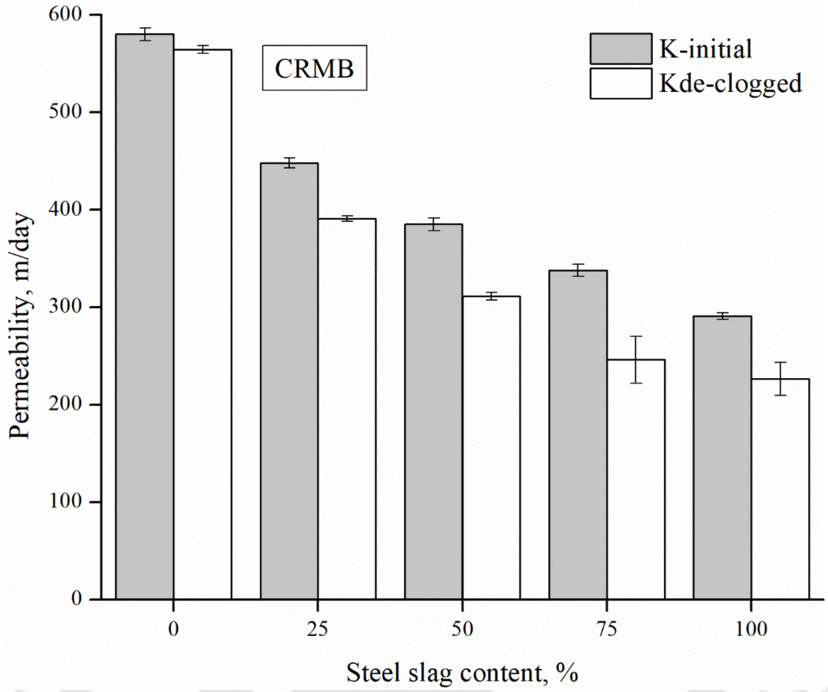


Figure 5.10: Initial and de-clogged permeability of CRMB-OGFC mixes

The de-clogged permeability is considered as benchmark for the stepwise clogging procedure performed subsequently and discussed in the next section. The de-clogged permeability is slightly lower compared to the initial permeability before clogging. After de-clogging procedure the initial permeability is not regained, which may be due to the migration of sand particles deeper into the pores and channels within the OGFC specimens, which are not removed during de-clogging. De-clogged permeability was approximately 86% and 93% (on average) of the initial permeability, respectively, for PMB-OGFC and CRMB-OGFC mixes.

5.2.4 Clogging Rates and Stepwise Clogging

Initial clogging rate ($CR_{initial}$) indicates the decrease in permeability on initial clogging. It was determined as follows:

$$CR_{initial} = \frac{K_{Clogged} - K_{initial}}{m_{sand}} \tag{5.1}$$

where, $K_{Clogged}$ is the initial clogged permeability of OGFC mixes; $K_{initial}$ is the initial permeability of OGFC mixes, and m_{sand} is the mass of the graded sand (g) added as clogging material. After de-clogging, a stepwise clogging procedure was again attempted to observe a long term effect of continuous clogging happening in field, on the permeability characteristics of OGFC mixes. The de-clogged OGFC specimens were clogged stepwise by evenly spreading 14 g graded sand in each step on top of the compacted OGFC specimen.

The variation of the permeability with stepwise clogging is shown in Figures 5.11 and 5.12 for PMB- and CRMB-OGFC mixes respectively. Each permeability values shown is an average of three measurements. It is observed that the permeability of all OGFC mixes decreases with the increase in the rate of loading of graded sand, during the stepwise clogging. As observed in Figures 5.9 and 5.10 and discussed above, the de-clogged permeability of the OGFC mixes is less compared to the initial permeability due to partial blocking of the pores, and the length of blockage tends to increase further with the incremental addition of sand. The clogged permeability can be restored to de-clogged permeability but not to the initial permeability even after de-clogging/flushing operations on the OGFC specimens. This is due to the fact that de-clogging can effectively remove the accessible top particles only but may not completely remove the ones trapped deep within the pores of the specimen. For both PMB and CRMB mixes, it is observed that the permeability decreases with an increase in percentage replacement of EAF steel slag. However, mixes up to 100% replacement satisfy the minimum requirement *i.e.* 100 m/day, except in some cases of CRMB-OGFC mixes. Watson *et al.* (2018) recommended that the permeability of OGFC mixes should be at least 50 m/day. All combination of OGFC mixes including control mixes had permeability higher than 50 m/day even after secondary stepwise clogging.

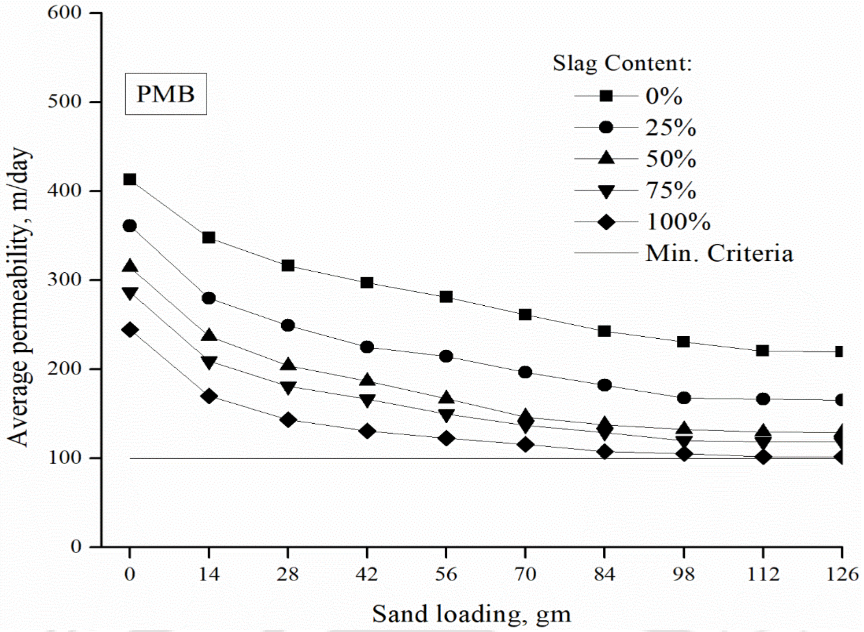


Figure 5.11: Average permeability reduction curves resulting from stepwise clogging procedure for OGFC mixes with PMB binder

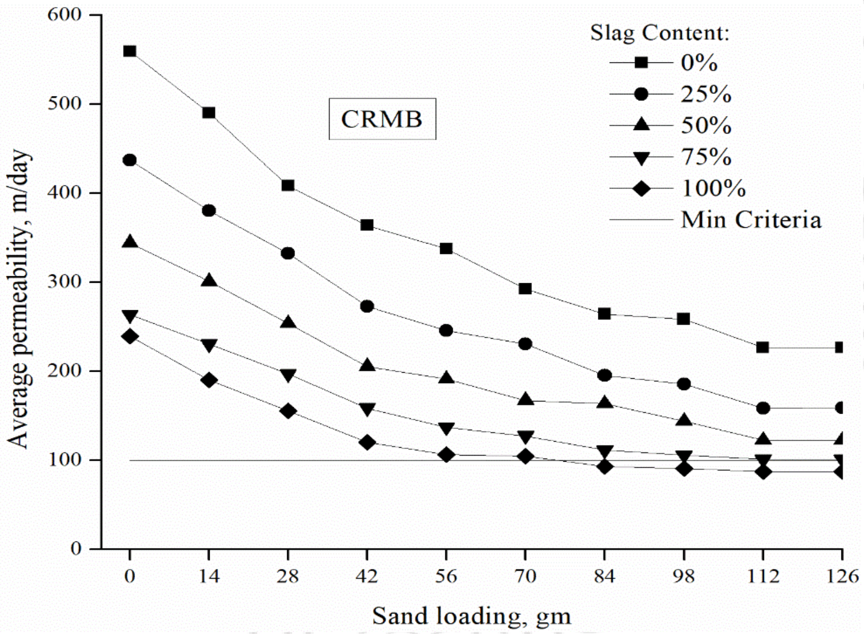


Figure 5.12: Average permeability reduction curves resulting from stepwise clogging procedure for OGFC mixes with CRMB binder

Following the stepwise clogged permeability evaluation, the parameter 'secondary clogging rate ($CR_{secondary}$)' is determined as the slope of the permeability curve shown in Figures 5.11 and 5.12. $CR_{secondary}$ indicates the reduction in permeability for unit addition of the clogging material (graded sand) in the stepwise clogging procedure. The secondary clogging rate ($CR_{secondary}$) is compared to the initial clogging rate ($CR_{initial}$) for every combination of OGFC mixes, and the results are shown in Figures 5.13 and 5.14 for PMB-OGFC and CRMB-OGFC mixes.

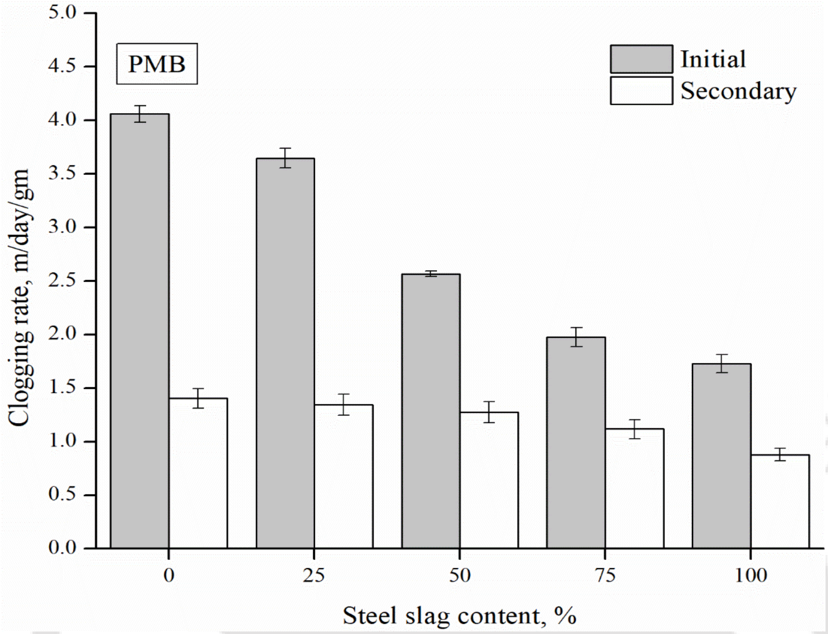


Figure 5.13: Initial and secondary clogging rates of OGFC mixes with PMB binder

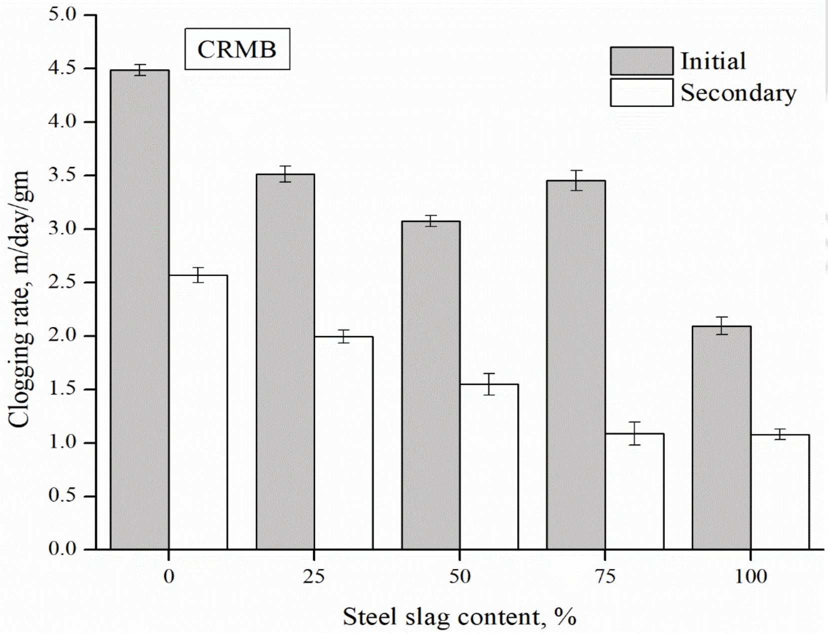


Figure 5.14: Initial and secondary clogging rates of OGFC mixes with CRMB binder

A significant difference between the initial and secondary clogging rate is observed for all combinations of OGFC mixes. It is found that the initial clogging rate is much higher than the secondary clogging rate, which indicates that the decrease in permeability due to initial clogging is higher than due to secondary (stepwise) clogging. A similar observation was found by other investigators (Fwa *et al.*, 1999; Tan *et al.*, 2003; Suresha *et al.*, 2010b; Martin *et al.*, 2013; Chen *et al.*, 2015). The secondary clogging rate is much lower (about half) than the initial clogging rate. During the design and planning of OGFC courses, the secondary clogging rate is a vital parameter as it simulates the clogging and de-clogging cycles of OGFC pavement in practice. Hence, it can be considered as an effective clogging rate. It is further observed that the primary clogging rate is around 50% higher than the secondary clogging rate in case of OGFC mixes with both PMB and CRMB binders.

5.3 FRICTIONAL CHARACTERISTICS OF OGFC MIXES WITH EAF STEEL SLAG

5.3.1 Frictional Characteristics: British Pendulum Number

Skid resistance or frictional resistance is a characteristic of the road surface that enables a driver to command longitudinal and lateral control of vehicle over the road surface and thus it directly quantifies the safety aspects of a road surface. In this study, frictional characteristics of OGFC mixes with different contents of EAF steel slag were determined in terms of British pendulum number (BPN) using British pendulum tester in accordance with ASTM E303 (2013), under both dry and wet conditions.

The BPN tests results under dry (BPN_{dry}) and wet (BPN_{wet}) conditions, for OGFC mixes at different contents of EAF steel slag for PMB and CRMB binders are presented in Figures 5.15 and 5.16, respectively. Both BPN_{dry} and BPN_{wet} values are found to increase with an increase in the EAF steel slag content. The improvement in skid resistance with increase in slag content is attributed to high angularity, high abrasion resistance and rough surface texture of the EAF steel slag when compared to the natural aggregates, as also observed from the physical properties shown in Table 3.2 of Chapter 3.

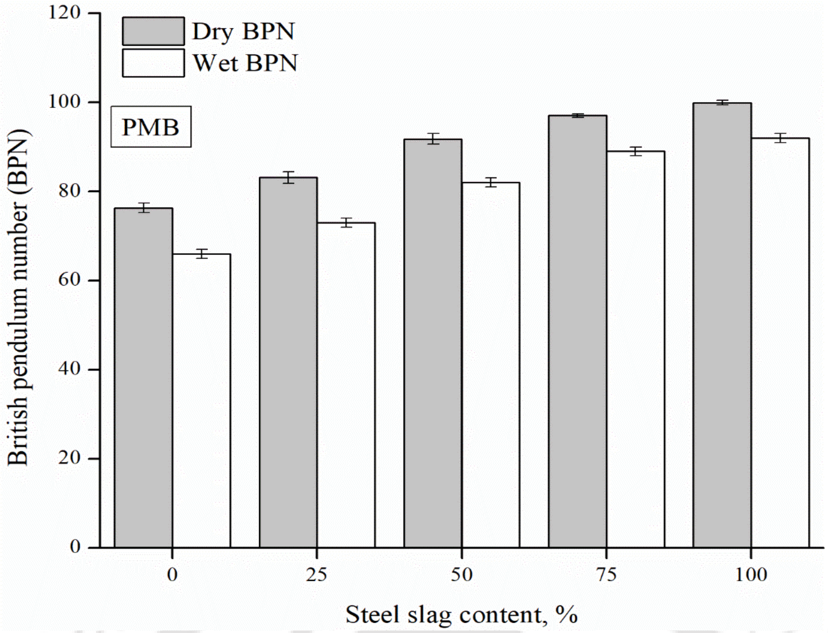


Figure 5.15: British Pendulum Number (BPN) of Mixes with PMB Binder

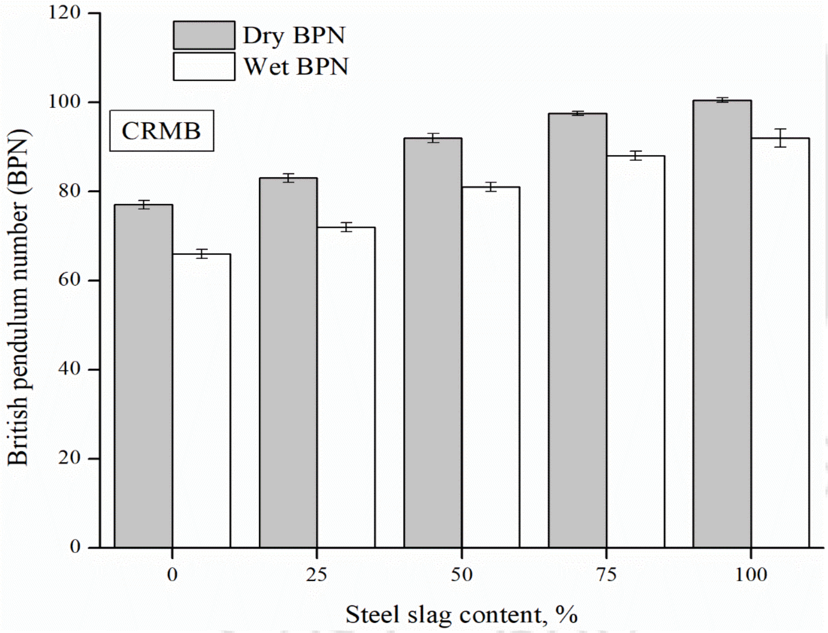


Figure 5.16: British Pendulum Number (BPN) of mixes with CRMB binder

These results are in agreement with earlier studies showing that desirable properties of steel slag, such as hardness, abrasion resistance, shape, texture, angularity, greatly influence pavement frictional characteristics (Haddock and O'Brien, 2013; Kogbara *et al.*, 2016). OGFC mixes with CRMB binder show slightly higher BPN values compared to mixes with PMB binder, which may be due to the moderately higher air void contents and a resultant rough texture in CRMB-OGFC mixes. Tables 5.1 and 5.2 show the results of ANOVA performed on frictional performance parameters in terms of dry BPN and wet BPN results at 5% significance level. Steel slag content (SC) is found to have statistically significant effect on the dry and wet BPN values.

Table 5.1: ANOVA results for dry BPN of OGFC mixes

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type (BT)	1	1.019	0.336	No
Slag content (SC)	4	230.301	<0.001	Yes
BT:SC	4	0.041	0.996	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	NS		S	S	S	
100%	S	S	S	NS	S	S	S	NS

Note: 'S': Significant; 'NS': Not Significant; 'DF': Degree of Freedom

Table 5.2: ANOVA results for wet BPN of OGFC mixes

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type	1	0.692	0.425	No
Slag content	4	181.04	<0.001	Yes
BT:SC	4	0.115	0.974	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				NS			
50%	S	S			S	S		
75%	S	S	S		S	S	NS	
100%	S	S	S	NS	S	S	S	NS

Note: 'S': Significant; 'NS': Not Significant; 'DF': Degree of Freedom

Binder type (BT) is found to have no significant effect on BPN values. Non-significant interaction between the two factors (binder type and slag content) indicates that the both dry and wet BPN values follow a similar trend for varying slag contents for both binder types. Multiple comparison results show that substitution of natural aggregates by steel slag leads to significant changes in the BPN values (in comparison to control mixes).

5.3.2 Frictional Performance of OGFC Mixes with EAF steel slag at Variable Water Depth

Although OGFC mixes are designed for high permeability to avoid water from standing on the surface, however to see the effect of any possible water film on its frictional characteristics, BPN values were measured for a theoretical water depth varying from 0 to 1 mm with an increment of 0.1 mm at all contents of EAF steel slag with both binders. Quantity of water to produce a particular theoretical water depth was obtained by the product of top surface area of the specimen and the required water depth. The obtained quantity/volume was evenly sprayed over the top surface of the specimen. The variation of BPN with an increase in water film/depth as well as EAF slag content for both PMB-OGFC and CRMB-OGFC mixes are presented in Figures 5.17 and 5.18, respectively. The BPN values of OGFC mixes, as expected, decrease with the increase in theoretical water depth. It is observed that the OGFC mix that exhibits highest BPN value in dry condition maintains its hierarchy in wet condition as well, with a mild fall in the BPN values from dry to wet conditions.

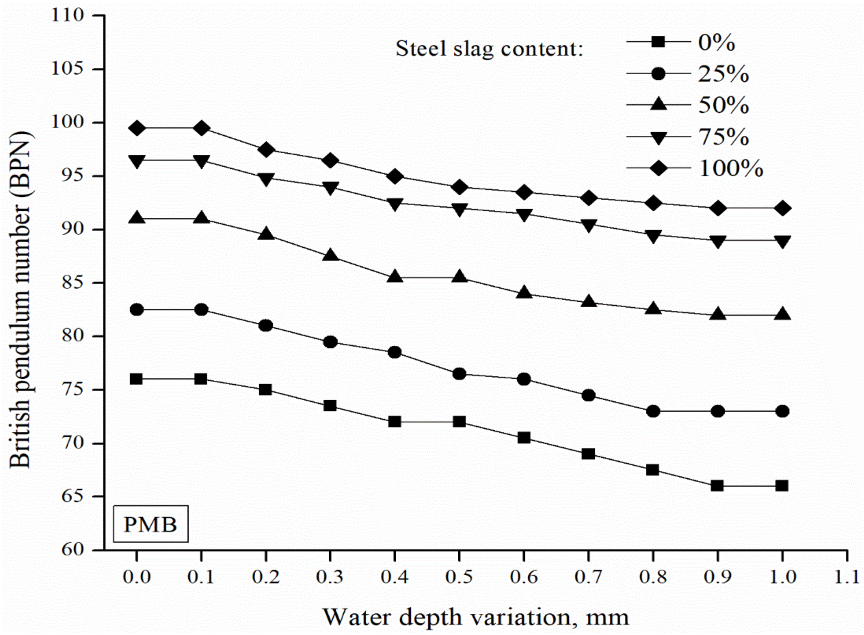


Figure 5.17: Variation of BPN of PMB-OGFC mixes with water depth

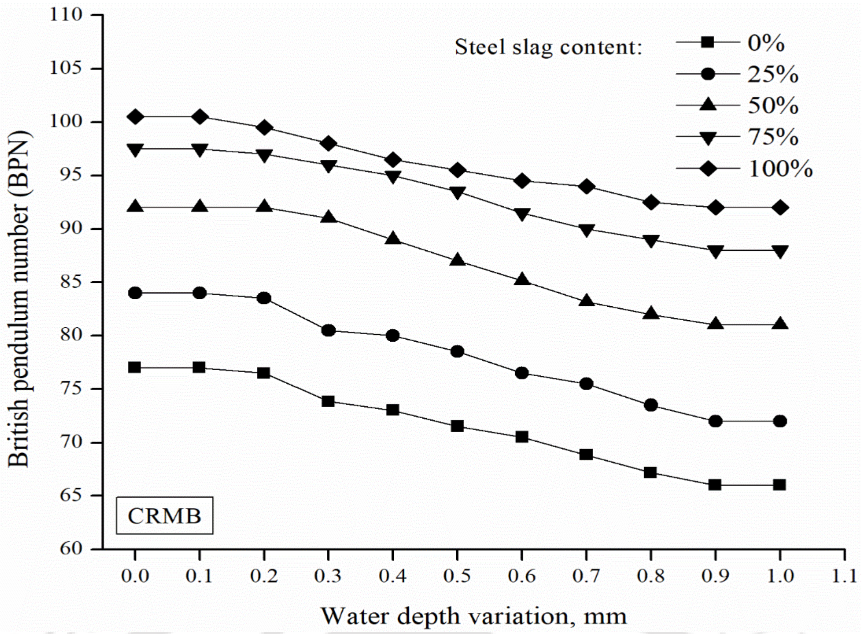


Figure 5.18: Variation of BPN of CRMB-OGFC mixes with water depth

Frictional performance in terms of BPN of OGFC mixes decreases with the increase in theoretical water depth regardless of the binder type and increase in percentage replacement of the coarse natural aggregate with EAF steel slag. It is observed that OGFC mixes containing CRMB binder show slightly higher BPN than the corresponding mixes with PMB binder (Figure 5.19). This is most likely due to the slightly higher air voids content of OGFC mixes with CRMB binder compared to those with PMB binder. Higher air voids contents leads to higher macro-texture and more aggregate surfaces being exposed to the surface leading to higher asperities and frictional resistance.

Table 5.3 presents the results of ANOVA performed on BPN results of OGFC mixes (with varying contents of EAF steel slag) at different theoretical water depths for both CRMB and PMB binders. Based on the ANOVA, steel slag content (SC), theoretical water depth (TWD) and binder type (BT) are found to have significant effect on the BPN values. A higher F-value for slag content indicates that it has highest influence on BPN values followed by TWD and binder type. Non-significant interaction (BT:SC, BT:TWD and SC:TWD) indicates that BPN values follow a similar trend for varying slag contents and TWD for both binder types. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the BPN values in comparison to control mixes with natural aggregates alone.

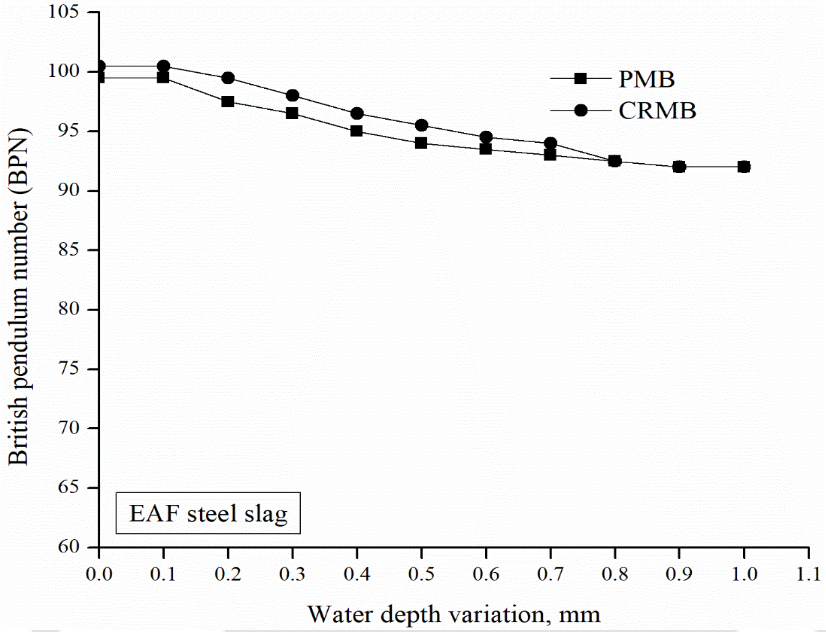


Figure 5.19: Variation of BPN with binder type and water depth for OGFC mixes with 100% EAF slag

Table 5.3: ANOVA results for BPN of OGFC mixes

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type (BT)	1	14.33	0.0002	Yes
Slag content (SC)	4	1897.54	<0.001	Yes
TWD	10	114.845	<0.001	Yes
BT:SC	4	0.382	0.821	No
BT:TWD	10	2.013	0.585	No
SC:TWD	40	0.583	0.973	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	S	S	S	S	S	S

Note: 'S': Significant; 'NS': Not Significant; 'DF': Degree of Freedom, 'TWD': theoretical water depth

For frictional evaluation phase of the study, a small extension of the work, beyond the scope of the objectives defined, was made to compare friction properties of OGFC mixes with those of dense graded bituminous mixes. Bituminous concrete (BC) mix with 13.2 mm NMAS, a commonly used dense graded mix in India, was selected for comparison with OGFC mixes. BC mixes were prepared only at 0% and 100% replacement of natural aggregate with EAF steel slag with both PMB and CRMB binders used in OGFC mixes. From the results of BPN tests presented in Figures 5.20 and 5.21, as expected it is found that the BPN values of dense graded bituminous concrete (DGBC) are lower than those of OGFC mixes.

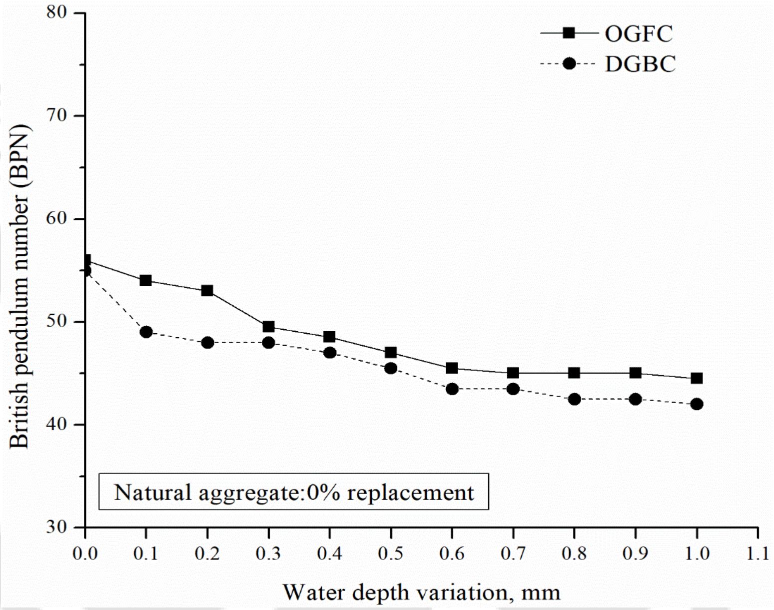


Figure 5.20: Variation of BPN with mix type and water depth

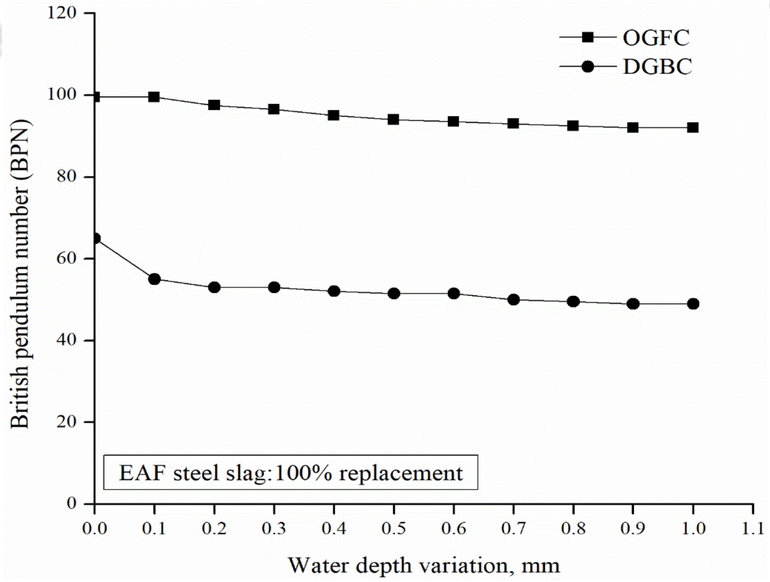


Figure 5.21: Variation of BPN with mix type and water depth

Increase in BPN values with incorporation of EAF steel slag is quite significant in case of OGFC mixes compared to DGBC mixes. This encourages the use of EAF steel slag in OGFC mixes to utilise the desirable characteristics of the slag in a more efficient manner. Decrease in BPN values with the introduction of water, *i.e.* the rate of fall in BPN with water depth is also high in the case of DGBC mixes compared to OGFC mixes.

5.3.3 Texture Depth (TD) Evaluation

For texture depth evaluation, slabs (dimensions: 152×152×50 mm) of OGFC mixes with different EAF steel contents, were first prepared and then tested by the volumetric technique as per ASTM E965 (2015) guidelines. To evaluate texture depth, a known volume of sand was spread over test surface in the form of a circle with the help of a spreading tool. The spreading was continued till the surface voids were filled flush with the tips of surrounding aggregates. Using the volume of sand used and the area of the circular patch, the texture depth was determined. The texture depth values found for OGFC mixes at different EAF steel slag contents with both PMB and CRMB binders are presented in Figure 5.22.

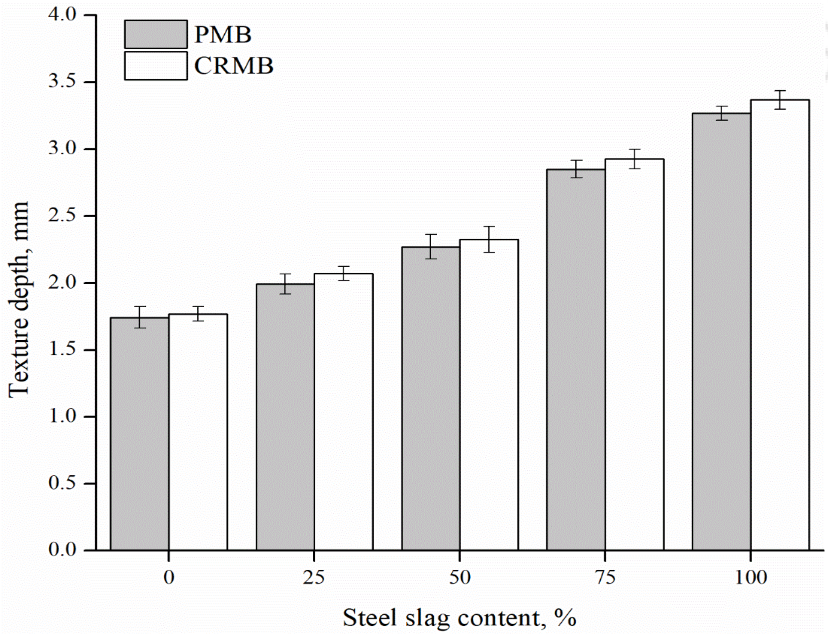


Figure 5.22: Texture depth of OGFC mixes

It is observed that the TD values of OGFC mixes increase with an increase in EAF steel slag content. This is likely due to higher angularity and rough surface texture of the EAF slag aggregates, which greatly influence pavement surface texture depth (Hall *et al.*, 2009). Figures 5.23 and 5.24 show the variation of wet and dry BPN with TD at varying EAF slag contents for PMB and CRMB binder respectively.

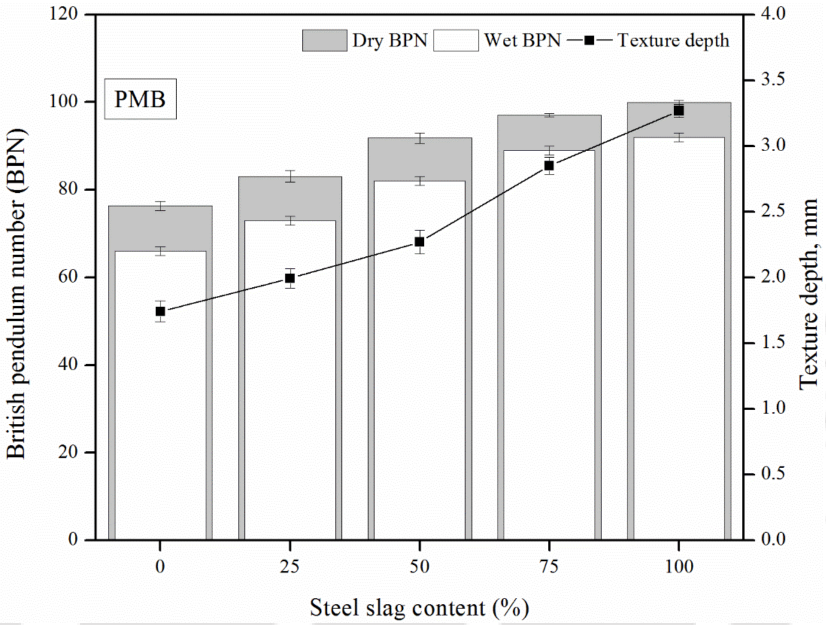


Figure 5.23: Average dry BPN and TD of bituminous mixes with PMB binder

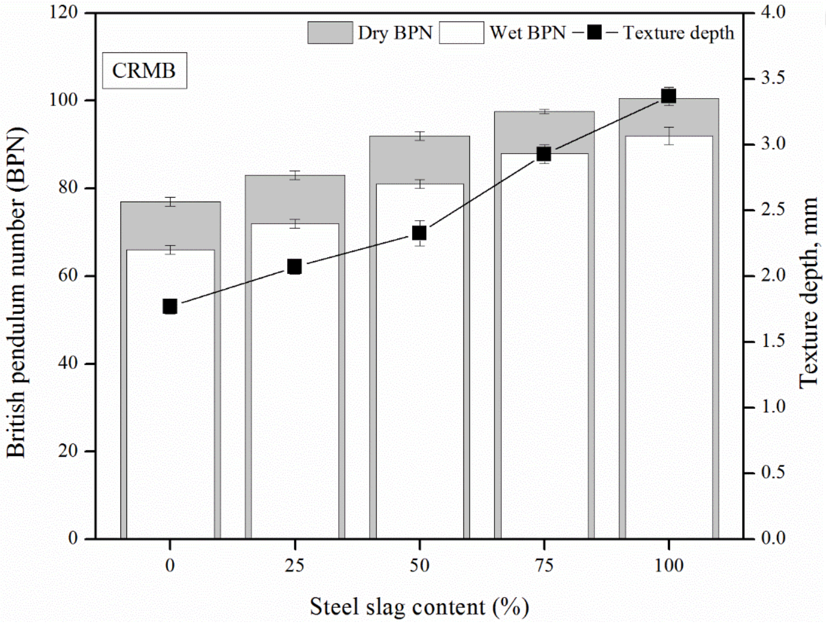


Figure 5.24: Average dry BPN and TD of bituminous mixes with CRMB binder

Both BPN and texture depth values show an increase with increase in EAF slag content. Higher texture depth induces higher deformation of rubber slider of the British pendulum tester, thus increasing the hysteresis component (related to the energy lost due to deformation of vehicle tyre) of friction. This results in superior frictional performance of mixes with higher texture depth. Thus, a higher texture depth can also be perceived in terms of improved frictional performance.

Table 5.4 presents the results of ANOVA performed on texture depth results. Based on the ANOVA, steel slag content and binder type are found to have significant effect on texture depth. A higher F-value for slag content indicates that it has higher influence on texture depth as compared to binder type. Non-significant interaction between the two factors (binder type and slag content) indicates that texture depth values follow a similar trend for varying slag contents for both binder types. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the texture depth values in comparison to control mixes.

Table 5.4: ANOVA results for TD of OGFC mixes

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type (BT)	1	190.965	<0.001	Yes
Slag content (SC)	4	13755.4	<0.001	Yes
BT:SC	4	1.5	0.364	No

Multiple comparisons based on Tukey’s procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	S	S	S	S	S	S

Note: ‘S’: Significant; ‘NS’: Not Significant; ‘DF’: Degree of Freedom

5.3.4 Relationship between BPN and Texture Depth

From the texture depth and BPN results of OGFC mixes, it is found that texture depth plays an important role in developing friction between a bituminous surface and a rubber element grazing over it, *i.e.* higher texture depth enhances the frictional performance. To comprehend the relationship between texture depth and friction, texture depths are plotted against corresponding BPN_{Dry} and BPN_{Wet} values (Figure 5.25). A good linear relationship is observed between texture depth and BPN in both dry and wet conditions with R^2 of 0.91 in dry condition and 0.93 in wet condition as seen from Figure 5.25. This indicates that surfaces with higher texture depth are expected to have higher friction coefficients/resistance.

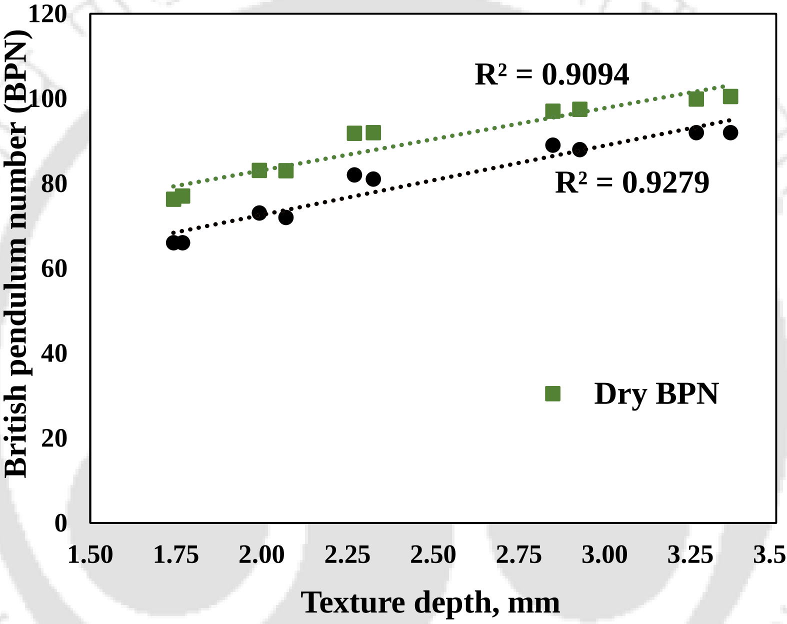


Figure 5.25: BPN vs texture depth

5.4 SUMMARY

This chapter discussed the influence of varying percentages of coarse natural aggregate replacement by EAF steel slag on the permeability characteristics, clogging characteristics and frictional characteristics of OGFC mixes. The OGFC mixes were prepared at five EAF steel slag contents as coarse aggregate replacement (0, 25, 50, 75 and 100%) and two modified binders (PMB and CRMB). The results of permeability and clogging characteristics in terms of porosity, initial permeability, clogged permeability, de-clogged permeability, and permeability with stepwise clogging were discussed. Frictional characteristics were evaluated in terms of dry BPN, wet BPN, texture depth and BPN at varying water depths.

Permeability of the OGFC mixes increased with an increase in porosity for all combination of mixes. Permeability values of EAF slag incorporated OGFC mixes were lower than the OGFC mixes with natural aggregates alone (control mixes), due to the moderately lower porosity in case of OGFC mixes with EAF slag. The mixes with CRMB binder showed slightly higher permeability when compared to mixes with PMB binder. With the initial application of graded sand as a clogging material, a quick drop in the permeability was observed. After the de-clogging process, the permeability was restored to approximately 86% and 93% of the initial permeability for PMB-OGFC and CRMB-OGFC mixes respectively. The secondary clogging rate for the OGFC mixes at all EAF steel slag contents was about 50% of the initial clogging rate. OGFC mixes with EAF steel slag showed higher frictional resistance and texture depth. A good correlation was observed between the texture depth and BPN values of OGFC mixes. Statistical analyses showed that EAF steel slag content had significant effect on permeability, frictional characteristics and texture depth of OGFC mixes.

Chapter 6

PERFORMANCE CHARACTERISTICS OF OGFC MIXES WITH EAF STEEL SLAG

6.1 INTRODUCTION

The main motive behind using EAF steel slag as a replacement of coarse natural aggregates in OGFC mixes is: to lower down the consumption of natural aggregates; to reduce environmental impact due to large scale mining and quarrying of natural aggregates; and to minimise the deposition of steel slag in large spaces/open lands, without compromising their performance. Due to high percentage of air voids, OGFC mixes may face performance problems, more often related to ravelling and permeability. A careful mix design may be a starting step to address some of the performance related problems. From Chapters 4 and 5, it is apparent that OGFC mixes containing EAF steel slag are able to meet and even improve the design parameters in terms of air voids content, draindown, abrasion loss in unaged and aged conditions, and the performance parameters in terms of permeability and frictional characteristics. The international standard (ASTM D7064) prescribes acceptance criteria for the design of OGFC mixtures in terms of air voids content, binder draindown, unaged abrasion loss and aged abrasion loss. However, only conformity to the design specifications may not be good enough to ensure that the constructed facilities will perform satisfactorily. It is therefore also quite essential to evaluate various performance characteristics of OGFC mixtures with industrial by-product EAF steel slag. This chapter presents results of evaluation of OGFC mixes in terms of their performance properties, which include resistance to moisture-induced damage, permanent deformation, stiffness modulus and fatigue characteristics.

OGFC mixtures are generally characterised by a high percentage of air voids that helps to: ease the surface water drain off; improve skid resistance and visibility; and minimise tyre-pavement noise levels. Due to high air void content, quick oxidation of binder film and moisture intrusion may occur that may have an adverse influence on the structural durability of bituminous mixes because of the possible/probable damage to the cohesive and adhesive bonds (Caro *et al.*, 2008; Hesami *et al.*, 2015). Cohesive failure is defined as the loss of strength of the binder film, whereas adhesive failure is demarcated as the loss of bond between aggregate and bitumen interface. Among the two failures, adhesive failure is accredited as a more common failure in the bituminous pavements (Hunter and Ksaibati, 2002; Kumar and Anand, 2011; Caro *et al.*, 2008). Many researchers have studied the moisture susceptibility of bituminous mixes and have reported that the aggregate type plays a significant role in moisture damage (Zhang *et al.*, 2018). Moisture damage is a quite common distress in bituminous mixes, and leads to many concurrent surface distresses such as ravelling, shoving, cracking, corrugations, rutting *etc*. Worldwide, a huge budget is spent annually to renovate the pavement distresses initiated by the unfavourable effects of moisture on bituminous mixes. Evaluation of the effect of aggregate type on the performance and durability of an asphalt mixture for moisture damage is therefore quite important. Further, OGFC mixes are specially designed to allow the flow of water through them and it is thus more important to examine their resistance to moisture-induced damage.

This chapter presents the results and analyses of performance properties of OGFC mixes including resistance to moisture-induced damage, permanent deformation, stiffness modulus and fatigue life. The detailed experimental plan followed for moisture susceptibility evaluation was shown in Figure 3.21 whereas the detailed experimental plan for other performance properties was presented in Figure 3.26 of Chapter 3. OGFC mixes were prepared with five percentages of EAF steel slag: 0, 25, 50, 75 and 100% and two types of modified binders: polymer modified binder (PMB) and crumb rubber modified binder (CRMB). The moisture susceptibility parameters were evaluated through modified Lottman test, wet abrasion loss test, stripping test, and modified boiling water test. Rutting performance of the OGFC mixes were evaluated through static creep, dynamic creep, and indirect tensile stiffness modulus (ITSM) tests. Hamburg wheel tracking test was also conducted on OGFC mixes to evaluate the combined effect of rutting and moisture. The static creep test was used to determine the permanent deformation characteristics of OGFC mixtures subjected to a constant load of 100 kPa. Dynamic creep evaluated the permanent deformation characteristics of OGFC mixtures under dynamic load (100 kPa) with square waveform. Static and dynamic creep tests were performed at 40 °C. The ITSM test was conducted at 20 °C to evaluate the stiffness moduli of OGFC mixes under a haversine load waveform. Hamburg wheel tracking test was performed at 40 °C under water using a reciprocating steel wheel carrying a load of 705 N. Indirect tensile fatigue test (ITFT) was performed at 20 °C to assess the fatigue life of OGFC mixes subjected to a repeated haversine load.

6.2 PERFORMANCE PROPERTIES OF OGFC MIXES WITH EAF STEEL SLAGS

6.2.1 Moisture Susceptibility of OGFC Mixes

Presence of moisture causes damage to the adhesion bond between bitumen and aggregate surface and accelerates the progress of distresses such as cracking, ravelling and potholes (Li *et al.*, 2015). It is highly important to evaluate moisture damage properties of OGFC mixes with EAF steel slag as they are designed for quick drainage benefits and are in frequent contact with water. In the present study the moisture susceptibility of OGFC mixes was assessed by four different test protocols: (1) modified Lottman test (2) wet abrasion loss (WAL) method, (3) static immersion test, and (4) modified boiling water test.

6.2.1.1 *Modified Lottman test results*

Modified Lottman test determines the loss of tensile strength of a bituminous mixture due to interaction of water. This test determines the indirect tensile strength (ITS) of both unconditioned and conditioned specimens. For conditioning, the specimens are subjected first to vacuum saturation followed by freeze-thaw cycles. The ratio of ITS values of conditioned specimens to unconditioned specimens is termed as tensile strength ratio (TSR). This test was performed using the guidelines stipulated in AASHTO T 283 (2003) and ASTM D7064 (2013).

Figure 6.1 presents the results of ITS for PMB-OGFC mixes measured in dry (unconditioned) and wet (moisture conditioned) states at various EAF slag substitution percentages. ITS for wet specimens was evaluated after subjecting them to 1 and 5 freeze-thaw (FT) cycles. Figure 6.2 shows the same parameters for CRMB-OGFC mixes. The mean dry ITS of all combinations of OGFC mixes ranged from 462 to 608 kPa and 445 to 601 kPa respectively for PMB- and CRMB-OGFC mixes. The average wet ITS after one freeze-thaw cycle for all OGFC mixes ranged from 382 to 543 kPa and 367 to 533 kPa respectively for PMB- and CRMB-OGFC mixes while wet ITS after five freeze-thaw cycles ranged from 367 to 537 kPa and 352 to 521 kPa for PMB- and CRMB-OGFC mixes, respectively. PMB-OGFC and CRMB-OGFC mixes with EAF steel slag show higher ITS values under both dry and wet conditions compared to the control mixes (with 0% EAF steel slag). Higher ITS values obtained for OGFC mixes on EAF slag substitution indicates higher cohesive strength of mixes with EAF steel slag than the mixes with natural aggregates.

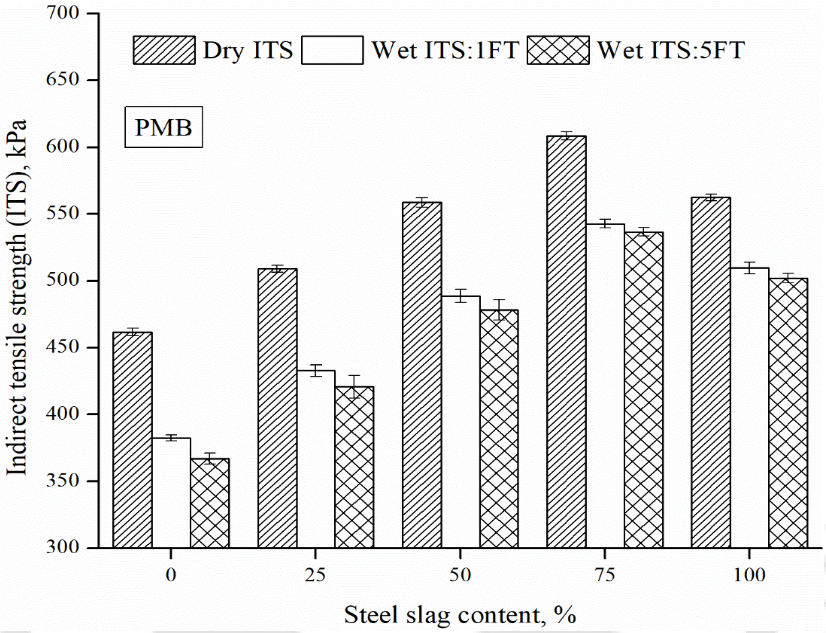


Figure 6.1: Variation of ITS results of PMB-OGFC mixes

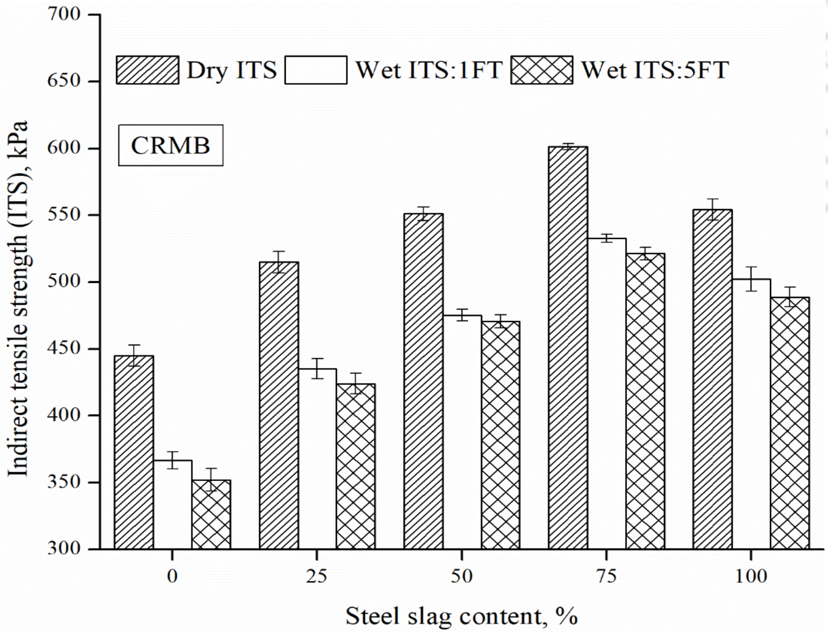


Figure 6.2: Variation of ITS results of CRMB-OGFC mixes

This can be attributed to the enhanced aggregate structure of the EAF steel slags compared to the natural stone aggregates. Improvement in ITS values for dense graded and gap-graded asphalt mixes with EAF steel slag has also been reported previously (Asi *et al.*, 2007; Oluwasola *et al.*, 2015). It is further observed that the dry and wet ITS values increase till 75% EAF slag content and then decrease with the additional increment in EAF steel slag content. This is possibly due to the variation of design air void content and residual binder content, as relatively high air void percentages and greater residual binder may reduce the strength of the mixture (Teoh, 2008). Among all combinations of mixes, the mixes corresponding to 75% replacement and 0% replacement represent the upper and the lower extremes of both dry ITS and wet ITS values for both PMB- and CRMB-OGFC mixes.

It is seen that all combinations of mixes (at five slag substitution percentages and both modified binders) show higher ITS in the dry condition compared to the wet condition. The continuity of pores in the mixes creates spaces for water immersion. Hence, when ice forms inside the cavities of the OGFC mix during freezing procedure, it may consequently form cracks. OGFC mixes with EAF slag show improved resistance to moisture damage after the wet conditioning process compared to the mix with natural aggregates. The greater specific gravity of EAF steel slag results in the presence of higher residual binder content in the lithic skeleton. This assures adequate covering of aggregates with a thicker film of asphalt binder and consequently more effective fortification against water. Visual observations of fractured faces of conditioned OGFC specimens during ITS testing also didn’t reveal any stripping for all percentage replacements with PMB and CRMB modified binders.

The variation of TSR values with respect to increase in EAF steel slag content for both PMB and CRMB binders is presented in Figure 6.3. The TSR values improved with increase in the EAF steel slag content. The improvement in resistance to stripping and moisture damage may be explained by EAF slag’s irregular surface texture and hydrophobic nature that permits the asphalt binder to penetrate deeper in the aggregate surface and form more stronger asphalt-aggregate bond.

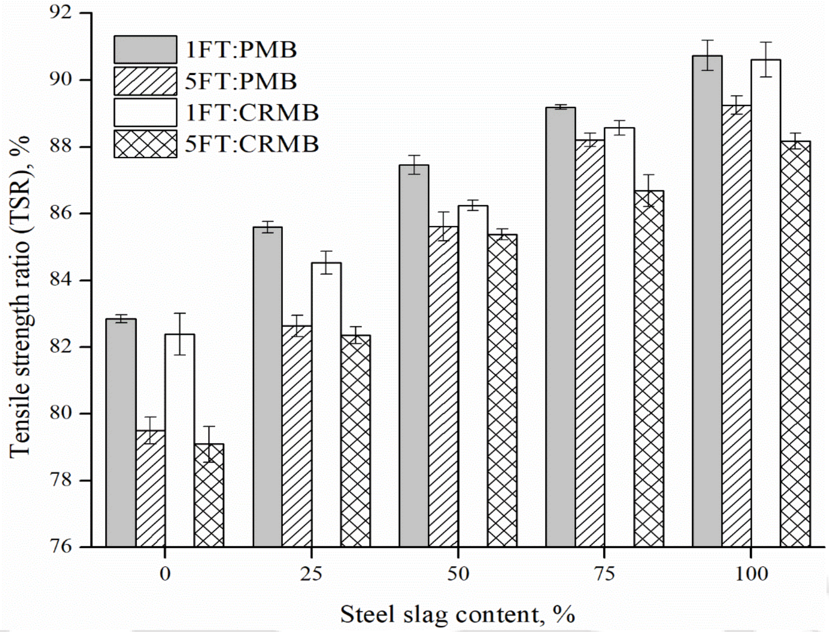


Figure 6.3: Results of tensile strength ratio of OGFC mixes

In terms of chemical composition of the aggregates highlighted in Table 3.5, CaO/SiO_2 ratio was 2.404 and 0.162 for EAF steel slag and natural aggregates, respectively. The higher CaO/SiO_2 ratio for EAF steel slag provides higher aggregate-binder adhesion than the natural aggregates (Xie *et al.*, 2012). It can be seen that the TSR values for all combinations of OGFC mixes with EAF steel slag and the two binders *i.e.* PMB and CRMB, are well above 80%, the lower limit recommended by ASTM D7064 specifications after 5 FT cycles. PMB and CRMB control mixes (mixes with natural aggregate) did not satisfy the TSR requirement after 5 FT cycles. Watson *et al.* (2004) also developed a performance-based mix design for OGFC mixtures. They recommended that the TSR should be at least 70% for OGFC mix, meanwhile the conditioned tensile strength should be greater than 345 kPa. Based on this criterion, all combination of OGFC mixtures including control mixes met the requirement.

ANOVA was performed on two Modified Lottman test parameters (wet ITS and TSR values) to investigate the effect of three factors: slag content, binder type, and FT cycle. The ANOVA results of wet ITS and TSR values are presented in Tables 6.1 and 6.2. Steel slag content, binder type and FT cycle are found to have statistically significant effect on the wet ITS and TSR values. A higher F-value for slag content in both cases (Table 6.1 and 6.2), indicates that it has the highest influence on the both wet ITS and TSR followed by FT cycle and binder type.

Table 6.1: ANOVA results for wet ITS values

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type (BT)	1	8.743	0.005	Yes
Slag content (SC)	4	348.6	<0.001	Yes
FT cycle	1	11.7	0.001	Yes
BT:SC	4	1.03	0.406	No
BT:FT	1	0.015	0.904	No
FT:SC	4	0.172	0.951	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	S	S	S	S	NS	S

Note: 'S': Significant; 'NS': Not Significant; 'DF': Degree of Freedom

Table 6.2: ANOVA results for TSR values

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type (BT)	1	29.11	<0.001	Yes
Slag content (SC)	4	574.39	<0.001	Yes
FT cycle	1	269.05	<0.001	Yes
BT:SC	4	0.638	0.638	No
BT:FT	1	0.001	0.978	No
FT:SC	4	0.745	0.549	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	S	S	S	S	S	S

Note: 'S': Significant; 'NS': Not Significant; 'DF': Degree of Freedom

Non-significant interactions between the factors (binder type and slag content; binder type and FT cycle; FT cycle and slag content) indicate that the wet ITS values follow a similar trend for varying slag contents for both binder types and FT cycles. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the wet ITS and TSR values (in comparison to control mixes).

6.2.1.2 Wet abrasion loss test results

The wet abrasion loss (WAL) test was used as another approach to measure the resistance to moisture induced damage of compacted OGFC mixes. The test was carried as per South African Code (Sabita Manual, 1995) at a test temperature of 25 °C. In order to evaluate the wet abrasion loss of the OGFC specimens, the OGFC specimens were subjected to moisture conditioning in the same manner as used in modified Lottman test for both 1 and 5 FT cycles. After moisture conditioning, the resistance to abrasion of the wet/conditioned specimens, were evaluated by means of Cantabro abrasion test. The variation of WAL values with slag percentage for mixes with both binders is presented in Figure 6.4.

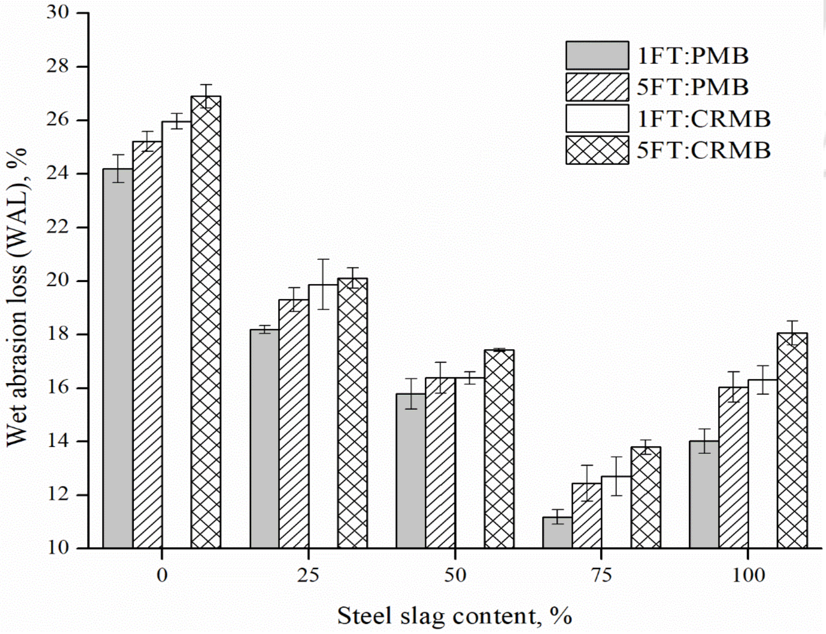


Figure 6.4: Results of wet abrasion loss (WAL) test of OGFC mixes

It can be observed that the percentage WAL of OGFC mixes decreases with increase in the percentage replacement of EAF steel slag up to 75% and then it slightly rises with a further addition of the EAF steel slag. Similar observations are found for mixes with both modified binders. Abrasion loss is less in EAF steel slag-OGFC mixes due to the improved bond strength. The increase in abrasion loss at 100% EAF slag replacement can be explained by the variation in stone-on-stone contact criteria of the designed OGFC mixes with steel slag replacement (Figure 6.5) as OGFC mixes with a lower VCA_{mix}/VCA_{drc} ratio represent improved wet abrasion loss performance compared to mixes with a higher VCA_{mix}/VCA_{drc} ratio (Suresha *et al.*, 2009a).

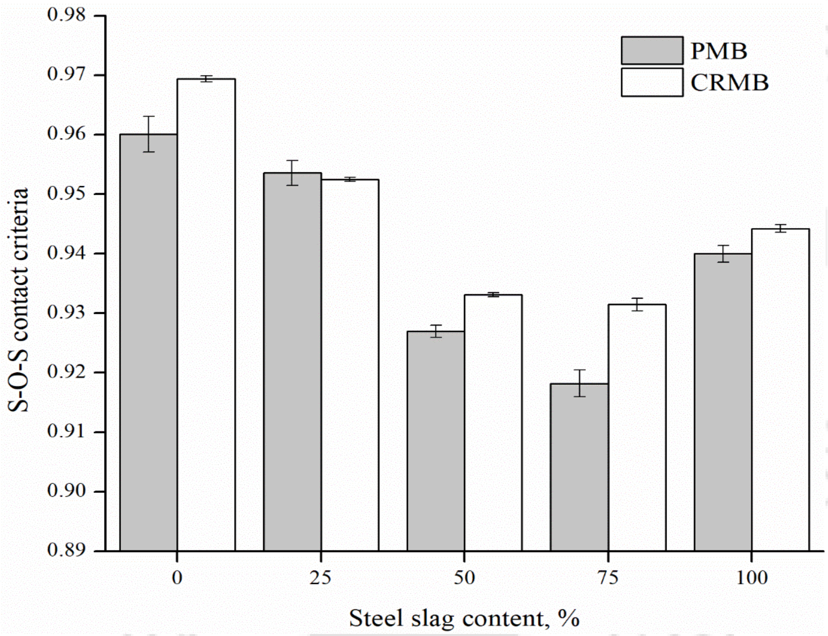


Figure 6.5: Variation of S-O-S contact criterion in terms of VCA_{mix}/VCA_{drc} ratio

Increase in freeze-thaw cycles increases the abrasion loss. Table 6.3 shows the results of ANOVA performed on WAL results at 5% significance level. Steel slag content, binder type and number of FT cycles are found to have statistically significant effect on the WAL values, same as in case of modified Lottman test. Further, a higher F-value for slag content indicates that it has the highest influence on the WAL values as compared to binder type and FT cycle. Non-significant interactions between the factors (binder type and slag content; binder type and FT cycle; FT cycle and slag content) indicates that the WAL values follow a similar trend for varying slag contents for both binder types and FT cycles. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the WAL values (in comparison to control mixes).

Table 6.3: ANOVA results for WAL values

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type (BT)	1	69.89	<0.001	Yes
Slag content (SC)	4	609.42	<0.001	Yes
FT cycle	1	39.43	<0.001	Yes
BT:SC	4	1.63	0.185	No
BT:FT	1	0.27	0.603	No
FT:SC	4	1.44	0.239	No

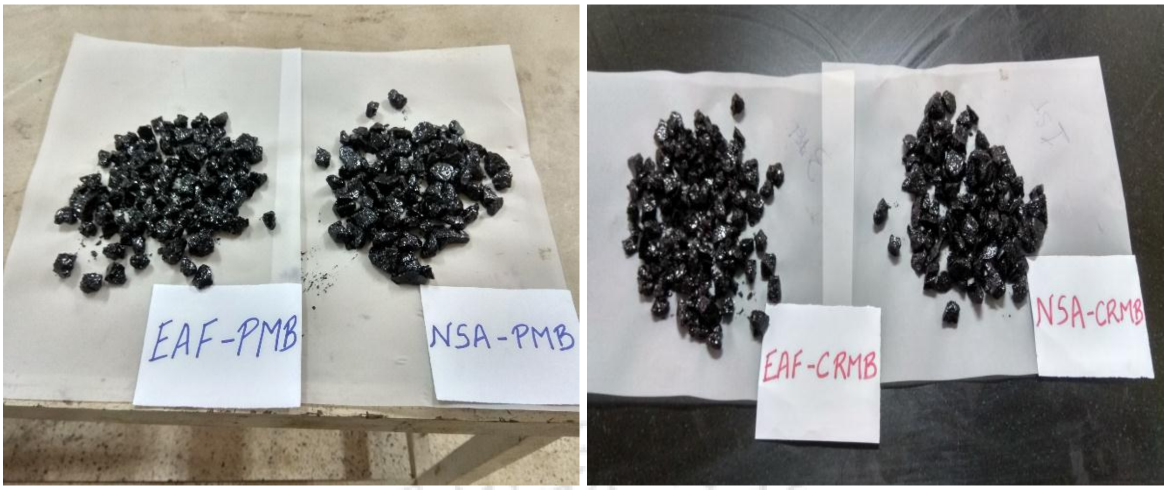
Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	NS	S	S	S	NS	S

Note: 'S': Significant; 'NS': Not Significant; 'DF': Degree of Freedom, 'FT': number of freeze-thaw cycle, 'BT': binder type, 'SC': slag content

6.2.1.3 Static Immersion Test

The static immersion test is a simple visual evaluation test used to measure the adhesion properties of loose bituminous mixes. The static immersion test was carried out as per the IS 6241 (2000) specifications to evaluate the extent of stripping of the binder from the aggregates. The ratio of the uncovered area to the total area of aggregates observed visually, expressed as a percentage is termed as stripping value of the aggregate. Indian Roads Congress (IRC-111, 2009) has specified maximum stripping value of aggregates as 5%. Results of the static immersion test indicated no noticeable stripping for OGFC mixes with different slag contents, including the control mixes. Figure 6.6 indicates the stripping test results of control mixes and mixes with 100% EAF steel slag with both modified binders.



(a) (b)

Figure 6.6: Stripping test results of control mixes and mixes with 100% EAF steel slag: (a) PMB binder, (b) CRMB binder

6.2.1.4 Modified Boiling Water Test

A modified boiling water test was also attempted to examine the effect of water at boiling temperature on the bond between aggregate (natural and EAF steel slag aggregates) and asphalt binder. The test is used to examine chemical compatibility between the aggregate and asphalt binder. The testing was performed for all OGFC mixes and adhesive damage (*AD*) was estimated by the following expression:

$$AD = \frac{W_{cab} - \left(W_{caa} + W_{fp}\right)}{W_{cab} - W_{a}} \times 100 \qquad (6.1)$$

where, *AD* is the adhesive damage (%), W_a is the dry weight of the aggregate, W_{cab} is the weight of the bitumen covered aggregate before test, W_{caa} is the dry mass of the bitumen coated aggregate after test. The addition of boiling water may detach some parts from the surface of aggregate and the corresponding dry mass is reported as W_{fp}. Therefore, $W_{cab}-(W_{caa}+W_{fp})$ is the mass of asphalt binder stripped from the aggregate surface. The variation of adhesive damage percentage determined using modified boiling test with respect to increase in the partial replacement of EAF steel slag is presented in Figure 6.7. It is observed that the percent adhesive damage or stripping continuously decreases with increase in EAF steel slag content. Results indicate improvement in moisture resistance of OGFC mixes with increase in EAF steel slag substitution percentage.

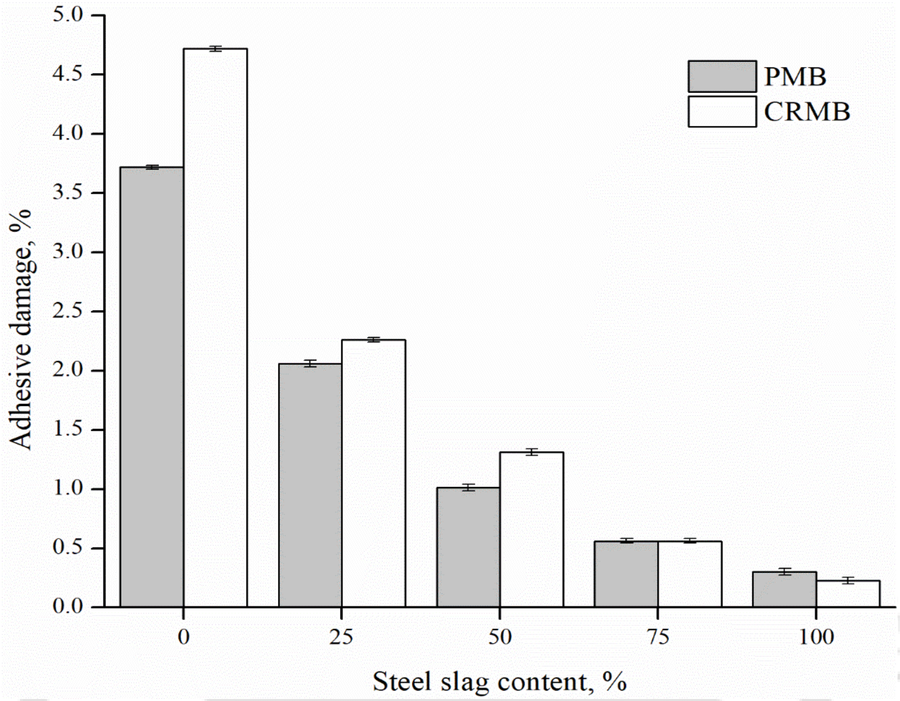
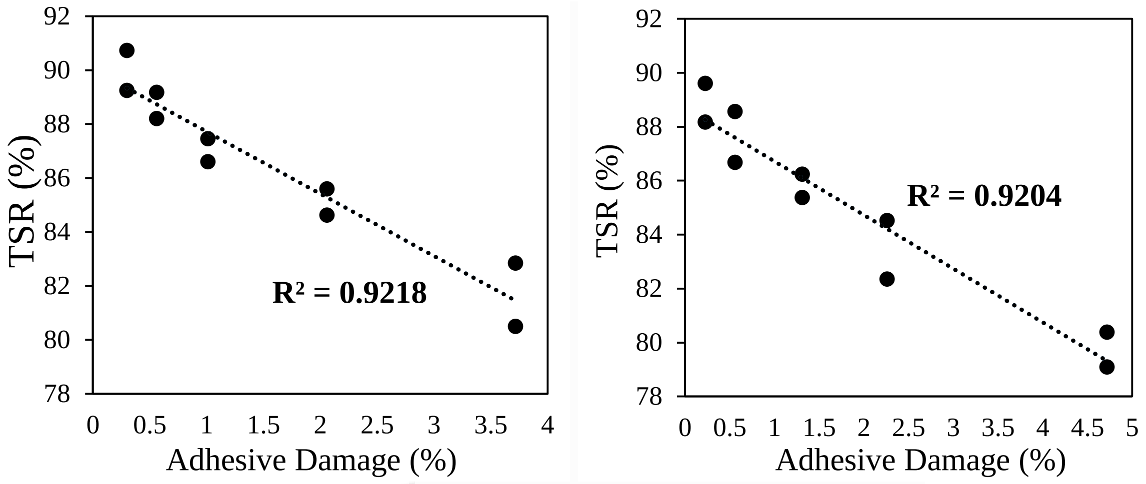


Figure 6.7: Results of modified boiling water test

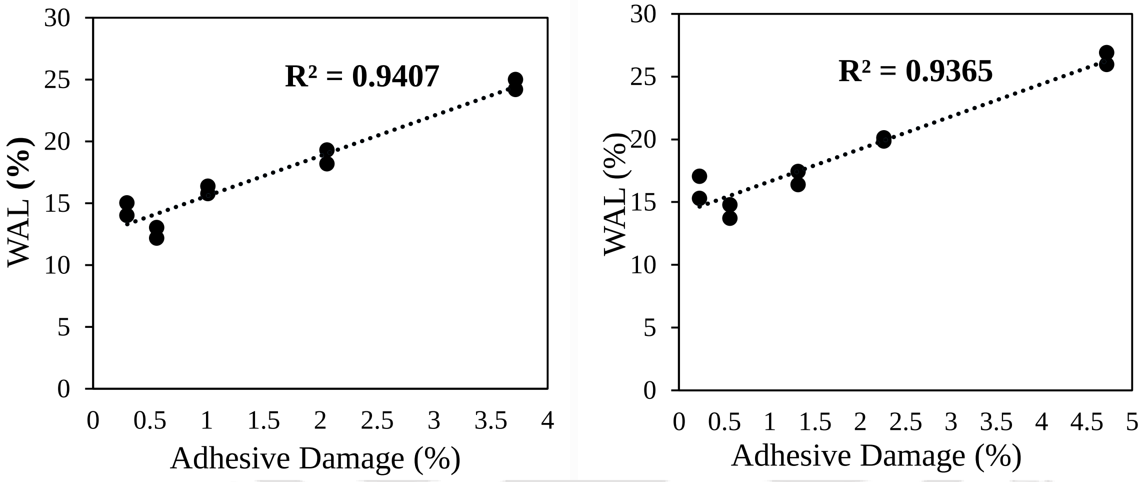
6.2.1.5 Correlations among boiling water, TSR and WAL tests

Correlation analysis was performed to identify relationships among the moisture susceptibility tests considered in the study. The experimental results of adhesive damage and TSR are correlated for mixes with both PMB and CRMB and the results are presented in Figure 6.8. Similarly, the correlation between adhesive damage and WAL test outcomes and that between TSR - WAL test results were attempted and are presented in Figures 6.9 and 6.10, respectively. Figure 6.8 indicates that the coefficient of determination (R^2) for PMB and CRMB are 0.922 and 0.920 respectively for the case of TSR and adhesive damage results, whereas Figure 6.9 shows R^2 of 0.941 and 0.937 for PMB and CRMB respectively for the case of correlation between WAL and adhesive damage results.



(a) (b)

Figure 6.8: Correlation between TSR and adhesive damage for (a) PMB and (b) CRMB binders



(a) (b)

Figure 6.9: Correlation between WAL and adhesive damage for (a) PMB and (b) CRMB binders

Figure 6.10 shows R^2 values of 0.892 and 0.881 for PMB and CRMB respectively for correlation between TSR and WAL test results. Good correlations are observed among TSR, adhesive damage, and WAL values. High correlation was found between adhesive damage and WAL, and adhesive damage and TSR. A higher correlation indicates that the TSR test and WAL test results are well correlated to the modified boiling water test. High correlation between TSR and adhesive damage from modified boiling water test was reported earlier also in a study conducted with dense graded asphalt mixes (Amelian *et al.*, 2014).

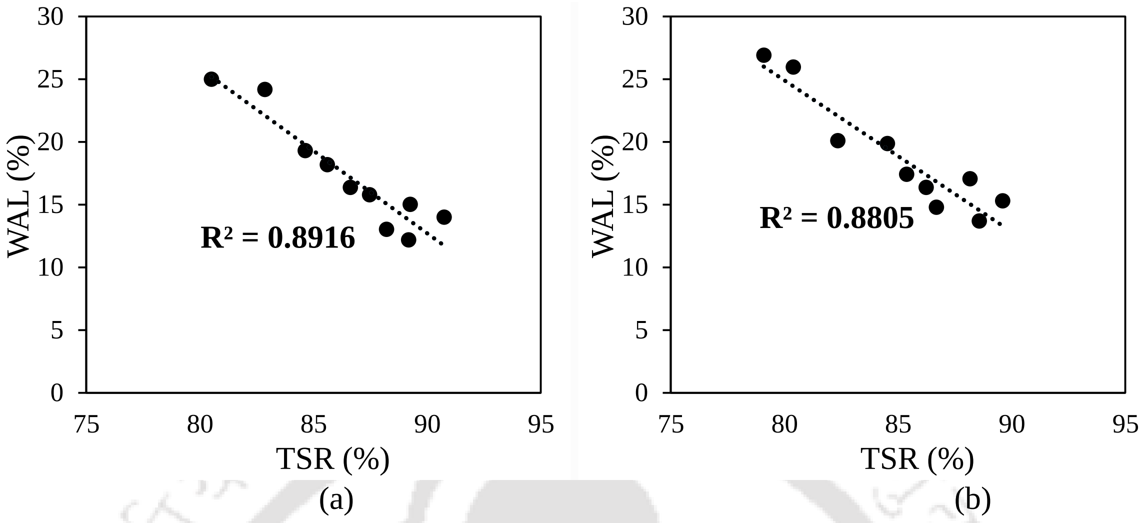


Figure 6.10: Correlation between WAL and TSR for (a) PMB and (b) CRMB binders

6.2.2 Static Creep

Static creep test is relatively less expensive and simple test to assess deformation resistance under a constant load. Static creep test was used to determine the permanent deformation of OGFC mixes. This test was performed at 40 °C as per BS 598-111 (1995) on a universal testing machine (UTM). Five important strain components can be identified from the strain *vs*. time graph generated from the test: initial strain, final strain, total strain, reversible strain, and permanent strain. The schematics of these strains are shown in Figure 6.11. The strain generated after 15 s from the start of loading is referred as initial strain. The strain generated during 15 s to 3600 s loading period is referred as final strain. The sum of the initial strain and final strain is the total strain. After loading period, the recovered s

train from the starting of the unloading till 1 h (at the end of unloading period) is referred as reversible strain. Permanent strain is the residual strain remaining at the end of the unloading period (1 h).

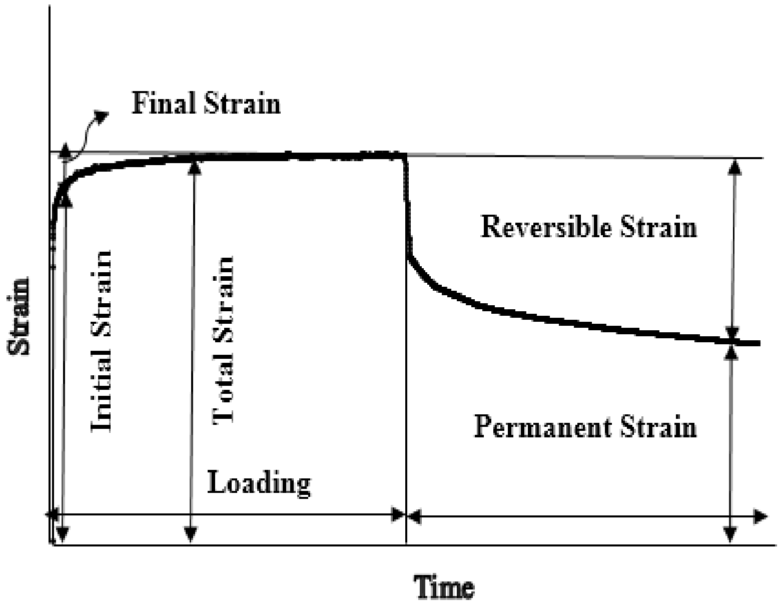


Figure 6.11: Strain components measured in a static creep test

Figure 6.12 shows the total strain values for each OGFC-steel slag mix with both PMB and CRMB binders. It is seen that the total strain reduces with an increase in percentage substitution of coarse natural aggregates with EAF steel slag up to 75% replacement and then increases further at 100% replacement. Steel slag-OGFC mixes show lower total strain values, varying from 46-76% and 26-77% respectively, for PMB-OGFC and CRMB-OGFC mixes compared to the control mixes. The decrease in strain with increase in EAF steel slag content is attributed to rougher surface texture, higher angularity and higher specific gravity of the steel slag resulting in improved bond strength (Pasetto and Baldo, 2010). The residual binder content in the mixes increases with an increment of slag percentage due to the higher specific gravity of the steel slag. The increased residual binder and the rougher surface of EAF steel slag help to enhance the bond in the OGFC mix up to 75% substitution, however the further increment of residual binder (at 100% replacement) makes the binder film more thicker. This very high thickness of asphalt binder film may result in the loss of adhesive bond between aggregate particles and leads to the loads being carried by the asphalt binder instead of the aggregate structure. Therefore, mixes with 100% coarse steel slag show slightly higher strain. Mixes with PMB binder show lower total strain than the mixes with CRMB binder. Table 3 shows the results of ANOVA performed on total strain results at 5% significance level. Steel slag content and binder type are found to have statistically significant effect on the total strain values.

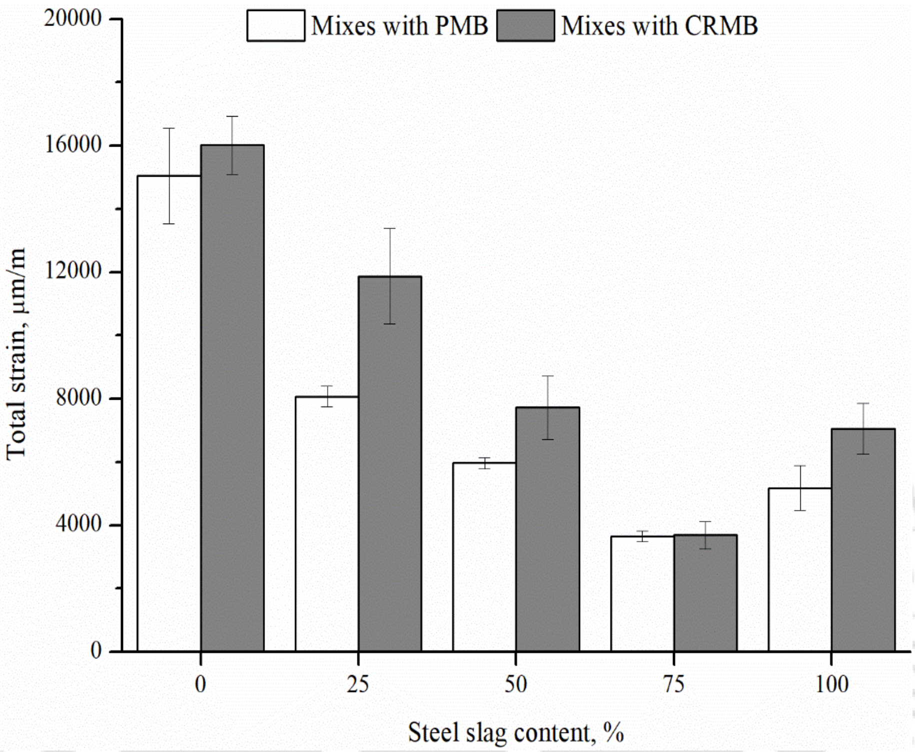


Figure 6.12: Total strain results from static creep test

Table 6.4: ANOVA results for total strain from static creep test

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type	1	8.41	0.015	Yes
Slag content	4	51.10	<0.01	Yes
Interaction	4	1.19	0.37	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	NS	S	S	S	NS	S

Note: 'S': Significant; 'NS': Not Significant; 'DF': Degree of Freedom

Further, a higher F-value for slag content indicates that it has higher influence on the total strain as compared to binder type. Non-significant interaction between the two factors (binder type and slag content) indicates that the total strain values follow a similar trend for varying slag contents for both binder types. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the total strain values (in comparison to the control mixes).

The reduction in strain after removal of the load is termed as recovery of an asphalt mixture. During the loading process, the mixture undergoes a deforming process that consists of elastic and plastic strain components. Both viscoelastic and viscoplastic strains accumulate under creep loading. After elimination of the load, elastic strain is instantly recovered and during the unloading period the viscoelastic strain recovers (depending on the length of recovery period). At end of the unloading time, the remaining strain consists of the plastic and viscoplastic components plus the remainder of viscoelastic strain that has not been recovered, which may result in cracking and permanent deformation in the sample (Carvalho, 2012). Development of cracks and accumulation of creep, results in alligator cracking and rutting respectively, which are the two foremost distresses in bituminous pavements.

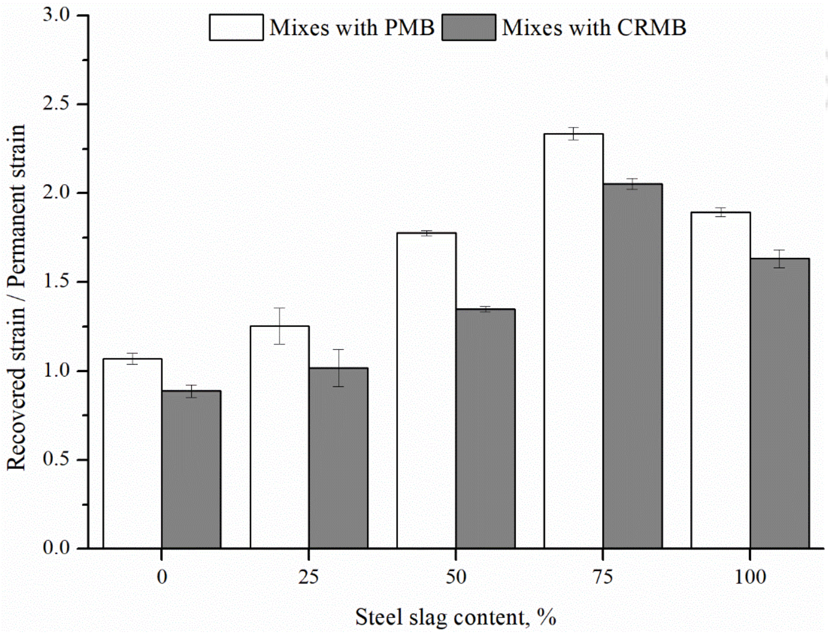


Figure 6.13: Ratio of recovered strain to permanent strain from static creep test

Figure 6.13 presents the results of the ratio of recovered strain to permanent strain (R-P ratio) of OGFC mixes. The ratio indicates relative distribution of recovered and permanent strains in the mix. A higher ratio is desirable as it corresponds to better strain recovery properties. The R-P ratio increases with increase in percentage substitution of coarse natural aggregates with EAF steel slag up to 75% and then it slightly reduces at 100% replacement. It is further observed that PMB mixes have higher R-P ratio than the mixes with CRMB binder. It may be due to the higher elasticity (elastic recovery) of PMB binder than the CRMB binder (Table 3.1).

6.2.3 Dynamic Creep

Rutting or permanent deformation is one of the most common forms of distress on bituminous pavements. It is defined as the progressive accumulation of permanent deformation of each pavement layer under repetitive traffic loading (Matthews and Monismith, 1992; Balghunaim *et al.*, 1988). It generally manifests as depressions along the wheel path of vehicles. Dynamic creep test was used to determine the permanent deformation characteristics of OGFC mixes under repetitive loads. The dynamic creep test was performed at 40 °C with a square load waveform at 0.5 Hz frequency according to BS DD 226 (1996) specifications. Accumulated axial strain in the specimen was measured as a function of number of cycles. The test was run for 10000 cycles. The accumulated strain plots of OGFC mixes with all steel slag contents and PMB and CRMB binders are presented in Figures 6.14 and 6.15. It is observed that the addition of EAF steel slag reduces the axial strain of the OGFC mixes. Steel slag-OGFC mixes present lower accumulated strain values, varying from 45-77% and 31-79% respectively, for PMB-OGFC and CRMB-OGFC mixes, compared to the control mixes. This shows that the EAF steel slag-OGFC mixes demonstrate higher rutting resistance than the control mix. The results could be ascribed to high bearing strength, angularity and hardness of EAF steel slag aggregates.

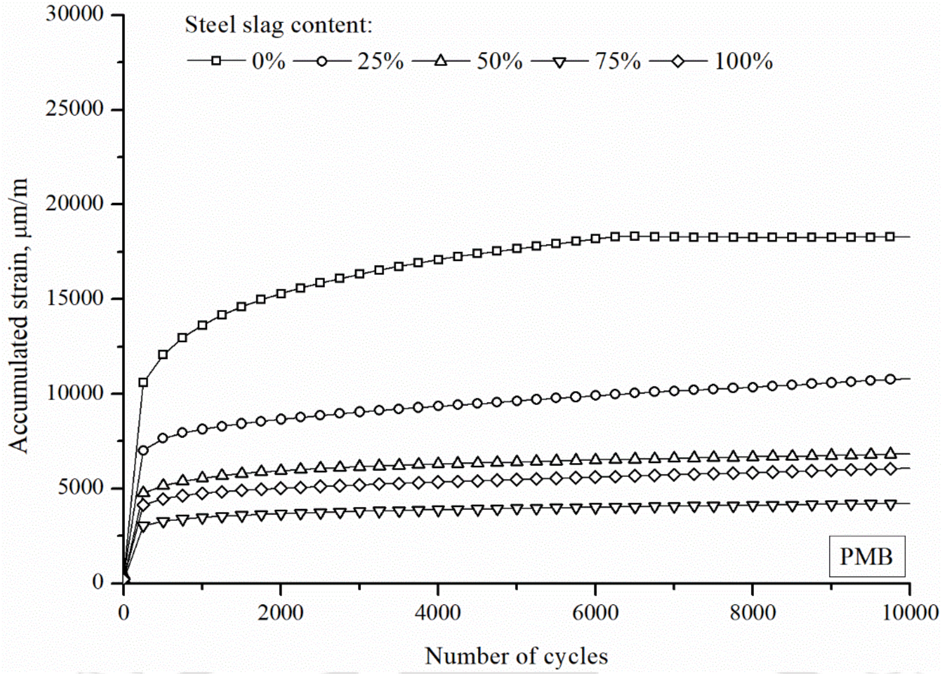


Figure 6.14: Accumulated strain result for mixes with PMB binder

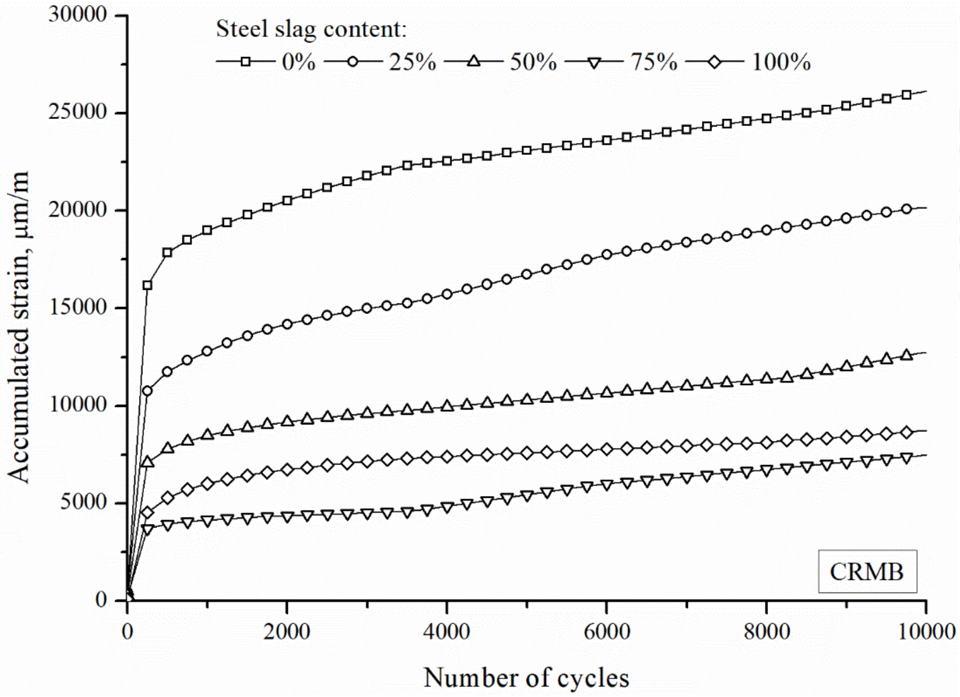


Figure 6.15: Accumulated strain result for mixes with CRMB binder

As the steel slag aggregate is rougher than the natural aggregate, a better mechanical interlock (cohesive bond) between the binder and steel slag aggregate is developed, leading to high permanent deformation resistance. Beyond 75% steel slag content there is slight increase in the accumulated strain; however, it remains lower than the control mix.

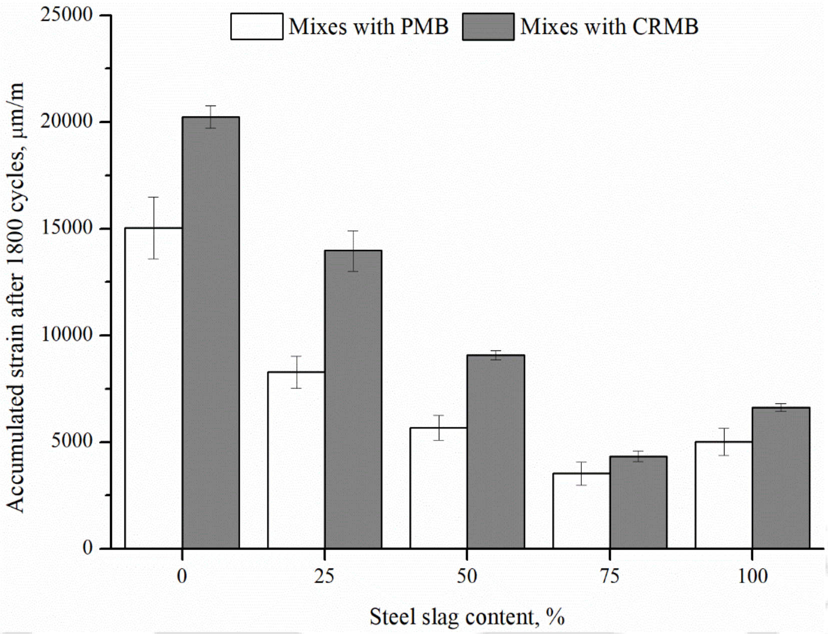


Figure 6.16: Accumulated strain after 1800 cycles from dynamic creep test

Figure 6.16 shows the accumulated strain values after 1800 cycles also from the dynamic creep test. It is seen that the strain decreases with increase in percentage substitution with EAF steel slag up to 75% and then increases with further increment in steel slag content. It is to be noted that similar trend was also observed in the static creep test results. It is seen that the resistance to permanent deformation increases with increase in percentage substitution with EAF steel slag up to 75% and then decreases at 100% substitution. This can be explained by high angularity, rough texture and high specific gravity of the EAF slags that favour high internal friction and hence an improved densification resulting in high resistance to permanent deformation. The decrease in permanent deformation resistance at 100% substitution is due to the presence of higher residual binder, as discussed in the case of static creep test.

Table 6.5 shows the results of ANOVA performed on accumulated strain after 1800 cycles at 5% significance level. Steel slag content and binder type are found to have statistically significant effect on the accumulated strain values. Further, a higher F-value for slag content indicates that it has higher influence on the accumulated strain as compared to binder type. Non-significant interaction between the two factors (binder type and slag content) indicates that the accumulated strain values follow a similar trend for varying slag contents for both binder types. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the accumulated strain values in comparison to control mixes.

Table 6.5: ANOVA results for accumulated strain after 1800 cycles

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type	1	71.37	<0.01	Yes
Slag content	4	93.10	<0.01	Yes
Interaction	4	3.70	0.08	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	NS	S	S	S	NS	S

6.2.4 Hamburg Wheel Tracking Device Test

The HWTD test was performed at 40 °C for 20,000 passes of a loaded steel wheel carrying 705 N load. Accumulated rut depth in the specimen was measured as a function of number of passes. The accumulated rut depth plots of OGFC mixes at all EAF steel slag contents with PMB and CRMB binders are presented in Figures 6.17 and 6.18. In the initial stages of the test, the rut depth increases rapidly due to secondary compaction of the test specimen, after which the rate of increase in rut depth becomes gentle and steady. EAF steel slag-OGFC mixes present lower rut depth values as compared to the control mixes, varying from 15-60% and 14-61% respectively, for PMB-OGFC and CRMB-OGFC mixes.

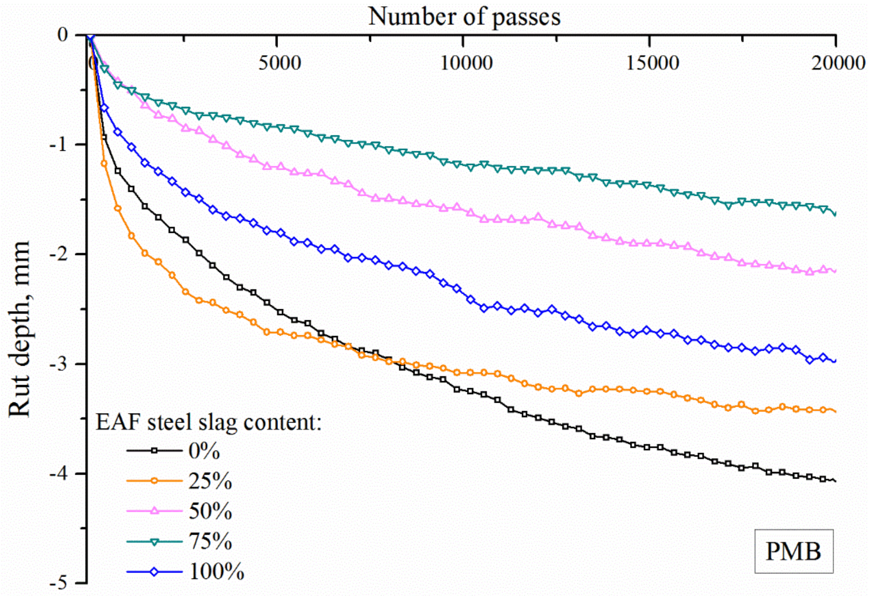


Figure 6.17: HWTD test results for PMB-OGFC mixes

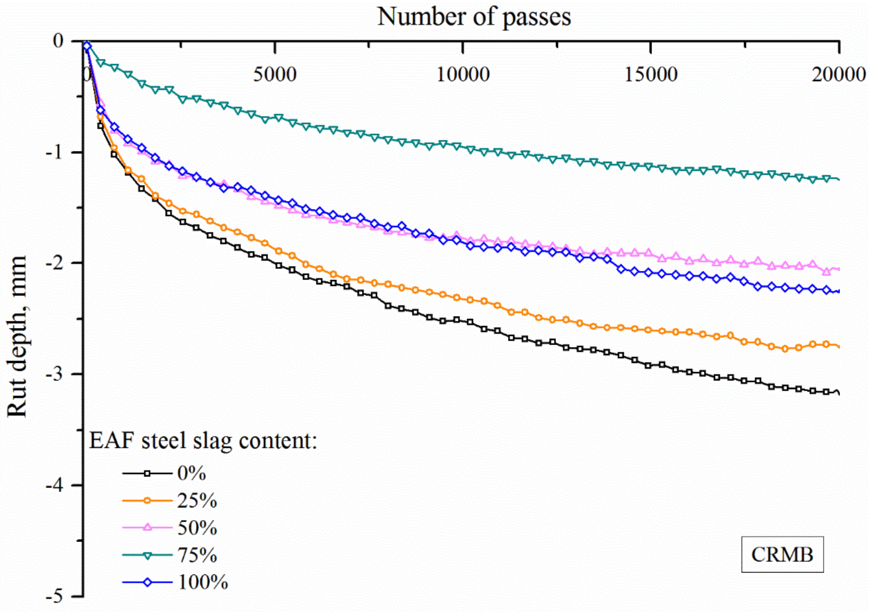


Figure 6.18: HWTD test results for CRMB-OGFC

This shows that the EAF steel slag-OGFC mixes demonstrate higher rutting resistance than the control mix. It is observed that with increase in EAF steel slag content beyond 75% there is slight increase in the rut depth; however, it still remains lower than the control mix. The high strength, angularity and rough surface texture of EAF steel slag provides an effective interlock between the aggregates in OGFC mixes. This helps to reduce changes in the orientation of aggregates through rearrangement under the passes of HWTD, and therefore enhances the permanent deformation resistance.

The HWTD test results are also in agreement with the results of dynamic creep and static creep tests. The decrease in rutting resistance at 100% substitution is likely due to the existence of higher residual binder as discussed in the case of static creep test. It is further observed that up to the maximum number of passes used in the test, there is no stripping in all OGFC mixes (all slag contents and both binders) as there is no change in the slope of the rut depth versus number of passes curves beyond the initial change due to secondary compaction. This indicates superior resistance of all OGFC mixes to the effects of moisture, which may be attributed to the better asphalt bonding with rough and open textured EAF steel slag aggregates having higher calcium oxide content (EAF steel slag has a CaO/SiO_2 ratio of 2.410, which is much higher than that for the natural aggregates which is 0.162). Table 6.6 presents the results of ANOVA performed on rut depth obtained after 20,000 passes. Based on the ANOVA, EAF steel slag content and binder type are found to have significant effect on rut depth.

Table 6.6: ANOVA results for HWTD rut depth

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type	1	50.00	<0.01	Yes
Slag content	4	82.17	<0.01	Yes
Interaction	4	1.82	0.18	No

Multiple comparisons based on Tukey's procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				NS			
50%	S	S			S	S		
75%	S	S	NS		S	S	S	
100%	S	NS	S	S	S	NS	NS	S

A higher F-value for slag content indicates that it has higher influence on rut depth as compared to binder type. Non-significant interaction between the two factors (binder type and slag content) indicates that rut depth values follow a similar trend for varying slag contents for both binder types. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the rut depth values in comparison to control mixes.

6.2.5 Indirect Tensile Stiffness Modulus (ITSM) Test Results

Stiffness is considered as a measure of the ability of the bituminous layer to distribute a load. Stiffness modulus is one of the fundamental characteristics of an asphalt mixture and is also used as an input parameter for pavement design models. In this study, the ITSM was measured using indirect tension test jig in accordance with EN 12697-26 (2012) procedures. The tests was performed at 20 °C for evaluating the stiffness modulus.

The stiffness modulus results of OGFC mixes with different percentage substitution of EAF steel slag and both modified binders (PMB and CRMB) are presented in Figure 6.19. The stiffness modulus values of the OGFC mixes increase with the substitution of natural aggregates with EAF steel slag.

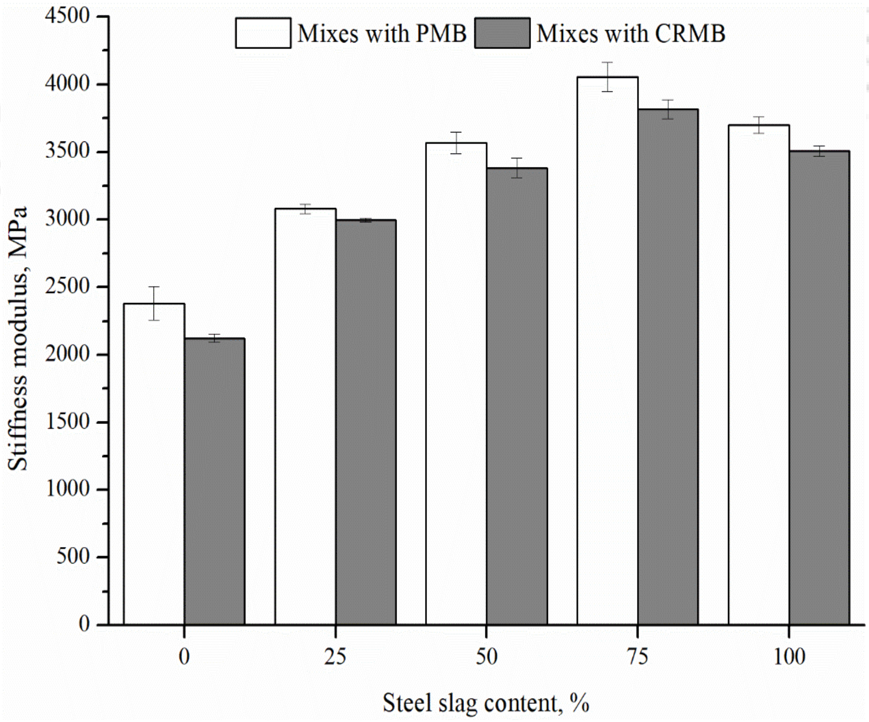


Figure 6.19: Stiffness modulus results of OGFC mixes

At 100% steel slag replacement, a slight decrease in stiffness modulus is observed, as further increase in residual binder content, because of replacement of natural aggregates with high specific gravity EAF slag, may have resulted in load transmission more through binder than through aggregates. Steel slag-OGFC mixes show higher values of stiffness modulus as compared to the control mixes, varying from 30-71% and 41-80% for PMB-OGFC and CRMB-OGFC mixes, respectively. The enhanced stiffness modulus of OGFC mixes with EAF steel slag is attributed to greater adhesion between the slag and modified binders and higher internal friction, which is due to rough surface texture and as well as due to higher strength and angularity of EAF steel slag aggregates.

Table 6.7 shows the results of ANOVA performed on stiffness modulus results. Steel slag content and binder type are found to have significant effect on stiffness modulus. Further, a higher F-value for slag content indicates that it has higher influence on stiffness modulus as compared to binder type. Non-significant interaction between the two factors (binder type and slag content) indicates that stiffness modulus values follow a similar trend for varying slag contents for both binder types. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the stiffness modulus values in comparison to control mixes.

Table 6.7: ANOVA results for stiffness modulus

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type	1	32.42	<0.01	Yes
Slag content	4	309.14	<0.01	Yes
Interaction	4	0.891	0.49	No

Multiple comparisons based on Tukey’s procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	NS	S	S	S	NS	S

6.2.6 Fatigue Resistance

Fatigue cracking is one of the key distresses in asphalt pavements. Repeated traffic loading is the main factor responsible for fatigue cracking and it can result in a significant drop in the serviceability of the pavement. Fatigue performance of OGFC mixes was evaluated through indirect tensile fatigue test (ITFT) at 20 °C in terms of fracture life (*i.e.* the number of load cycles until complete failure of the specimen). Fracture life results of OGFC mixes for all percentage substitution of EAF steel slag with both PMB and CRMB binders are presented in Figure 6.20. It is observed that all steel slag-OGFC mixtures have higher fracture life values compared to mixes with natural aggregates. Steel slag-OGFC mixes show higher fracture lives varying from 82-234% and 78-214% respectively, for PMB-OGFC and CRMB-OGFC mixes compared to their control mixes.

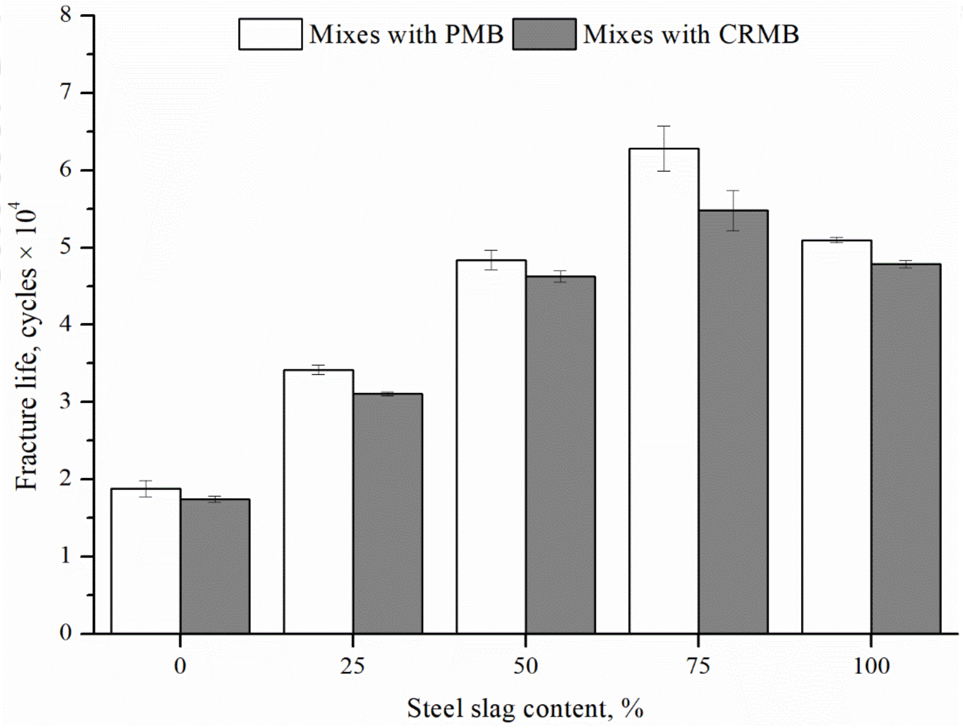


Figure 6.20: Fracture lives of OGFC mixes

Higher fracture life results for steel slag-OGFC mixes may be attributed to the angularity of the coarse EAF steel slag aggregates resulting in increased internal friction angle of mixes and improvement in the particle interlocking (Kavussi and Qazizadeh, 2014). Fracture life of OGFC mixes increases with increase in EAF steel slag up to 75% then slightly decreases with further increment. The fatigue life improvement up to 75% EAF steel slag is observed because EAF steel slag improves the interlocking of the aggregate structure, whereas in case of mixes by 100% EAF steel slag substitution the decrease in fatigue life is due to increased amount of residual binder due to high specific gravity of EAF steel slag.

Table 6.8 presents the results of ANOVA performed on fracture life results. Based on the ANOVA, steel slag content and binder type are found to have significant effect on fracture life. A higher F-value for slag content indicates that it has higher influence on fracture life as compared to binder type. Non-significant interaction between the two factors (binder type and slag content) indicates that fracture life values follow a similar trend for varying slag contents for both binder types. Multiple comparison results show that substitution of natural aggregate by EAF steel slag leads to significant changes in the fracture life values in comparison to control mixes.

Table 6.8: ANOVA results for fracture life

Factor	**DF**	**F value**	**P Value**	**Significance**
Binder type	1	39.53	<0.01	Yes
Slag content	4	1015.02	<0.01	Yes
Interaction	4	2.604	0.07	No

Multiple comparisons based on Tukey’s procedure

	PMB				**CRMB**			
	0%	25%	50%	75%	0%	25%	50%	75%
25%	S				S			
50%	S	S			S	S		
75%	S	S	S		S	S	S	
100%	S	S	S	S	S	S	S	S

6.3 SUMMARY

This chapter presented the results of performance characteristics of OGFC mixes at different contents of electric arc furnace (EAF) steel slag. OGFC mixes were fabricated with five percent replacements of natural aggregates with EAF steel slag and two modified asphalt binders (polymer and crumb rubber modified). Moisture susceptibility characteristics were evaluated through modified Lottman test, wet abrasion loss test, static immersion test, and modified boiling water test, whereas rutting and fatigue performance was evaluated through static creep, dynamic creep, Hamburg wheel tracking test, indirect tensile stiffness modulus, and indirect tensile fatigue tests. The test results of all performance tests were presented and discussed in this chapter.

In comparison to OGFC mixes with natural aggregates, addition of EAF steel slag resulted in improvement in indirect tensile strength, both in dry and wet conditions for mixes with both binders. OGFC mixes with EAF steel slag were able to meet the minimum TSR requirement of 80% even after use of five freeze-thaw cycles conditioning, indicating an improved moisture damage resistance. The boiling water test results also indicated a decrease in the adhesive damage with increase in partial replacement of natural aggregates with EAF steel slag, *i.e.* the bonding behaviour of the EAF steel slag with the modified binder was better than that with natural aggregates. No stripping of binder from aggregates was observed for all combination of bituminous mixes with both modified binders in static immersion test. The OGFC mixes with PMB binder showed high resistance to moisture when compared to mixes with CRMB binder. A close and significant relationship was observed for adhesive damage obtained from modified boiling test to TSR test results and WAL test results. This supported that the modified Lottman test and WAL test are sensitive enough to measure the effect of moisture destruction.

Both PMB- and CRMB-OGFC mixes with all percentage substitution of coarse natural aggregate with EAF steel slag showed improved performance in terms of static creep, dynamic creep, Hamburg wheel tracking, stiffness modulus and fracture life in comparison to control mixes (without EAF steel slag). Mixes prepared with PMB binder presented better performance in terms of permanent deformation, stiffness modulus and fatigue life as compared to the mixes with CRMB binder. OGFC mixes with 75% substitution of coarse natural aggregates with EAF steel slag presented the best performance.

Chapter 7
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 SUMMARY

Open graded friction course (OGFC) is a hot mix asphalt (HMA) surface course designed for high air void content (generally more than 18% by mix volume) and enhanced pavement skid resistance, especially during wet weather conditions. High air void content makes OGFC mixes permeable to allow a quick and effective removal of surface water from them laterally to the edges of the pavement. OGFC mixes have several established benefits such as mitigation of hydroplaning (due to quick drainage of water from pavement surface), improved frictional resistance, reduced pavement noise, reduced splash and spray, and better visibility of pavement markings. For OGFCs, the coarse aggregates (size greater than 2.36 mm) comprise more than 90% of the total aggregates. The coarse aggregate skeleton of OGFC mixes achieved through selection of a uniform gradation of aggregates with low fine content, provides the necessary stone-on-stone contact condition for efficient distribution of traffic loads. OGFC mixes demand good quality aggregates that are angular and possess high resistance to abrasion, crushing, and polishing. Construction of a vast capacity of infrastructure has put an immense pressure on the conventional sources of natural stone aggregates. Mining and quarrying of natural aggregates poses severe environmental concerns such as deforestation, loss of natural landscape and dust generation. In many regions of India, environmental concerns have put restrictions on quarrying and extraction of natural aggregates from mountains and rivers respectively. This has created a scarcity of good quality natural aggregates and has resulted in an overall increase in the cost of highway projects. Highway and asphalt researchers are continuously exploring alternative highway construction materials, especially the aggregates, as they constitute main share of bituminous mixes and other courses of a pavement and are also the main load-carrying component.

India is the third largest steel producer in the world with a steel production of 101.4 million tonnes (MT) in 2017 (World Steel, 2018). About 12 MT of steel slag is generated annually in India, but merely 20% is put to applications and the rest is indiscriminately dumped in nearby landfills as waste and remains unutilised. Steel production in India is done through two main processes: electric arc furnace process (share of 56.8%), and basic oxygen furnace process (share of 42.8%). Electric arc furnace (EAF) steel slag is the major waste generated from steel-making industries that utilise electric arc furnace process of steel production. The demand for natural aggregates is continuously increasing whereas the availability and extraction of good quality aggregates is becoming more and more difficult and expensive day-by-day. Therefore, it is high time for Indian highway professionals and researchers to explore for alternate materials that can be used as aggregates in road construction. This will not only help to achieve sustainability in road construction but will also reduce the exploitation of natural resources. Steel slag is one such alternate material lying in millions of tonnes in India as a waste/by-product. Desirable characteristics of EAF steel slag such as high strength, porous/rough surface texture, high angularity, good resistance to abrasion and polishing makes it a potential candidate for total/partial replacement of natural aggregates in OGFC mixes.

The present study evaluated design and performance characteristics of OGFC mixes with EAF steel slag as partial/total replacement of conventional coarse aggregates. The main objectives of this research were: (1) design of OGFC mixes with different percentages of EAF steel slag as substitution of natural coarse aggregates; (2) characterisation of OGFC mixes through evaluation of the effect of EAF steel slag content on mix design parameters and on performance properties including permeability and clogging characteristics, frictional characteristics, moisture induced damage resistance, fatigue life, permanent deformation resistance and stiffness modulus.

To achieve the framed objectives, the present study included two types of aggregates (natural and EAF steel slag aggregates), two modified binders (polymer and crumb rubber modified binders), and cellulose fibre as stabilising additive. Five percentages (0, 25, 50, 75 and 100%) of natural coarse aggregates were replaced with EAF steel slag at three binder contents (5.5, 6 and 6.5%). The variations in stone-on-stone contact, air voids content, binder draindown, unaged abrasion loss and aged abrasion loss were observed for OGFC mixes with different EAF slag contents for optimum binder content determination. After finalising the OBC content, the OGFC mixes were evaluated for permeability and clogging characteristics, frictional characteristics, moisture susceptibility, stiffness modulus, fatigue life and permanent deformation resistance.

7.2 CONCLUSIONS

The basic premise of this research study was to evaluate the feasibility to use EAF steel slag in OGFC mixes at a favourable combination, in order to utilise an industrial waste and to safeguard the natural resources of aggregates, without compromising the properties and performance characteristics of OGFC mixes. Based on the findings of the study from the laboratory experimentation and statistical analyses, the following conclusions are made:

- EAF steel slag aggregates showed good physical properties in terms of flakiness and elongation index, abrasion loss, crushing strength and impact value compared to the natural aggregates. Chemical composition analysis revealed that, EAF steel slag aggregates had higher calcium oxide and lower silicon oxide content, compared to natural aggregates that made the EAF steel slag alkaline. The alkaline nature of the EAF steel slag improved the bond with the asphalt binder and therefore the resistance towards moisture induced damage. TCLP analysis indicated no harmful behaviour with the use of EAF steel slag aggregates in terms of leaching. EAF steel slag aggregates were found to satisfy all requirements of aggregates for being used in OGFC mixes.
- OGFC mixes containing EAF steel slag were able to meet all OGFC mix design criteria in terms of air voids content, abrasion loss and binder draindown, up to 100% replacement of natural aggregates.
- EAF slag-OGFC mixes showed improved frictional characteristics when measured in terms of BPN and texture depth, which was attributed to high angularity and rougher texture of EAF steel slag aggregates. Statistical analysis showed that the frictional performance of OGFC mixes was not significantly affected by the difference in binder type. Pavement friction is regarded as the most important factor influencing the wet weather road safety aspect. Hence, use of OGFC mixes with steel slag will help to enhance the safety on roads, especially in hilly and high rainfall regions of India.
- OGFC mixes with EAF steel slag replacement were able to meet the minimum permeability requirement of 100 m/day under both clogged and de-clogged conditions. The secondary clogging rate of OGFC mixes, a vital parameter in long term performance, was quite lower (about 50%) than the initial clogging rate.

- In comparison to OGFC mixes with natural aggregates, increase in EAF steel slag content improved moisture susceptibility parameters in terms of indirect tensile strength (both dry and wet) as well as tensile strength ratio (TSR), wet abrasion loss and adhesive damage when examined through modified Lottman test, wet abrasion loss test and modified boiling test, respectively. Statistical analysis on moisture susceptibility parameters: wet ITS and TSR results, showed that the EAF steel slag content had the highest influence on moisture damage behaviour. OGFC mixes with EAF steel slag showed an improved moisture damage resistance compared to those with natural aggregates.
- OGFC mixes with EAF steel slag aggregates led to improvement in the resistance of OGFC mixes towards permanent deformation as compared to mixes containing natural aggregates, when measured through static creep and dynamic creep tests. The results of Hamburg wheel tracking tests further corroborated the enhanced deformation resistance of OGFC mixes with the incorporation of EAF steel slag. Furthermore, up to the maximum number of passes in the Hamburg wheel tracking test, there was no evidence of stripping in OGFC mixes with all slag replacement percentages and both binders.
- Addition of EAF steel slag enhanced the fatigue performance of OGFC mixes in terms of increase in fracture life, with both PMB and CRMB binders as determined from the indirect tensile fatigue test. Physical and chemical characteristics of the EAF steel slag aggregates led to improvement in the resistance of OGFC mixes towards fatigue.
- The OGFC mixes with PMB binder demonstrated higher density and resistance to abrasion compared to the mixes with CRMB binder. Mixes prepared with PMB

binder presented better performance in terms of permanent deformation, stiffness modulus and fatigue life as compared to the mixes with CRMB binder.

- Results indicate that 75% is the optimum content for replacement of the coarse natural aggregates with EAF steel slag in OGFC mixes with both PMB and CRMB binders. OGFC mixes with 75% substitution of coarse natural aggregates with EAF steel slag presented the best performance in terms of design parameters (*i.e.* unaged abrasion loss, aged abrasion loss) and performance parameters (*i.e.* permanent deformation, stiffness modulus and fatigue life) among all the combinations studied. However, mixes with 100% replacement of coarse natural aggregate with EAF steel slag also met relevant requirements for an OGFC mix.
- The use of OGFC will be highly beneficial for Indian regions that receive high rainfall. Use of EAF steel slag, a steel industry by-product, will lead to more economical OGFC mixes. This is because the cost of natural aggregate can be saved by replacing it with industrial waste EAF steel slag. Utilisation of steel slag as a replacement of natural aggregate with EAF steel slag in OGFC mixes may be considered as an emerging option, which can save the rapidly diminishing natural aggregates, minimise the cost of landfilling, and mitigate the environmental pollution caused due to its dumping as a waste. The potential use of EAF steel slag in OGFC mixes will further help in maintaining the ecological sustainability.

7.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The thesis presented the evaluation of OGFC mixes as a function of EAF steel slag content and modified binder type. Based on the present research, the following recommendations are made for future work:

- Evaluation of the performance of OGFC mixes with steel slag aggregates from basic oxygen furnace (BOF) process.
- Evaluation of the performance of OGFC mixes with different sources of EAF steel slag and natural aggregates.
- The present investigation was limited to laboratory study. To estimate advantages of OGFC mixes containing steel slag aggregates in terms of road safety and design life (long term performance), field sections must be laid and monitored.

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