UTILISATION OF BASIC OXYGEN FURNACE STEEL INDUSTRY SLAG IN OPEN GRADED ASPHALT FRICTION COURSE MIXES

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By

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CERTIFICATE

This is to certify that the thesis titled *"Utilisation of Basic Oxygen Furnace Steel Industry Slag in Open Graded Asphalt Friction Course Mixes"* submitted by **Santanu Pathak** (Roll No. 176104003) 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 him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard for fulfilling the requirement 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 my knowledge and belief.

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DECLARATION

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ABSTRACT

India has the second-largest road network in the world, with a total road length of about 62 lakh kilometres (or 6.2 million kilometres). Of the paved roads, more than 90% are of the flexible type which usually consist of bituminous wearing and binder courses built over a granular base course and sub-base course, and all these courses finally rest upon the compacted soil subgrade. Dense graded bituminous mixes quite commonly used in wearing courses/ surface courses of flexible pavements contain about 3-5% air voids and are relatively impervious to water. With an adequate camber, a densely graded and relatively impermeable bituminous surface allows quick removal of rainwater from the road surface. However, on wider asphalt pavements, especially in heavy rainfall regions or during heavy precipitation, a thin layer of water usually forms/exists on the pavement surface, which may result in hydroplaning (resulting in reduced skid resistance), splash and spray of rainwater runoff, reduced visibility, and glare at night. Wet weather conditions account for about 30% of the total road fatalities in India. On high speed-corridors with multiple lanes, constructed in high rainfall regions of the country, it is desirable to have surface courses that allow quick removal/drainage of rainwater to maintain adequate skid resistance and visibility even during wet weather conditions.

Open graded asphalt friction courses (OGAFCs) are special hot mix asphalt surface courses designed and constructed with the benefits of reduced hydroplaning, enhanced skid resistance (under both dry and wet surface conditions), reduced splash and spray of rainwater runoff, better visibility, and reduced glare. These mixes are characterised by high air voids content (18-25% of the mix volume) achieved by adopting a uniform aggregate gradation that predominantly comprises of single-sized coarse aggregates (coarse aggregates having size > 2.36 mm having a share of about 90% or more). The open structure of OGAFC courses allows rainwater to enter and flow within it laterally and finally exit through the day-lighted pavement edges. Their use thus reduces the chances of hydroplaning and improves the skid resistance and visibility. They also help to reduce the tyre-pavement interaction noise. OGAFC mixes demand good quality road aggregates, particularly in terms of shape, strength, and resistance to moisture. The current restrictions on quarrying non-renewable natural aggregate sources, higher cost of good quality road construction aggregates as well the quest to achieve sustainability in highway construction, have motivated researchers and practitioners to explore alternative road-making aggregates.

Steel slag is an industrial by/co-product obtained from the steelmaking industries during pig iron or scrap steel conversion to industrial quality steel. Based on the furnace used in the conversion process, steel slag is divided into two types: basic oxygen furnace (BOF) slag and electric-arc furnace (EAF) slag. Currently, India is the second-largest global producer of steel, with annual steel production of 108.5 million tonnes (MT). It is estimated that India alone generates about 20 MT of steel slag annually, of which about 80% remains unutilised in nearby landfills. Globally, about 70% of the generated steel slag is BOF in nature. Steel slags have high strength and good abrasion resistance and have shown good potential in past research studies for use as an alternative to natural road aggregates in conventional dense graded bituminous mixtures. However, their use in OGAFC mixes have not been explored in detail. Along with the aggregate type, asphalt binder type also plays an important role in the performance of an OGAFC mix.

With this background, this study investigated the utilisation of BOF steel slag in OGAFC mixes as a replacement to coarse natural aggregates in five percentages (0, 25, 50, 75, and 100%) with two types of modified binders (polymer modified bitumen (PMB) and crumb rubber modified bitumen (CRMB)). The ten OGAFC mix combinations formulated were first evaluated for mix design parameters, including air voids content, stone-on-stone contact, Cantabro abrasion loss (measured in unaged and aged conditions), and binder draindown. OGAFC mixes with the different percentages of BOF slag and the two modified binders were then evaluated for functionality, durability, and performance attributes. The functionality of the OGAFC mixes was examined in terms of drainability (permeability) characteristics, clogging resistance, and frictional properties. The clogging potential of the OGAFC mixes was evaluated through the determination of resistance to particle-related clogging, stripping-related clogging, and deformation-related clogging. Frictional properties were examined considering the effect of surface condition (dry, wet, and ponding), measurement of adhesion and hysteresis component of skid resistance, and the variation of friction with slip speed, along with the evaluation of the effect of polished aggregates on frictional characteristics of OGAFC mixes.

The durability of OGAFC mixes was assessed in terms of the resistance to moisture induced damage and the resistance to long-term binder draindown. The moisture damage potential of the OGAFC mixtures was evaluated under different moisture conditioning environments by varying the pH of the conditioning water. Moisture damage characterisation was performed through modified boiling water test, modified Lottman test, and wet abrasion loss test. The long-term binder draindown potential of the mixes was examined by subjecting the mixes to different conditioning protocols. The effect of long-term binder draindown on OGAFC mix characteristics was further assessed by determining permeability, moisture damage resistance, ravelling potential and permanent deformation characteristics of OGAFC mixes at different BOF steel slag contents with both modified binder types. Finally, the mechanical performance of the BOF steel slag incorporated OGAFC mixes were evaluated in terms of rutting resistance, cracking potential, fatigue life, and modulus properties.

Results of the study indicated that an increase in the percentage incorporation/ content of BOF steel slag enhanced the stone-on-stone contact and improved the resistance to ravelling of OGAC mixes. At 6.0% binder content (by weight of the mixture), all mix design parameters were found to meet the specified requirements stated by the ASTM D7064 (2013) for the different OGAFC mix combinations. The drainability test results indicated that permeability of the OGAFC mixes decreased with an increase in steel slag content, but the clogging resistance was found to improve with an increase in BOF steel slag content. De-clogging operations of vacuum cleaning and flushing were able to restore 85% and 90% of the initial permeability of OGAFC-PMB and OGAFC-CRMB mixes respectively. The incorporation of BOF steel slag showed an enhancement in the resistance towards both stripping-related clogging and deformation-related clogging. The results of characterisation of friction properties revealed that using steel slag in OGAFC mixes considerably enhanced the frictional resistance of the mixes under all three surface conditions (dry, wet, and ponding). For all three surface conditions and both modified binders, every 25% increment in steel slag content was able to improve the skid resistance of OGAFC mixes by about 12 BPN (British pendulum number).

The moisture susceptibility test results showed that an acidic environment exacerbated the moisture damage; however, OGAFC mixtures containing BOF steel slag showed better performance than the control mixture (with natural aggregates only). OGAFC mixes with more than 50% steel slag content were only able to retain the minimum tensile strength ratio requirement of 80% under acidic environmental conditioning. The inclusion of BOF slag in OGAFC mixtures enhanced resistance to moisture damage under both pH environments. The long-term binder draindown test results revealed that conditioning of OGAFC mixes at 160°C for 8-hours was able to simulate the long-term binder draindown of the mixes. OGAFC mixes with higher BOF steel slag content showed higher ravelling and rutting resistance and lower moisture damage when compared with the control mixture after being subjected to long-term binder draindown. The mechanical performance test results indicated that the use of BOF steel slag not only improved the performance of OGAFC mixes in terms of rutting resistance, cracking potential, and modulus properties; it also increased the fatigue life of OGAFC mixes.

From the evaluation of different parameters of OGAFC mixes at variable contents of BOF steel slag with both binders, it is finally concluded that OGAFC mixes with 100% BOF steel slag substitution exhibited the best functionality, durability and performance properties. OGAFC mixes with PMB binder showed better moisture susceptibility and performance properties (rutting resistance, cracking potential, fatigue life, and modulus properties). OGAFC mixes with CRMB binder showed better results for permeability, skid resistance, and resistance to long-term binder draindown.

Keywords: *open graded asphalt friction course, BOF steel slag, mix design, functionality, durability, performance.*

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(Santanu Pathak)

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LIST OF ABBREVIATIONS

AAL	Aged Abrasion Loss
AAS	Atomic Absorption Spectroscopy
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
ANOVA	Analysis of Variance
APAO	Amorphous Poly Alpha Olefin
APT	Accelerated Pavement Rutting Test
ASTM	American Society for Testing and Materials
ASV	Aggregate Soundness Value
AV	Air Voids
BC	Binder Content
BOF	Basic Oxygen Furnace
BPN	British Pendulum Number
BPN_1	Wet British pendulum number
BPN_2	Hysteresis
BPT	British Pendulum tester
BT	Binder Type
CA	Coarse Aggregate
COC	Cleveland Open Cup
CRMB	Crumb Rubber Modified Bitumen
CT	Computed Tomography
DFT	Dynamic friction tester
DGAC	Dense Graded Asphalt Concrete
DGBC	Dense Graded Bituminous Concrete
DGHMA	Dense Graded Hot Mix Asphalt
DOT	Department of Transportation

EAF	Electric-arc Furnace
EN	Environment Type
ETP	Ethylene Terpolymer
FA	Fine Aggregate
FDOT	Florida Department of Transportation
FESEM	Field Emission Scanning Electron Microscopy
FHWA	Federal Highway Administration
FT	Freeze-Thaw
GDP	Gross Domestic Product
HMA	Hot Mix Asphalt
HSA	High Surface Area
HWTD	Hamburg Wheel Tracking Device
IRC	Indian Roads Congress
ITF	Indirect Tensile Fatigue
ITS	Indirect Tensile Strength
ITSM	Indirect Tensile Stiffness Modulus
LA	Los Angeles
LAAV	Los Angeles Abrasion Value
LLD	Load-Line Displacement
LVDT	Linear Variable Displacement Transducer
Max.	Maximum
Min.	Minimum
MMLS3	Third-Scale Model Mobile Load Simulator
MoRTH	Ministry of Road Transport and Highways
MQ	Marshall Quotient
MT	Million Tonnes
MTD	Mean Texture Depth
NA	Not Applicable
NAPA	National Asphalt Pavement Association
NCAT	National Center 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

NS	Not Significant
NSA	Natural Stone Aggregate
OBC	Optimum Binder Content
OGAFC	Open Graded Asphalt Friction Course
OGFC	Open Graded Friction Course
PA	Porous Asphalt
PAV	Pressure ageing vessel
PC	Polishing Cycle
PEM	Permeable European Mixes
PFC	Permeable Friction Course
PMB	Polymer Modified Bitumen
PMGSY	Pradhan Mantri Gram Sadak Yojana
PSV	Polished Stone Value
PVC	Polyvinyl Chloride
QA	Quality Assurance
QC	Quality Control
R&B	Ring and Ball
RCA	Recycled Concrete Aggregate
RM	Resilient Modulus
RMS	Retained Marshall Stability
RTFOT	Rolling Thin Film Oven Test
S	Significant
SAIL	Steel Authority of India Limited
SARDP-NE	Special Accelerated Road Development Programme for the North East Region
SBS	Styrene-Butadiene-Styrene
SC	Slag Content
SCB	Semi Circular Bend
SGC	Superpave Gyratory Compactor
SHIP	State Highways Improvement Programme
SMA	Stone Matrix Asphalt
SN	Skid Number
S-O-S	Stone-on-stone
SSA	Steel Slag Aggregate
SSD	Saturated Surface Dry
TCLP	Toxicity Characteristics Leaching Procedure

TD	Texture Depth
TSR	Tensile Strength Ratio
UAL	Unaged Abrasion Loss
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
US	United States
USA	United States of America
USD	United States Dollar
USEPA	United States Environmental Protection Agency
UTM	Universal Testing Machine
VCA	Voids in coarse aggregate
VCA_{drc}	Voids in Coarse Aggregate for the Dry-Rodded Condition
VCA_{mix}	Voids in Coarse Aggregate for the Compacted Mix
VCA-ratio	Voids in coarse aggregate ratio
VG	Viscosity Grade
WAL	Wet Abrasion Loss
WHO	World Health Organisation
WMA	Warm Mix Asphalt
XRF	X-ray Fluorescence

LIST OF SYMBOLS

$\lvert m_{75} \rvert$	absolute value of the post peak slope in SCB test
a	cross-sectional area of standpipe of the falling head permeameter
A	cross-sectional area of the specimen
b	thickness of specimen used in the SCB test
$CR_{initial}$	initial clogging rate
$CR_{secondary}$	secondary clogging rate
CT_{Index}	cracking tolerance index
D	average diameter of sample
D_{MTD}	average diameter of the sand patch in mean texture depth evaluation
dU/da	change of strain energy with notch depth
F	applied peak load for evaluation of modulus strength
G^*	complex modulus
G_{CA}	bulk specific gravity of the coarse aggregate fraction
G_f	failure energy obtained through SCB test
G_{mb}	bulk specific gravity of the compacted mixture
G_{mm}	theoretical maximum specific gravity
h	height of specimen
h_0	Initial height of specimen for static and dynamic creep test
h_1	initial head of water in the falling head permeameter
h_2	final head of water in the falling head permeameter
I_a	particle index or angularity coefficient
$ITS_{conditioned}$	indirect tensile strength of the conditioned set
$ITS_{unconditioned}$	indirect tensile strength of the unconditioned set
J_c	J-integral
K	permeability of compacted specimen
K_{dc}	de-clogged permeability
K_i	initial permeability of OGAFC mixes

K_{sc}	surface clogged permeability
L	distance travelled by water through a compacted specimen in the permeability test
l_{65}	displacement corresponding to the 65%, peak load measured at the post peak stage in SCB test
l_{75}	displacement corresponding to the 75%, peak load measured at the post peak stage in SCB test
l_{85}	displacement corresponding to the 85%, peak load measured at the post peak stage in SCB test
M	mass of compacted specimen in air
m_{10}	mass of the compacted aggregates corresponding to 10 blows in particle index test
m_{50}	mass of the compacted aggregates corresponding to 50 blows in particle index test
M_R	resilient modulus
m_{sand}	mass of graded sand used for surface clogging in permeability test
n	porosity of compacted specimen
P	mass of sample after Cantabro abrasion loss test
P_0	mass of sample before Cantabro abrasion loss test
P_{65}	75% of the peak load measured at the post peak stage in SCB test
P_{75}	65% of the peak load measured at the post peak stage in SCB test
P_{85}	85% of the peak load measured at the post peak stage in SCB test
P_{CA}	percent coarse aggregate in the total mixture
s	bulk specific gravity of aggregate used in particle index test
S_m	stiffness modulus of the specimen
t	time required to drop of water from h_1 to h_2
T	temperature
t_c	temperature correction applied for water viscosity considering 20°C as standard test temperature in permeability test
V	bulk volume of compacted specimen
v	volume of cylinder in particle index test
V_{10}	volume of the compacted aggregates corresponding to 10 blows in particle index test
V_{50}	volume of the compacted aggregates corresponding to 50 blows in particle index test
V_a	air voids content of the compacted asphalt mix
VCA_{DRC}	voids in Coarse Aggregate for the Dry-Rodded Condition

VCA_{mix}	voids in Coarse Aggregate for the Compacted Mix
V_{MTD}	volume of standard sand used for sand patch in mean texture depth evaluation
W_1	weight of wire basket in binder draindown test
W_2	weight of sample and wire basket in binder draindown test
W_3	weight of tray in binder draindown test
W_4	weight of tray after being kept for 1 hour in the oven in binder draindown test
W_a	dry weight of the aggregate in modified boiling water test
W_{caa}	weight of binder coated aggregate after the test in modified boiling water test
W_{cab}	weight of binder coated aggregate before the test in modified boiling water test
W_f	work of failure in SCB test
W_{fp}	detached quantity of aggregate in modified boiling water test
Z_{RM}	recoverable horizontal deformation in RM test
Z_{SM}	amplitude of horizontal deformation during the load cycle in ITSM test
α	level of significance in ANOVA analysis
γ_s	bulk density of coarse aggregate fraction in dry-rodded condition
γ_w	density of water
δ	phase angle
$\Delta h(t)$	change in specimen height at any time '*t*' in static and dynamic creep test
μ	Poisson's ratio
$\mu\varepsilon$	micro-strain
$\varepsilon(t)$	axial strain at any time in static and dynamic creep test

Chapter 1: Introduction

1.1 Background Information

India has a large road network with a total length of about 62 lakh kilometres (km) or 6.2 million km, which stands second in the world. The existing road network mainly comprises of: Expressways and National Highways (1.36 lakh km or 0.136 million km); State Highways (1.77 lakh km or 0.177 million km); and Major District Roads, Other District Roads, and Village Roads (59 lakh km or 5.9 million km) (MoRTH, 2021). Based on the type of pavement, roads are broadly classified into two types – flexible pavement (Figure 1.1) and rigid pavement (Figure 1.2).

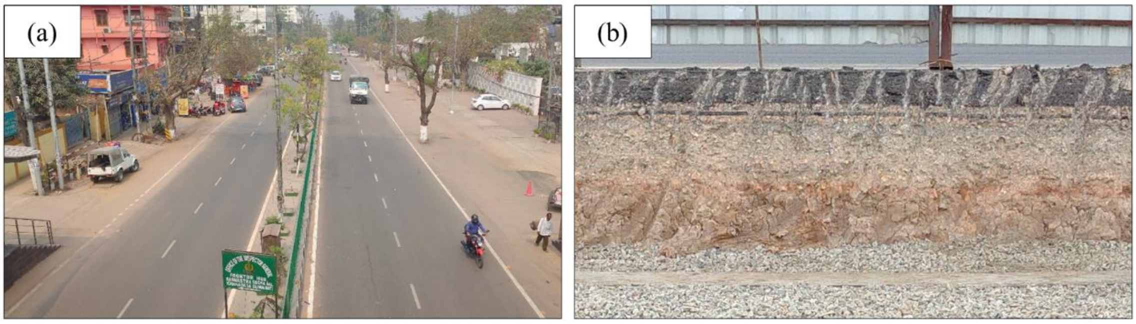


Figure 1.1: A typical flexible pavement: (a). general view, and (b). sectional view.

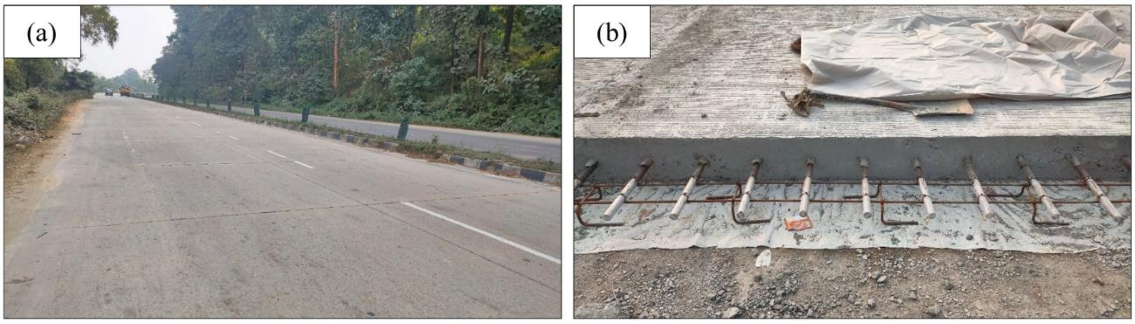


Figure 1.2: A typical rigid pavement: (a). general view, and (b). sectional view.

Majority of roads in India are flexible pavements that consist of bituminous wearing and binder courses built over a granular base course and sub-base course, and all these courses finally rest upon the compacted soil subgrade. The topmost layer is termed the surface course or wearing course of a flexible pavement, and it mainly comprises of a dense graded bituminous layer with an air void content in the range of 3 to 5 percent. A dense graded and relatively impermeable wearing bituminous course with an adequate camber forms a strong and durable surface that also prevents entry of surface water in the pavement structure/surface. However, on wider asphalt[1] pavements, especially under heavy precipitation, a thin layer of water usually exists on the pavement surface, which can lead to hydroplaning, splash/spray and reduced visibility. Hydroplaning is the situation when a vehicle tyre moving at high speed runs over a thin sheet of water present on the road surface and it results in the loss of contact of the tyre with the pavement surface, which may lead to the loss of control of the vehicle. The skid resistance/frictional characteristics of impermeable/dense-graded bituminous surfaces get reduced due to hydroplaning, especially during precipitation or wet weather conditions, and thus increases the chances of road accidents. Presence of this thin sheet of water also leads to glare and reduction in visibility.

[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.

Figure 1.3 illustrates a schematic view of hydroplaning, splash and spray of rainwater as well and the glare due to presence of a film of water on the pavement surface. The combined action of hydroplaning, splash and spray of the rainwater runoff, and glare effect significantly affects driving safety, especially during wet weather conditions. According to the World Health Organization (WHO), road accidents are the eighth leading cause of death and global fatalities. Road accidents contribute about 13 lakhs (or 1.3 million) fatalities each year, with approximately 5 crore (or 50 million) people suffering severe injuries. At this rate, it is predicted that road accidents will become one of the leading causes of death by 2030, with an approximate death expectancy of 24 lakhs (or 2.4 million) per year (WHO, 2018).

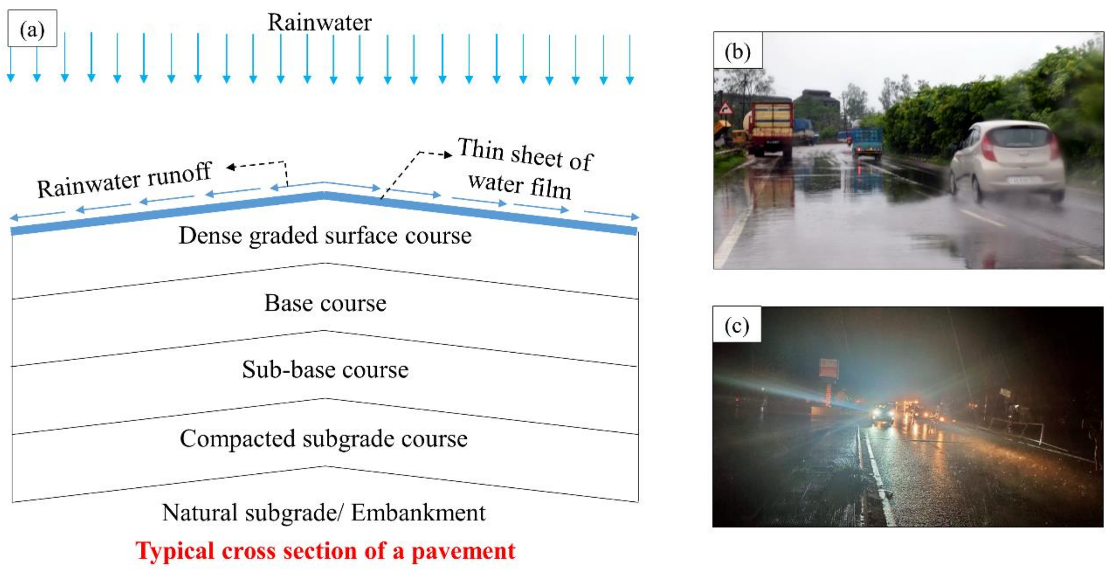


Figure 1.3: Hydroplaning in a dense graded surface course: (a). schematic view, (b). splashing and spraying of rainwater runoff, and (c). glare at night.

In India 4,49,002 road accidents were registered in the year 2019, which accounted for 1,51,113 fatalities translating to an average of 51 accidents and 17 fatalities every hour (MoRTH, 2019). These traffic accidents led to an economic loss of about 3% of India's GDP (approximately 58 billion USD value) (UNESCAP, 2016). In addition to the driver's fault, pedestrian or vehicle deformity, poor pavement surface characteristics/conditions also form a notable cause for road accidents. Pavement surface frictional resistance/skid resistance plays an important role in road safety especially under wet weather conditions. Lack of pavement friction and wet weather conditions caused 5.21% and 7.61% of total road accidents in India in 2015 and 2016, respectively (MoRTH, 2015, 2016). In 2019 wet weather conditions alone accounted for about 30% of the total road fatalities in India (MoRTH, 2019).

In the interest of better road safety during wet weather conditions, it is highly desirable to prevent the accumulation of rainwater on the pavement surface. In high rainfall regions, this can be achieved by adopting special types of pavement surface courses that have high permeability and allow quick drainage of water. A quick removal of surface water will inhibit formation of water film and will thus help to maintain a continuous contact between the vehicle tyre and the road surface for safe travel. Open graded asphalt friction courses (OGAFCs) are special-purpose asphalt courses/mixes with a large percentage of air voids (more than 18% of mix volume) that allow quick removal of surface water and offer a high friction pavement surface under both dry and wet weather conditions.

An open structure in OGAFC is achieved by using narrowly-graded coarse aggregate gradation with a low proportion of fine aggregates. The open structure allows rainwater to enter and flow within this course laterally to the day-lighted edges and reduces the formation of water films on the pavement surface. This quick removal of surface water helps reduce hydroplaning, minimise splash and spray, reduce glare, and improve visibility, especially under wet weather conditions (Kandhal, 2002; Choudhary *et al.*, 2017; James *et al.*, 2017). With high air voids and lower fine aggregate content, the macrotexture of the OGAFC mix is also quite better than the conventional dense-graded mixes and thus helps to provide enhanced surface friction and skid resistance. The open structure further reduces tyre pavement interaction noise by absorbing the noise at the source making the pavement relatively quieter.

Figure 1.4(a) illustrates a schematic diagram showing the transverse flow of rainwater runoff through the interconnected voids of OGAFC, while Figures 1.4(b) and 1.4(c) show the presence and absence of a thin film of water at the surface of a dense graded asphalt and OGAFC specimen, respectively. It can be clearly seen that OGAFC allows the rainwater runoff to flow through its network of voids, thereby negating the presence of thin film water over its surface.

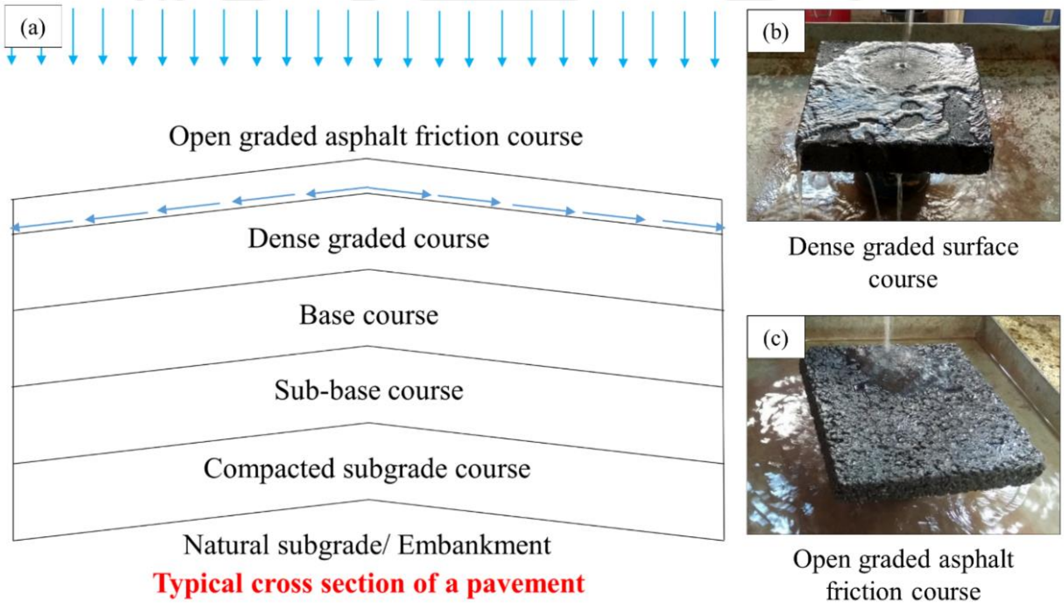


Figure 1.4: Water drainage in an OGAFC: (a). schematic view, (b). presence of water film over a dense graded surface course, and (c). absence of water film over an OGAFC.

The use of OGAFC results in enhanced driving safety during wet weather conditions. Use of OGAFC has led to a reduction of 29–41% in road accidents (Oh *et al.*, 2010) and 100% reduction in fatalities (King *et al.*, 2013) related to wet weather conditions. OGAFC mixes are also referred as open graded friction course (OGFC), permeable friction course (PFC), and permeable European mixes (PEM) in various parts of the world and can be considered as synonyms to each other. Coarse aggregates constitute almost 90 percent of the total aggregates in the OGAFC aggregate structure. OGAFC mixes require good quality coarse aggregates to be able to distribute the traffic loads through stone-on-stone contact while allowing stability and a high void structure to perform the drainage functions.

High-speed corridors comprising of national highways and expressways in India form a relatively small share (2%) in the total road network but they carry about 87% of passenger traffic and 60% of freight traffic of the country. The road infrastructure is therefore continuously undergoing rapid expansion under various ambitious programs/ schemes of Government of India, including National Highways Development Programme (NHDP), National Highways Interconnectivity Improvement Project (NHIIP), State Highways Improvement Programmes (SHIPs), Bharat Nirman, Bharatmala Pariyojana, Special Accelerated Road Development Programme for the North- East (SARDP-NE), Pradhan Mantri Gram Sadak Yojana (PMGSY), *etc*.

While road infrastructure development is crucial for the economic and strategic development of the country, there is no denying that highway construction demands enormous quantities of natural resources, especially stone aggregates. The demand for aggregates for pavement construction has been continually increasing, and at the same time, sources near urban and other sub-urban areas are getting depleted. Moreover, the availability of natural aggregates in many plain and hilly regions of the country is scarce because of mining/quarrying restrictions, deforestation and environmental protection regulations, and appreciating land values. The depleting natural sources of aggregates and adverse environmental impacts of mining and quarrying have compelled researchers to explore wastes and industrial by-products as alternative aggregate materials. Utilisation of waste and industrial by-products in pavements will also contribute toward environmental protection and resource conservation.

As of 2021, India is the second-largest steel producer in the world, with a steel production of 108.5 million tonnes (MT) in the year 2020 (Worldsteel, 2021). Steel slag is an industrial by/co-product obtained from steel-making industries during the conversion of iron to steel. The conversion of iron to steel takes place either in a basic oxygen furnace (BOF) or an electric arc furnace (EAF), thus constituting the two main types of steel slag: BOF steel slag and EAF steel slag. Presently, there are 17 BOF units and 48 EAF units of steel plants in India. These units are mainly spread across the following states — Jharkhand, West Bengal, Odisha, Chhattisgarh, Andhra Pradesh, Karnataka, Tamil Nadu, Maharashtra, Gujarat, Uttar Pradesh and Haryana (Indian Bureau of Mines, 2018a). Steel slag accounts for approximately 20% of crude steel output. About 20 MT of steel slag is produced annually in India of which only 17–20% is reused. The remaining 80% of the steel slag produced in steel plants is generally disposed of by indiscriminate dumping in nearby landfills, which causes serious environmental problems (Indian Bureau of Mines, 2018b).

Due to its favourable physical and chemical characteristics, steel slag has a good potential for use as a road making aggregate. Nowadays, environmental legislations and economics have also persuaded the steel industries to minimise the generation of steel slags and maximise their recycling or reutilisation. Due to the increasing awareness for environment protection, disposal, recycling, and reuse of wastes without harming the environment has become a prime concern. Efforts are needed to explore the utilisation of steel slag. The use of steel slag in OGAFC mixes could be a promising option for its bulk utilisation.

1.2 Problem Statement

Safety concerns associated with the conventional dense graded bituminous mixes under wet weather conditions are hydroplaning, splash and spray of rainwater runoff, reduced skid resistance, and hindered visibility. In 2016, a total of 54,670 road accidents occurred during wet weather conditions leading to 17,081 fatalities, while poor visibility during night-time driving resulted in 3,833 road accidents and 1,631 fatalities throughout the country (MoRTH, 2016). In the interest of better road safety in heavy rainfall regions, it is desirable to have pavement surface courses that inhibit the accumulation of surface rainwater or the formation of a water film on the pavement surface. This can be achieved by adopting an OGAFC course, a special purpose thin bituminous overlay/course, with significantly high air voids. OGAFC mixes have high permeability and allow quick removal of surface water. Thus, an absence of water on the pavement surface will eliminate hydroplaning and will provide adequate skid resistance and visibility under wet weather conditions.

There are some important aspects that need proper attention to achieve the desired performance from an OGAFC course. The higher air voids content achieved through a relatively small amount of fine aggregate content makes OGAFC mixes prone to ravelling and binder draindown. Further, an exposure to rainwater (or moisture) for a longer period also raises the concerns related to moisture-induced damage. These challenges are usually addressed by the use of strong aggregates, stiffer grade binders (like modified binders), and additives (like cellulose fibres) in OGAFC mixes. Modified binders like polymer modified bitumen and crumb rubber modified bitumen are relatively stiffer grades of bitumen which prevents the binder draindown and develops a better adhesion with the aggregate surface, resisting the ravelling, moisture damage and ageing.

The high porosity of OGAFC mixtures is attained by adopting single-sized coarse aggregates with low fine aggregate content. The traffic load endured by an OGAFC mixture is resisted through its coarse aggregate skeleton having proper stone-on-stone contact. OGAFC mixtures thus demand quality road aggregates, especially in terms of strength, shape, and texture. Continuous demand for good building and construction natural aggregates has resulted in environmental challenges and a sharp increase in their cost. The accessibility and availability of natural aggregates have even dwindled in many regions.

To sustain the huge demand for natural aggregates and maintain a balance in the environment, researchers have been trying to reuse various industrial wastes (Tchobanoglous, 1993) and marginal aggregates (Kumar and Sharma, 2014) in construction activities. Steel slag, obtained during the conversion of iron or steel scrap to industrial quality steel, is one such industrial by-product that can be included in the inventory of road making aggregates. The desirable physical and chemical properties as strength, hardness, angularity, rough-texture and basicity of steel slag are expected to make it a suitable candidate for OGAFC mixes and may help to bring down the demand and dependence on the natural aggregates.

Under this perspective, the present study evaluates the effect of varying percentage substitution of coarse natural stone aggregate with BOF steel slag on the functionality, durability, and performance of OGAFC mixes with different modified binders. This study evaluates the effect of BOF steel slag substitution and modified binder types on the mix design parameters measured in terms of stone-on-stone contact, air voids content, binder draindown, unaged and aged abrasion loss. The study further evaluates the functionality of the OGAFC mixes incorporating BOF steel slag in terms of its permeability, clogging, and frictional characteristics. It also assesses the durability of the OGAFC mixtures in terms of their resistance to moisture induced damages and long-term binder draindown potential. The study further examines the performance of the BOF steel slag incorporated OGAFC mixes through the measurement of rutting resistance, cracking potential, fatigue life, and modulus properties.

1.3 Objectives of the Study

The main aim of the study is to evaluate the characteristics of OGAFC mixes with the replacement of coarse natural aggregates by BOF steel slag. The BOF steel slag is incorporated in OGAFC mixes through five different substitution/replacement percentages of the coarse aggregate fraction of the natural aggregates. The study includes one type of natural stone aggregate, one type of BOF steel slag, and two types of modified binders (PMB: polymer modified bitumen and CRMB: crumb rubber modified bitumen). The following objectives are formulated for the study:

1. Characterisation of natural stone aggregate, BOF steel industry slag, and modified binders selected for the study.
2. Determination of volumetric and design parameters of OGAFC mixes with varying percentages of BOF steel slag aggregate as a replacement of natural coarse aggregates.
3. Evaluation of functionality of OGAFC mixes with and without BOF steel slag aggregates in terms of drainability, clogging, and frictional characteristics.
4. Assessment of durability of OGAFC mixes with and without BOF steel slag aggregates in terms of moisture susceptibility and long-term binder draindown potential.
5. Evaluation and comparison of performance properties of OGAFC mixes with varying replacement percentages of natural coarse aggregates by BOF steel slag in terms of rutting resistance, cracking potential, fatigue life, and modulus properties.

1.4 Organisation of the Thesis

The contents of this thesis have been organised into eight chapters. Chapter 1 introduces the research area, provides background information on OGAFC mixes and BOF steel slag, and highlights the research problem and objectives of the research work. Chapter

2 includes a more in-depth look at OGAFC mixes (including historical timeline, advantages, and challenges) and steel slag (production, utilisation, and properties). It further covers an extensive review of literature related to this research and the identification of research gaps. Chapter 3 presents the selection of materials, their characterisation, experimental programme, and test procedures used to achieve the framed objectives. Chapter 4 presents the mix design test results of OGAFC mixes with varying substitution percentages of BOF steel slag. Chapter 5 presents the functional properties of BOF steel slag incorporated OGAFC mixes in terms of permeability, clogging, and frictional resistance. Chapter 6 assesses the durability of OGAFC mixes incorporating BOF steel slag aggregates in terms of their moisture susceptibility and long-term binder draindown potential. Chapter 7 presents the performance test results of BOF-OGAFC mixes regarding rutting resistance, cracking potential, fatigue life, and modulus properties. Finally, Chapter 8 summarises the study and presents the conclusions drawn from the results and their analyses, and the recommendations for future research.

Chapter 2: Review of Literature

2.1 General

Open graded asphalt friction courses (OGAFCs) are widely used in different regions/countries such as United States of America, European countries and other countries across the globe. They offer several associated benefits in terms of improved skid resistance, increased visibility, lower tyre-pavement interaction noise and higher safety, especially under wet weather conditions. Throughout the world, researchers have conducted several research studies on the various design and performance aspects of OGAFC mixes under diverse environmental and vehicular loading conditions. Simultaneously, the practice of using industrial waste steel slag as a replacement of natural aggregates in bituminous mixes is also gaining popularity among researchers and practitioners. This chapter presents a comprehensive review of literature on OGAFC mixes that covers their historical timeline, advantages and challenges, and the design and performance aspects. It also presents a review of studies on the production and generation of industrial waste steel slag and its application as road aggregates in bituminous mixes.

2.2 OGAFC: Definitions, historical timeline, advantages and challenges

OGAFC is a special type of hot mix asphalt (HMA) designed for high air voids content, attained by a coarse aggregate skeleton with adequate stone-on-stone contact providing durability to the mixture in order to assist drainage during heavy precipitation (Kline, 2010). During a rainfall event, the OGAFC mix structure permits the rainwater to infiltrate vertically and then flow sideways through the drainage path created by the chain of interconnected air voids. The cross slope (or camber) assists the sideways flow within the OGAFC to the adjacent storm water collecting units at the edge of the road (Kandhal, 2016).

OGAFC mixtures have been reported to be used since early 1944 in the state of California (Huber, 2000). They began to gain popularity across the United States after the two Federal Highway Administration’s (FHWAs) programs Federal Highway Safety Program Management Guide (Highway Safety Program 12) and Instructional Memorandum (Skid Accident Reduction Program in 1970’s (Kandhal, 2002). Mixed responses were observed by different agencies regarding OGAFC implementation mainly due to its short pavement life (reported to be from 7 to 13 years) and frequently observed failures (Huber, 2000). OGAFC mixtures were reported to fail prematurely due to ravelling, clogging of the surface pores, stripping and de-bonding of the OGAFC with the underlying dense graded HMA course. Furthermore, cold climatic states also reported the issue of frost formation (Root, 2009). Around 2000, the National Center for Asphalt Technology (NCAT) suggested the use of new generation OGAFC mixtures which were adopted from the European countries where they were called Permeable European Mixes (PEM) or Permeable Friction Courses (PFC) or Porous Asphalt (PA) (Kline, 2010; Huber, 2000). The new generation OGAFC mixes were composed of larger coarse aggregate fraction and smaller fine aggregate portion resulting in a high air voids content of 18-22% along with the recommendation to use polymer modified binders with/without the addition of fibres (Kandhal and Mallick, 1999). These new generation OGAFC mixes aided in overcoming the drawbacks previously been faced by various agencies related to in-field implementation.

The primary motivation behind the use of OGAFC mixtures was to bring down the count of road accidents, especially during wet weather conditions (Chen *et al.*, 2017). However, there are many other advantages associated with OGAFC in terms of driving comfort and environmental benefits (Kandhal, 2016). The interconnectivity of the voids in OGAFC mixtures provides high permeability/quick-drainability of rainwater runoff which reduces the concern of standing water on pavements and diminishes the splash/spray of the runoff during wet weather conditions (King *et al.*, 2013). A reduction of 90-95% in splash and spray of rainwater over a newly laid OGAFC was reported compared to a conventional dense graded HMA (Huber, 2000). Another study revealed that rainwater spraying behind the rear wheels of a vehicle mounted to a distance of about one meter in case of OGAFC surface compared to 5 to 10 meters for dense graded HMA (Nicholls, 1997). The quick drainage of rainwater runoff resulted in the reduction in the potential for hydroplaning (Kandhal and Mallick, 1999), thereby increasing the visibility and reducing the glare at night (Cooper *et al.*, 2004; Kandhal, 2002).

A study conducted on the evaluation of loss of visibility due to splash/spray of rainwater runoff reported that at a speed of 80 kmph the visibility loss over dense graded HMA and porous asphalt was about 55% and 28% respectively (Rungruangvirojn and Kanitpong, 2010). The surface texture of OGAFC mixtures helped in increasing the skid resistance (during both dry and wet weather conditions) (Pattanaik *et al.*, 2017) The skid resistance of OGAFC mixes was reported to increase by 6.3% and 16.4% (measured by British pendulum number) compared to dense graded HMA under dry and wet weather conditions, respectively (Yang and Zhongyin, 2005).

The aforementioned benefits of OGAFC collectively provide safer manoeuvrability of the vehicles and consequent decrease in the rate of traffic accidents. A study revealed a reduction of 29-41% in road accidents related to wet weather conditions after the installation of OGAFC (Oh *et al.*, 2010). Another study conducted in South Carolina showed a reduction of 23% in wet weather accidents when OGAFC was utilised as a surface layer (McGlumphy, 2017).

OGAFC mixtures were also reported to aid in the reduction of traffic noise generated by the tyre-pavement interaction (Bennert *et al.*, 2005). Studies have reported a decrease of about 50% in noise generation for OGAFC mixes, compared to dense graded HMA (Huber, 2000; Anderson *et al.*, 2013). Another study on OGAFC in Los Angeles revealed a decrease in noise generation by 2 dB within 32 months of service life compared to dense graded HMA. Cost-benefit analysis of the study revealed that due to the reduction in noise, a benefit of $12,057 was achieved (Gu *et al.*, 2018).

Despite the advantages, some challenges have been also reported with OGAFC mixtures especially in terms of their durability (with regard to disintegration and ravelling of aggregate particles) and functionality (related to clogging) (Hernandez-Saenz *et al.*, 2016). Other concerns reported with the use of OGAFC are – low contribution to pavement structural strength (Kandhal, 2016), frequent maintenance requirements (de-clogging and deicing) (Putman, 2012), use of comparably high quality aggregates than traditional dense graded HMA (Asi, 2007; Pattanaik *et al.*, 2017), and high construction cost (Arámbula *et al.*, 2013). However, recent studies on the cost-benefit analysis of OGAFC mixes reported a reduction in the net present value cost by 36% when compared with conventional dense graded HMA (Gu *et al.*, 2018).

OGAFC is highly popular in the United States and is widely accepted by various Departments of Transportation (DOTs) such as Alabama, Georgia, Florida, South Carolina, Texas, Arizona, Colorado, Utah, Michigan, New Jersey, Rhode Island, Vermont, Washington, Oregon, and California. It also has a large global acceptance and is practised in several other countries such as — Netherlands, Germany, Belgium, Spain, Switzerland, Italy, Denmark, the United Kingdom, South Africa, New Zealand, Australia, China, Japan and Malaysia (Stanard *et al.*, 2007). Recently, India has also released its own standard guidelines on OGAFC titled *"IRC 129 – 2019: Specifications for open-graded friction course"* and it is expected that the implementation of OGAFC will gain momentum in India in the near future.

2.3 Design, functionality, durability, and performance of OGAFC mixes

2.3.1 Design of OGAFC mixes

OGAFC mixes have been practised by road engineers for more than seventy-five years and it has undergone several modifications in its design procedure. OGAFC mixes have gained wide popularity after the mix design proposed by the FHWA in the early 1970's (Kandhal, 2002). FHWA published its first set of OGAFC mix design guidelines in 1974 which were modified twice in 1980 and 1990 (Watson *et al.*, 2003). The FHWA mix design specifications mainly suggested the use of good quality road aggregates corresponding to an open aggregate gradation with nominal maximum aggregate size of 9.5 mm. However, the selection of binder and additive was based on the availability in the local conditions. The binder content was determined based on the oil absorption test and the predominant aggregate particle size, while the mixing temperature was selected based on the binder draindown test (visual inspection only). The moisture sensitivity of the mixes was ascertained based on 50% retained strength (FHWA, 1990).

Kandhal and Mallick (1998) conducted a study on mix design procedures adopted by various states in the United States of America (USA) under a program organised by the NCAT. They found that there was no uniformity in the mix design methodology adopted by various states and 76% of the 43 surveyed states followed different mix design guidelines. In 2000, NCAT published guidelines on the design of OGAFC mixes titled *"Design, Construction and Performance of New-Generation Open-Graded Friction Courses"* based on the studies conducted in various parts of the USA and Europe (Mallick *et al.*, 2000). The design methodology was based on three primary components, namely material selection, gradation, and selection of optimum binder content. A detailed discussion on the three components is provided in the following sections.

2.3.1.1 Selection of materials

The requirements for aggregates for OGAFC included the use of crushed aggregates with minimum flat and elongated particles, strong and durable aggregate with a maximum Los Angeles abrasion value of 30% and a low water absorption (Mallick *et al.*, 2000). NCAT mix design methodology recommended the use of polymer modified binder (typically two PG grades higher than the binder used in the area) and fibres for the preparation of OGAFC mixes to attain better strength and durability. Use of polymer modified binder in the design and preparation of OGAFC mixes is reported to improve abrasion resistance, and reduce binder draindown and moisture susceptibility (Hassan and Al-Jabri, 2005; Liu and Cao, 2009; Xiao *et al.*, 2015). Apart from polymer modification, rubber modification of asphalt binder has also shown to improve OGAFC mix resistance towards abrasion, moisture damage, rutting, and draindown (Lyons and Putman, 2013; Xiao *et al.*, 2015; Shirini and Imaninasab, 2016; Sangiorgi *et al.*, 2017).

As OGAFC mixes demand stiffer and thicker films of binders to resist draindown, ravelling and moisture damage, use of fibres has been also recommended for stiffening of the asphalt binders (Mallick *et al.*, 2000; Pasetto, 2000; Punith and Veeraragavan, 2011). OGAFC mixes prepared with cellulose fibres showed a significant reduction in binder draindown and ravelling (Hassan *et al.*, 2005; Wu *et al.*, 2006; Lyons and Putman, 2013). Several other fibres like mineral fibres, date-palm fibres, textile fibres, polyester fibre, polyethylene fibres, basalt fibres, and glass fibres have reported to improve abrasion loss, binder draindown, and moisture susceptibility of the OGAFC mixes (Cooley *et al.*, 2000; Hassan and Al-Jabri, 2005; Wu *et al.*, 2006, Punith and Veeraragavan, 2011, Tanzadeh *et al.*, 2019).

2.3.1.2 Selection of aggregate gradation

Selection of aggregate gradation for OGAFC was based on the verification of stone-on-stone contact. The stone-on-stone contact was ascertained by comparing the voids in coarse aggregate (*VCA*) in the dry-rodded condition (VCA_{DRC}) to the *VCA* in the compacted OGAFC mixture (VCA_{mix}) (Kandhal, 2002). An OGAFC mixture was said to achieve proper stone-on-stone contact when the VCA-ratio (VCA_{mix}/VCA_{DRC}) was less than or equal to 1.0. Watson *et al.* (2004) and Alvarez *et al.* (2010b) further validated the *VCA*-ratio method for stone-on-stone contact through analysis of digital images of mix specimens. The dry-rodded method was selected based on the test results of a study conducted by Brown and Haddock (1997) where they compared the *VCA* of a porous aggregate skeleton through five different methods and concluded that the dry-rodded method reported the lowest *VCA* and the least aggregate breakdown. Henceforth, the *VCA* method was the most widely accepted test method to evaluate the stone-on-stone contact of an OGAFC mix. Figure 2.1 compares typical gradations recommended by FHWA (1974) and Mallick *et al.*

(2000) for preparation of OGAFC mixes. It can be seen that the gradation suggested by NCAT (Mallick *et al.*, 2000) is more uniform with lower fine content.

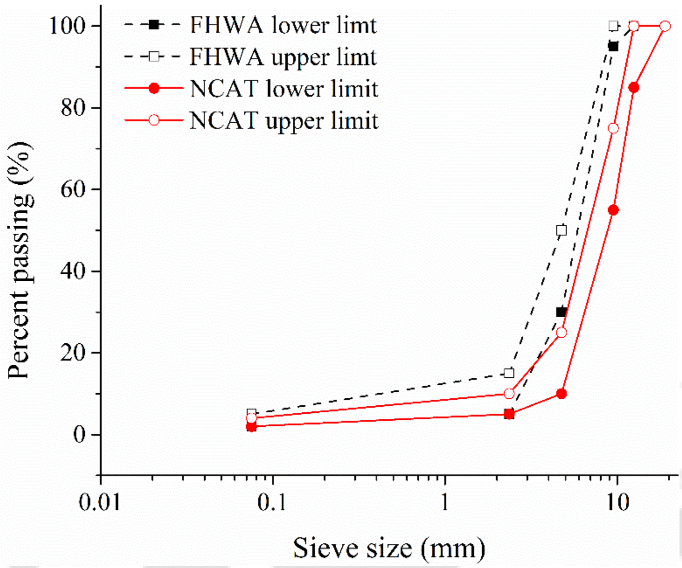


Figure 2.1: Recommended aggregate gradation by FHWA and NCAT.

2.3.1.3 Optimum binder content

The optimum binder content (OBC) for OGAFC was recommended to be selected on the basis of a minimum air voids content of 18%, maximum unaged abrasion loss of 20%, maximum aged abrasion loss of 30%, maximum binder draindown of 0.3%, and a minimum tensile strength ratio of 80% (Kandhal, 2002). Alvarez *et al.* (2008) recommended the use of dimensional analysis over vacuum seal method for calculating the bulk specific gravity of the OGAFC mix specimens for better reliability.

The abrasion loss test examined the ravelling potential of the OGAFC mixes. The common causes observed for ravelling were (1) use of a low asphalt binder content resulting in a thin asphalt film (Mallick *et al.*, 2000), (2) loss of adhesion between the aggregate surface and the asphalt film due to oxidative ageing and stiffening (Poulikakos *et al.*, 2003), (3) moisture induced damage (Suresha *et al.*, 2010a; Pattanaik *et al.*, 2019), and (4) improper compaction (Alvarez *et al.*, 2009). The most commonly adopted method to evaluate the ravelling potential of an OGAFC mix is the Cantabro abrasion loss test developed in Spain in 1990 (Pérez *et al.*, 1990; Khalid H and Walsh, 1997; Miró *et al.*, 2001; Herrington *et al.*, 2005; Suresha *et al.*, 2009a). The Cantabro abrasion loss test is conducted by placing a compacted OGAFC specimen in the drum of a Los Angeles abrasion machine without any abrasive charge (steel balls) and rotating the same for 300 revolutions at a speed of 30-33 rpm (Alvarez *et al.*, 2008). The percentage loss in mass is expressed as the abrasion loss value. Khalid *et al.* (1998) stated that this test is temperature sensitive and should be performed at 25°C.

The open structure of the OGAFC mixes makes them highly susceptible to ageing (oxidative hardening and stiffening) compared to conventional dense graded asphalt mixtures. This higher ageing leads to loss in the cohesive and adhesive strength of the OGAFC mix resulting in ravelling (Kandhal and Mallick, 1999). Various studies have been conducted to simulate the long-term ageing of OGAFC mixes in the laboratory by adopting different protocols with differences in ageing temperature and time. Table 2.1 summarises the major ageing conditions adopted by various researchers in the past. Currently, ageing at 60°C for 168 hours (7-days) in a forced draft oven is the most widely adopted ageing protocol to simulate the long-term ageing of OGAFC mixes (Kandhal and Mallick, 1999; ASTM D7064, 2013).

Table 2.1: Summary of long-term ageing protocols of OGAFC mixes.

Reference	*Ageing protocol*
Miró and Pérez (2001)	163°C for different periods of time (2, 4, 6, and 8 h)
Kandhal (2002)	85°C for 120 hours
Airey (2003)	85°C for 240 hours
Herrington *et al.* (2005)	3 days at 80°C at an air pressure of 2070 kPa
Alvarez *et al.* (2008)	60°C for 3 and 6 months

OGAFC mixtures exhibit an asphalt film thickness of about 30 µm compared to a film thickness of 8 µm for conventional dense graded mixes (Watson *et al.*, 2004b). The high asphalt film thickness and the lack of fines in the aggregate skeleton makes OGAFC mixes susceptible to binder draindown during mixing, hauling, and laying operations. In a study conducted by Mallick *et al.* (2000), it was found that binder draindown leads to formation of road sections that are susceptible to ravelling and relatively lower permeability. To ensure that the draindown of the asphalt binder is within permissible limits, NCAT (Mallick *et al.*, 2000) recommended the binder draindown test already in use for stone matrix asphalt and the same was adopted by ASTM D7064 (2013) for OGAFC. In this test, loose OGAFC mixes are prepared and conditioned in a wire basket (with 6.3 mm mesh size) at a temperature 15°C higher than the mixing temperature for 1 hour. The percentage of material (by weight) that drains through the wire openings is denoted as the draindown of the mixture. Wu *et al.* (2019) compared the binder draindown of OGAFC mixes through three different test methods — beaker method, wire basket method, and test pan method, and concluded that the wire basket test methodology was the most reliable.

Following the recommendations of the study conducted by NCAT, several agencies have published their own guidelines on the design of OGAFC mixes. The most prominent among them being the American Society for Testing and Materials (ASTM) specification — *"ASTM D7064: Standard Practice for Open-Graded Friction Course (OGFC) Mix Design"* which was first published in 2008 and later reapproved in 2013 (ASTM D7064, 2013). In 2021, the standard was modified and the use of warm mix technology in OGAFC was included (ASTM D7064, 2021). In 2019, India has also published its own specifications on the design of OGAFC mixes — *"IRC 129: Specifications for open-graded friction course"*.

2.3.2 *Functionality of OGAFC mixes*

Functionality is defined as the ability of an OGAFC mixture to retain its benefits/ advantages in the course of its service life (Hernandez-Saenz *et al.*, 2016). The main function of an OGAFC surface is to allow a free passage to the rainwater runoff through the network of interconnected air voids, thus it negates the possibility of hydroplaning and provides good frictional properties especially under wet-weather conditions. Earlier, permeability of an OGAFC mix was not considered a design parameter and no specific methodology was specified by any agency regarding the evaluation of permeability (Alvarez *et al.*, 2006). The NCAT (Kandhal, 2002) and ASTM D7064 (2013) in 2006, first recommended a minimum permeability value of 100 m/day for OGAFC mixes to ensure adequate drainability.

However, it is often believed that the minimum permeability value requirement should be selected on the basis of the expected rainfall intensity of the locality (Ongel *et al.*, 2009). Permeability of an OGAFC mixture has been evaluated using various types of falling head and constant permeameters. Table 2.2 summarises a list of permeameters used by researchers in the past to evaluate the drainage properties of OGAFC mixtures. From these studies, it can be concluded that the permeability of OGAFC mixtures vary over a wide range and is also influenced by intrinsic properties of the mix. Porosity, defined as the volume of inter-connected or water accessible air voids, is one such intrinsic property of an OGAFC mix governing its permeability. Cabrera and Hamzah (1996) concluded that permeability of an OGAFC mixture is directly dependent on its porosity. Alvarez *et al.* (2010c) also stated that porosity can be used as a surrogate to total air voids content for indirect measurement of permeability and that porosity gave a better correlation with permeability compared to air voids content.

Table 2.2: Summary of permeability measurements of OGAFC mixes.

Reference	*Type of permeameter*	*Permeability values (in m/day)*
Kandhal and Mallick (1999)	FDOT falling head permeameter	21–117
Fwa *et al.* (1999)	Customised falling head field permeameter	484–2169
Cooley *et al.* (2000)	Falling head permeameter	16–74
Suresha *et al.* (2009a)	Customised falling head permeameter	8–158
Alvarez *et al.* (2010c)	Falling head permeameter (ASTM PS129, 2001)	50–165
	Falling head field permeameter	
Hsu *et al.* (2011)	Constant head permeameter	80–137
Goh and You (2012)	Falling head permeameter (ASTM PS129, 2001)	10–190
Mansour and Putman (2013)	Customised falling head permeameter	25–415
Wurst and Putman (2013)	Customised falling head permeameter	239–482
Martin *et al.* (2014)	Customised falling head permeameter	20–390
Coleri *et al.* (2014)	NCAT field permeameter	26–242
	ASTM field permeameter	
Putman and Lyons (2015)	Customised falling head permeameter	225–475
Shirini and Imaninasab (2016)	Falling head permeameter (ASTM D3637, 1991)	54–122
Sangiorgi *et al.* (2017)	Falling head permeameter	67–153
Gu *et al.* (2018)	NCAT falling head field permeameter	25–59
Sarkar and Hojjati (2021)	NCAT falling head permeameter	348–511

The permeability of an OGAFC mixture depends on the selected aggregate gradation. Suresha *et al.* (2009b, 2010a) stated that OGAFC mixtures prepared with coarser open graded aggregate skeleton reported higher permeability values. Similar relationship between aggregate gradation and permeability was also reported by Mansour and Putman (2012) and Martin *et al.* (2014). However, drainage benefits associated with such high permeability can only be realized until the void structure of these mixtures remains mobilised and allows the flow of rainwater runoff. When these voids are clogged, the interconnectivity is disrupted and OGAFC mixtures may begin to behave like conventional dense-graded mixes (in terms of permeability), and the associated advantages of OGAFC may cease to exist. The prime reason for the clogging of these voids is associated with the deposition of dust and sand particles within the OGAFC mix that blocks the interconnectivity of the air voids.

Several studies have been conducted to understand the clogging potential of OGAFC mixtures. Kraemer (1990) examined the field permeability of OGAFC road sections in Spain and reported drainage time ranging from 25–75 seconds at the time of laying increased to 80–100 seconds and 160–400 seconds after 3 and 9 years of service life respectively. Mallick *et al.* (2000) also reported significant loss in OGAFC drainability following 2–3 years of service. Similarly, several case studies on the long-term serviceability of OGAFC mixtures conducted across the world such as Japan (Moriyoshi *et al.*, 2013), Canada (Gupta, 2014), China (Hu *et al.*, 2010) and Spain (Sañudo-Fontaneda *et al.*, 2018) stated that percolation capacity of OGAFC mixtures reduces with time when exposed to real traffic and environmental conditions.

Clogging is primarily associated with the intrusion of foreign particles like dust and stripped-off bitumen in the pores of an OGAFC mix (particle-related clogging) or related to the densification of the mix structure due to repeated wheel loading (deformation-related clogging) (Chen *et al.*, 2015b). Putman (2012) stated clogging as one of the prime reasons of failure/dysfunction of OGAFC mixes. The clogging has been attributed to the sediment deposition (by vehicles and rainwater) in the voids of these mixes, fat spots due to clumping of fibres, excessive binder draindown, and inadequate porosity as a result of poor aggregate gradation or over-compaction. Fwa *et al.* (1999) conducted one of the first studies investigating the particle-related clogging of OGAFC mixtures. It was shown that clogging led to a rapid initial loss in the permeability of OGAFC mixtures followed by a steady reduction.

Yong *et al.* (2008), Suresha *et al.* (2010b), and Pattanaik *et al.* (2018a) investigated both clogged and de-clogged permeability of OGAFC mixtures and concluded that particle related clogging has a significant effect on reducing the drainage potential of these mixtures. Martin *et al.* (2014) performed clogging of OGAFC specimens in the laboratory using graded sand and evaluated the permeability under three conditions: clogged, de-clogged, and step-wise clogged states. After de-clogging operation (through reverse flushing technique), only 69% of the initial permeability was restored. The initial clogging rate was reported to be twice the rate of subsequent clogging and loss in permeability was observed to be the highest during the process of initial clogging.

Chen *et al.* (2015b) and Suresha *et al.* (2010b) further examined the effect of aggregate gradation on particle-related clogging and concluded that OGAFC mixtures with larger nominal maximum aggregate size (NMAS) and coarser gradations were less susceptible to clogging. Chen *et al.* (2018) also investigated the effect of moisture conditioning on permeability characteristics of OGAFC mixtures and found that permeability of the conditioned OGAFC specimens decreased due to clogging by stripped off asphalt films.

Studies on deformation-related clogging of OGAFC mixtures are still limited. Coleri *et al.* (2013) examined the X-ray computed tomography (CT) images of OGAFC specimens before and after accelerated pavement rutting test (APT) for porosity profile and reported significant reduction in voids content throughout the depth. The study reported a 90% reduction in permeability of OGAFC mixes after 2000 cycles of APT. Chen *et al.* (2015b) also evaluated the permeability of OGAFC slab specimens subjected to wheel rut test and found that drainage characteristics differed significantly after rutting and concluded that initial air voids content and NMAS are important design parameters in countering deformation-related clogging. In another study, onset of 4.5 mm rut depth was considered as an indicator for maintenance operation of OGAFC sections due to the reduced permeability (Wu *et al.*, 2020b).

To overcome the problem of clogging, OGAFC mixtures require regular cleaning. Liu *et al.* (2020b) stated that a cleaning vehicle equipped with high-pressure water supply and vacuum system can effectively restore the permeability of an OGAFC section. However, the restoration of the permeability will be different for different regions across the pavement with the portion under the wheel load being restored least. Clogging potential of OGAFC mixes also depends on the vehicular speed/movement over the pavement. It has been reported that sections with high vehicular speed are less prone to clogging due to the suction applied by the vehicle tyres that flushes out the dust particles from the pavement (Gu *et al.*, 2018; Liu *et al.*, 2020b).

Apart from quick surface water removal, a good skid resistance is a vital function of an OGAFC surface to deliver traffic safety, especially under wet weather conditions. Asi (2007) defined skid resistance as the resistance offered by a road surface to the sliding and skidding action of a vehicle which is dependent on the forces developed at the tyre-pavement interface. Road accidents have been reported to decrease with the use of surface courses with adequate skid resistance (Araujo *et al.*, 2015). Compared to other conventional asphalt mixtures like gap graded and dense graded HMA mixes, OGAFC mixes have significantly higher friction values (Li *et al.*, 2007; Masad *et al.*, 2008; Hall *et al.*, 2009; Ongel *et al.*, 2009).

Kowalski *et al.* (2009) reported that texture depth and dynamic friction coefficient of OGAFC mixes was comparable to stone matrix asphalts and better than dense graded HMA mixes. McGhee and Clark (2010) examined and compared the skid resistance of the different road sections in Virginia using a locked-wheel skid trailer and found that OGAFC surfaces had higher friction by 10 SN (skid number) than stone matrix asphalt mixtures. Villani *et al.* (2014) reported that friction coefficients of OGAFC mixes were 20–25% higher than conventional AC10 mixes. Pattanaik *et al.* (2017) found that the skid resistance of OGAFC mixes was higher than dense graded HMA mixes and that OGAFC mix friction properties were highly dependent on the type of aggregate used. Wu and Abadie (2018) found that OGAFC mixes prepared with sandstone aggregate exhibited better skid resistance than mixes prepared with limestone aggregate. They also concluded that surface texture of a mix has a greater influence on skid resistance than aggregate type and that OGAFC mixtures presented better frictional properties than conventional HMA mixes. Zong *et al.* (2021) examined the frictional properties of OGAFC mixes prepared using four types of aggregate — 75# calcined bauxite, 88# calcined bauxite, limestone, and basalt using a dynamic friction tester (75# and 85# indicates 75% and 85% aluminium oxide (Al_2O_3) content respectively). It was concluded that 88# calcined bauxite exhibited the best frictional properties followed by limestone, basalt, and 75# calcined bauxite aggregate.

The skid resistance of OGAFC is also affected by the polishing action of the vehicle tyres. Studies conducted on the evaluation of polishing action of vehicle wheels on OGAFC mixes showed that skid resistance of a newly laid OGAFC section was relatively lower and increased with initial polishing, as the relatively thick film of asphalt binder wears off (Villani *et al.*, 2014; Wu and Abadie, 2018). Villani *et al.* (2014) stated that OGAFC mixes were able to retain a higher degree of skid resistance compared to AC10 (asphalt concrete) mixes when subjected to polishing. Further, compared to limestone OGAFC mixes, sandstone mixes were able to retain a higher degree of skid resistance when subjected to polishing. Jiang *et al.* (2020) used the MMLS3 (third-scale model mobile load simulator) accelerated abrasion test to polish the aggregates for preparation of OGAFC mixes and evaluated their skid resistance using the British pendulum test. It was concluded that for the first 5,000 cycles of abrasion, skid resistance was found to decrease (due to smoothening of the rugged and sharp aggregate edges present in the surface) which then increased till 20,000 abrasion cycles (due to wear out of the asphalt film). However, after 20,000 abrasion cycles, friction values were observed to decrease slowly with polishing (due to polishing of the aggregates). Zong *et al.* (2021) used a self-designed three wheel polishing device to study the effect of polishing on OGAFC mixes and concluded that mixes prepared with 88# calcined bauxite aggregate were least affected by polishing.

Pavement skid resistance plays a significant role in road safety during wet weather conditions and a higher skid resistance helps in reducing crashes related to wet pavements (FHWA, 1980; Hall *et al.*, 2009). Studies have shown that drivers are more likely to lose control of their vehicles during wet weather conditions and that 25% of highway crashes occur during such conditions (Kuemmel *et al.*, 2000). Studies have also confirmed that 70% of the accidents related to wet weather condition can be prevented by the application of surface course with a better frictional performance (Henry, 2000; McGovern *et al.*, 2011). OGAFC mixes are characterised by a higher surface texture, which along with a high drainability, results in a significant reduction in hydroplaning and thus helps to provide adequate skid resistance under wet weather conditions (Noyce *et al.*, 2005).

The skid resistance of a road surface reduces in the presence of water. Cerezo *et al.* (2014) reported that skid resistance of a road surface is independent of the water film when a vehicle is moving at lower speeds in the range of 30–50 kmph but decreases with an increase in the thickness of water film at higher vehicular speeds. The reduction in skid resistance in the presence of water film is attributed to the decrease in the contact area of the tyre and pavement in the presence of water. Similarly, Isenring *et al.* (1990) concluded that OGAFC mixes provide excellent skid resistance to high-speed operating vehicles under wet weather traffic conditions. Pattanaik *et al.* (2017) conducted a study to observe the decrease in skid resistance of OGAFC mixes prepared with three different aggregate sources in the presence of water. Skid resistance of the OGAFC mixes evaluated using a British pendulum tester were observed to decrease by 15–20% in the presence of 1 mm water film.

Punith *et al.* (2012) and Chen *et al.* (2013) reported that skid resistance of OGAFC mixes is quite independent of the binder type and additives used and is mainly dependent on the aggregate gradation and aggregate type (as discussed in the previous sections). On the contrary, Shirini and Imaninasab (2016) conducted a study to see the effect of crumb rubber modified and styrene-butadiene-styrene (SBS) modified asphalt binders on skid resistance properties of OGAFC mixtures. It was found that OGAFC mixes with crumb rubber reported a 30% higher skid resistance compared to mixes with SBS modified binder. Sarkar and Hojjati (2021) concluded that the use of glass fibres increased the skid resistance of OGAFC mixes by 16%. Yan *et al.* (2020) stated that OGAFC mixes prepared with waste tyre rubber and amorphous poly alpha olefin (APAO) compound exhibited an increase in skid resistance with an increase in the dosage of APAO compound.

Another important functionality related aspect of OGAFC mixes is the noise absorption. Noise generated at the vehicle tyre and pavement interface is one of the prime contributors to the total noise generated on a road (Chen *et al.*, 2018a). Noise generated at this interface is highly dependent on the macrotexture of the surface; high macrotextures are associated with higher noise generation due to the air pumping at the interface (Smit and Waller, 2007). However, the open structure of OGAFC mixes absorbs the noise generated at the interface. Gołebiewski *et al.* (2003) compared the noise absorption characteristics of OGAFC and dense graded HMA mixes and reported that OGAFC mixes showed excellent noise absorption at a speed range of 20–60 kmph. Also, compared to dense graded HMA mixes, OGAFC mixes reduced the noise generated at the tyre pavement interface by about 3 dB(A) (Kandhal, 2002; Bendtsen and Andersen, 2004). McDaniel *et al.* (2010) evaluated the noise absorption of OGAFC, stone matrix asphalt, and dense graded HMA mixes at a speed of 100 kmph. It was found that OGAFC mixes reported the lowest sound pressure levels among the three mixes. In the recent times, double layered OGAFC mixes have reported to exhibit better noise absorption properties than single layered OGAFC mixes (Pratico *et al.*, 2013; Tang *et al.*, 2015; Liu *et al.*, 2016). In the two layered OGAFC section, the bottom layer comprises of a coarser porous skeleton while the top layer is a finer porous structure.

Gu *et al.* (2018) performed cost-benefit analysis of OGAFC application by examining two field projects in the State of Nevada. The two projects evaluated were situated in the cities of Las Vegas (rural area) and Elko (urban area). Both projects had OGAFC and dense graded bituminous concrete (DGBC) sections. Functionality assessment in terms of permeability, frictional characteristics, and noise absorption was carried out in the field. The results indicated that Las Vegas OGAFC showed subsequently better functionality compared to the DGBC pavement section; while Elko OGAFC pavement section displayed relatively comparable functionality with the DGBC section even after two years of service life. The authors also performed a cost-benefit analysis which showed that OGAFC application in Las Vegas curtailed the net present value by about 36% as compared to DGBC. On the contrary, application of OGAFC in Elko resulted in an 86% increase in the net present value compared to the DGBC. Finally, the authors concluded that use of OGAFC is cost-effective in rural highways but may entail higher costs in urban areas due to rapid clogging of the pores compared to OGAFC constructed in rural areas.

Long-term binder draindown is another functionality aspect of OGAFC mixes during its service life and has gained global attention. Long-term binder draindown was reported in 1996 in a porous residential roadway in Macon (Georgia), where a loss of drainability with visible runoff was observed after six years of service life (Ferguson, 2005). Examination of the surface led to the hypothesis of gradual draindown of asphalt binder through the pores of the OGAFC layer under the influence of high summer temperature and gravity. During the summer season, heat softened the asphalt binder and it gradually migrated downward to the comparatively cooler interior/lower section of the OGAFC layer where it cooled down and clogged the pores, resulting in a decrease in the drainability. Long-term binder draindown has also been reported in several porous parking lots that had been in service for 6–22 years (Putman and Lyons, 2015). Studies have been conducted to simulate the long-term binder draindown phenomenon of OGAFC mixes in the laboratory by ageing OGAFC specimens at 60°C for 14-days (Wurst and Putman, 2013), 56-days (Lyons and Putman, 2013), and 84-days (Putman and Lyons, 2015) in a force draft oven, and measuring changes in the mix permeability and porosity. The studies concluded that long-term binder draindown does occur in OGAFC mixes as evidenced by permeability reduction as high as 54.5% after 56 days compared to the initial permeability (0 days) (Lyons and Putman, 2013).

2.3.3 Durability of OGAFC mixes

OGAFC mixes are characterised by a large network of interconnected air voids which make them susceptible to oxidative ageing and moisture damage. Ravelling and moisture induced damages are considered as the prime distresses in OGAFC mixes from the durability point of view (Zhang *et al.*, 2021). Repeated action of the vehicle wheels and environmental conditions may lead to the formation of micro-cracks within the OGAFC mix structure which over time gets entrapped by the rainwater runoff. During successive freezing and thawing cycles, this entrapped water expands the micro-cracks and thus may result in an adhesive failure. The lack of adhesion can result into distresses like ravelling and a low tensile strength. Mallick *et al.* (2000) and Kandhal (2002) recommended the use of modified Lottman test to evaluate the moisture susceptibility of OGAFC mixes. The test was conducted following the AASHTO T283 (2003) specifications with special recommendations for OGAFC mixes. The special recommendations included – preparation of OGAFC specimens using constant compaction effort (50 gyrations), vacuum saturation of 87.8 kPa for 10 minutes, submergence of specimen in water during freezing cycle, and application of five successive freezing and thawing cycles (ASTM D7064, 2013). The modified Lottman test uses the tensile strength ratio (TSR) to evaluate the moisture susceptibility. A minimum TSR value of 80% was recommended for OGAFC mixes (Mallick *et al.*, 2000; Kandhal, 2002; ASTM D7064, 2013).

TSR alone is not a good indicator of moisture susceptibility as mixes with higher TSR values have reported lower indirect tensile strengths (ITS) under both unconditioned and conditioned environments (Suresha *et al.*, 2009a, Chen *et al.*, 2013). Suresha *et al.* (2009), Alvarez *et al.* (2010), and Chen *et al.* (2018b) recommended the use of Cantabro abrasion loss test on specimens subjected to successive freeze-thaw cycles to evaluate the moisture susceptibility of OGAFC mixes. The moisture conditioning used was similar to the one recommended in ASTM D7064 (2013) for the evaluation of TSR. In this method, abrasion loss was measured and compared for both unconditioned and conditioned specimens in place of ITS.

South Africa and Spain recommend a maximum permissible wet abrasion loss value of 30% and 35%, respectively (Alvarez *et al.*, 2010; Sabita Manual, 2011). Hu *et al.* (2019) found that Cantabro abrasion loss test assessed the moisture susceptibility of OGAFC mixes in a better manner compared to other tests like the TSR test and Marshall stability test. The Hamburg wheel tracking device (HWTD) (AASHTO T234, 2016) is another widely accepted method to evaluate the moisture susceptibility of OGAFC mixes. The test examines the rutting induced in an OGAFC mix in the presence of water under moving wheel load at a selected temperature. Recent studies on OGAFC mixes have shown wide popularity of the HWTD test to assess the stripping resistance of OGAFC mixes (Zhang *et al.*, 2020; Lv *et al.*, 2020; Gu *et al.*, 2021; Yan *et al.*, 2021).

Moisture susceptibility of OGAFC mixes is significantly affected by aggregate and binder properties. Aggregate shape, mineral composition, and surface morphology are expected to influence the adhesive bond between the aggregate and asphalt binder. Tarrer and Wagh (1991) have classified aggregates into two types — hydrophobic and hydrophilic. The hydrophobic aggregates have a greater affinity for asphalt binder compared to water, while the hydrophilic aggregates have a greater affinity towards water. Similarly, aggregates with higher absorption and rougher surface texture are also expected to have a stronger bonding with the asphalt binder (Gu *et al.*, 2021).

Xiao *et al.* (2015) reported that moisture susceptibility of OGAFC mixes was governed by the aggregate gradation but was independent of the Los Angeles abrasion resistance of the aggregate. Polymer modified, rubber modified, high viscosity asphalt binders have shown to increase the TSR values of OGAFC mixes compared to neat/virgin binders (Kandhal and Mallick, 1999; Suresha *et al.*, 2009a, Liu and Cao, 2009; Chen *et al.*, 2013, Lyons and Putman, 2013; Shirini and Imaninasab, 2016; Sangiorgi *et al.*, 2017; Slebi-Acevedo *et al.*, 2020). Similar to modified binders, use of additives such as cellulose fibres, mineral fibres, date palm fibres, textile fibres, and nano-silica in OGAFC mixes have also shown to improve the moisture damage resistance (Cooley *et al.*, 2000; Hassan and Al-Jabri, 2005; Tanzadeh *et al.*, 2019). Further, moisture performance has also been reported to enhance by the use of hydrated lime and anti-stripping agents in OGAFC mixes (Ameri and Esfahani, 2008; Ma *et al.*, 2018; Gu *et al.*, 2021).

2.3.4 Performance of OGAFC mixes

Studies in the past have reported that structural and mechanical properties like indirect tensile strength (Xiao *et al.*, 2015), dynamic modulus (Wang *et al.*, 2014), rut depth (Gu *et al.*, 2018), and fracture life (Wu *et al.*, 2020a) of OGAFC mixtures are lower than those of dense graded hot mix asphalt (DGHMA). Due to the lower structural strength of OGAFC mixtures, they are not considered as a structural layer and are designed as a functional layer which is laid over a conventional DGHMA with the use of bonding agents, such as tack coats (Song *et al.*, 2015). In the recent past, researchers have investigated various ways to improve the mechanical performance OGAFC mixes. Table 2.3 summarises the major modifications done in OGAFC mixes to improve their structural contribution. It can be seen that modifications in aggregate gradation, binder type, and incorporation of fibres have proven effective in increasing the structural strength of OGAFC mixes. Despite these modifications, the specifications currently followed in different countries for production and construction of OGAFC mixes still do not consider it as a structural layer. Most studies on OGAFC have considered the functionality aspects and limited interest has been paid to the evaluation of mechanical strength parameters.

Table 2.3: Summary of modification approaches to enhance OGAFC mix performance.

Reference	*Modification*	*Effect of modification on performance*
Mallick *et al.* (2000)	Coarse sized aggregates	Lower rut depth.
Punith and Veeraragavan (2007)	Polyethylene fibre	Higher tensile strength, fatigue life, and rutting resistance.
Roque *et al.* (2009)	Polymer modified bonding agent	Improved cracking resistance.
Jeong *et al.* (2011)	Polymer modified bitumen	Improved rutting resistance.
Punith *et al.* (2012)	Crumb rubber and reclaimed polyethylene modified binder	Improved resilient modulus.
Frigio *et al.* (2013)	Coarse reclaimed asphalt	Improved tensile strength and fracture/cracking resistance.
Mansour and Putman (2013)	Gradation and porosity	Improved tensile strength with lower porosity.
Xiao *et al.* (2015)	Coarse aggregate gradation	Improved tensile strength and rut depth.
Chen *et al.* (2015a)	Polymer modified bitumen	Increased tensile strength and resilient modulus.
Yang *et al.* (2015)	Rubberised asphalt binder	Improved fatigue life.
Asmael (2019)	Steel fiber, glass fibers, polyvinyl chloride (PVC) and phenol resin	Improved tensile strength and rutting resistance.
Zhang *et al.* (2020)	Lignin, basalt, polyester, and polyacrylonitrile fibres	Decreased rut depth and increased fatigue life.
Yan *et al.* (2021)	High content polymer modified asphalt	Improved rutting and fracture/cracking resistance.

King *et al.* (2013) reported that after 18 months of operation, OGAFC road sections showed good rutting and fatigue cracking performance and met the requirements of conventional dense graded HMA mixes. Islam *et al.* (2018) evaluated the low temperature cracking potential of OGAFC mixes in terms of the dynamic modulus, indirect tensile strength, coefficient of thermal contraction, and creep compliance. They concluded that OGAFC mixes performed better than dense graded HMA mixes in resisting low temperature thermal cracking due to lower stiffness which resulted in a lower dissipation of energy for a given decrease in temperature. Wang *et al.* (2014) studied the rutting resistance and dynamic moduli of OGAFC test sections and concluded that fatigue life and rutting resistance of a pavement improves significantly with the application of OGAFC mix as the surface course.

2.4 Introduction to industrial waste steel slag

Historically, civil engineering is an activity that is associated with the huge consumption of natural resources for execution of construction and infrastructure projects. Typically, a four-lane kilometre-long concrete pavement demands 7800 tons coarse aggregates, 3240 tons sand, and 1620 tons cement; while a similar four-lane flexible pavement requires about 3600, 2400, 540, and 300 tons of coarse aggregate, fine aggregate, sand, and bitumen respectively (Dumitru *et al.*, 2000). During quarrying and dressing of the aggregates and other paving operations, about 1200 tons of harmful CO_2 gas is generated which is equivalent to the collective CO_2 emission by 210 cars in a year (estimates for a typical 1 km long four-lane highway) (Grubeša, 2016). It is becoming challenging to meet the escalating demand for construction materials. There is a need to explore techniques to introduce alternative materials to balance the ever-growing demands of road making aggregates. In civil engineering, alternative materials generally refer to the by-products/co-products/solid wastes generated during mining, industrial, agricultural, and domestic activities. Utilisation of solid wastes in civil engineering activities will result in the conservation of natural resources as well as the prevention of unsustainable waste disposal techniques.

Steel slag, a by-product/co-product of the steelmaking industries, is a solid waste that exhibits desirable properties allowing it to be listed in the inventory of road making aggregates. Steel slag is obtained as a by-product along with other exhaust gases during molten iron processing. The steelmaking operation involves the conversion of pig iron and steel scrap into industrial steel in the furnaces either in the presence of oxygen or with the aid of electricity. Steel slags are mainly named after the furnaces from where they are generated. Depending on the mode of smelting pig iron or scrap steel, steelmaking furnaces are broadly classified into two types – basic oxygen furnace (BOF) and electric-arc furnace (EAF).

2.4.1 Basic oxygen furnace steelmaking and slag generation

Basic oxygen furnaces (BOF) are found in an integrated steel mill in conjunction with a blast furnace as they feed in the molten pig iron obtained from the blast furnaces along with scrap steel as the prime raw material. At first, the furnace is usually charged with scrap steel followed by molten pig iron with the assistance of a crane. An oxygen lance is then lowered into the bottom of the furnace carrying about 99% pure oxygen at supersonic speed. The oxygen cuts through the unwanted carbon present in the pig iron and converts it to carbon monoxide (exothermic reaction), thereby raising the temperature within the furnace to about 1600-1700°C. At this temperature, the scrap steel starts to melt and maintains the temperature inside the furnace.

The molten steel inside the furnace comprises of several undesirable chemical elements which are removed by the addition of fluxing agents such as lime (CaO) or dolomite ($MgCa(CO_3)_2$). Addition of fluxing agents results in the formation of slag that floats on top of the molten steel due to its lower density. At the end of the blowing cycle that lasts for about 20 to 25 minutes, the BOF is tilted in one direction to collect the molten steel slag and then it is tilted in the other direction for collecting the molten steel for further processing. The molten slag collected is later processed and the final product obtained is termed as BOF steel slag (Schoenberger, 2001; Seetharaman, 2005; Yildirim and Prezzi, 2011).

Steel slag is a waste generated during the steelmaking process and its generation depends on the annual steel production. In the year 2020, 1878 million tonnes (MT) of crude steel was generated globally with China having a share of 56.7% (1064.8 MT) followed by India 5.8% (108.5 MT) (Worldsteel, 2021). According to a study conducted by the United States Geological Society (USGS) in 2020, about 190-280 MT of steel slag is generated globally in a year (USGS, 2020). Globally, about 70% of the generated steel slag is BOF in nature (Worldsteel, 2019) while the BOF slag generation share in India and the United States is about 42% (Indian Bureau of Mines, 2018b) and 30% (USGS, 2020), respectively. Also, India has about 17 BOF main units that generate about 12 MT of BOF steel slag annually (Indian Bureau of Mines, 2018b).

2.4.2 Electric-arc furnace steelmaking and slag generation

Electric-arc furnaces (EAF) demand high-power electric arcs, in place of highly pure oxygen (moving at supersonic speeds) to generate the heat required to carry out the smelting operations. EAF are stand-alone mini mills that are not dependent on the pig iron obtained from the blast furnaces and feed in scrap steel as the core raw material. EAF units resembles giant kettles equipped with graphite electrodes (typically three electrodes are used) with a spout or an eccentric notch on one side.

The steelmaking process in an EAF starts with charging the different grades and types of scrap steel into the furnace through the roof using scrap steel baskets. Graphite electrodes are lowered into the furnace penetrating the scrap metal following which an arc is struck through the electrodes that passes electricity amongst the scrap metal. This electric arc and the resistance offered by the scrap metal to oppose the flow of electricity generates a huge amount of energy (in the form of heat) igniting the smelting operations. As the scarp steel starts melting, the graphite electrodes are penetrated deeper into the layer of the scrap metal to further progress the melting process till a puddle of molten steel is generated in the furnace. Similar to the BOF process, lime or dolomite are introduced in EAF as fluxing agents for removal of unwanted impurities from the molten metal. The processed steel and slag are poured into separate ladles and carried for further processing operations. An EAF recycles about 300 tons of steel in one single cycle and the slag generated during this recycling process is termed as EAF steel slag (Schoenberger, 2001; Seetharaman, 2005; Yildirim and Prezzi, 2011).

Compared to BOF steel slag, the global percentage share of EAF steel slag is about 30% only (Worldsteel, 2019). However, in India and the United States, EAF steelmaking process holds a higher share of about 58% (Indian Bureau of Mines, 2018b) and 70% (USGS, 2020), respectively. Additionally, around 48 units of EAF are reported to be present in India that results in an annual EAF steel slag generation of about 8 MT.

Both BOF and EAF steel slags are obtained in hot molten form from their respective furnaces and are carried in industrial ladles to cooling pits for solidification and processing. Depending on the process of cooling and solidification, steel slags are classified as crystalline, granulated and expanded (or foamed) slag. Crystalline slags are obtained when the molten slag is allowed to cool to ambient temperature by casting in a trench. Once solidification of the molten mass initiates, its cooling process is accelerated with the introduction of water sprays resulting in the formation of cracks along the hardened molten mass thereby initiating crushing. The obtained slag is of crystalline form with distinctive vesicular or cellular structure resulting from the evading gas bubbles (Lewis, 1982). Granulated slags are produced by rapid quenching of molten slag with water (or air) to obtain a glassy structure with very little crystallisation. This process results in slag comparable to the size of sand grains and friable materials. Expanded or foamed slags are obtained under special cases with treatment of molten slag under controlled quantities of water, air, or foam. They are highly vesicular in nature and are much lighter in weight and are often referred as pelletised slag (Lewis, 1982).

2.4.3 Chemical characterisation of steel slag

Both BOF and EAF steel slags are generated as by-products/co-products during steelmaking operations as discussed in the preceding sections. The chemical composition of both steel slags is similar to a large extent. Calcium and iron oxides are the two major chemical constituents of both slags. Tables 2.4 and 2.5 provide a detailed review of the chemical composition of BOF and EAF steel slags, respectively, from various studies. CaO, FeO (and Fe_2O_3), and SiO_2 are the main chemical constituents of BOF steel slag. During smelting operations, large quantities of lime and dolomite are introduced into the furnace as fluxing agents (the prime constituent of the slag) and hence a high CaO content is typically observed in BOF steel slag. At the end of the process, a substantial percent of iron (Fe) remains present in the hot molten metal which cannot be recovered into steel. This iron in oxidised form is observed in the chemical composition of BOF steel slag.

Table 2.4: Chemical composition of BOF steel slag from reviewed literature.

Reference	*Percentage oxide composition*									
	CaO	*SiO_2*	*Al_2O_3*	*MgO*	*FeO/Fe_2O_3*	*SO_3*	*MnO*	*TiO_2*	*P_2O_5*	*Free CaO*
López-Díaz *et al.* (2018)	46.8	10.8	4.9	2.7	28.8	–	2.0	–	2.1	–
Li *et al.* (2018)	44.3	13.5	2.5	5.9	20.8	–	–	–	–	1.7
Qazizadeh *et al.* (2018)	45.2	18.5	4.6	4.7	15.6	0.7	3.0	2.4	1.7	–
Teixeira *et al.* (2019)	43.4	12.7	4.9	5.0	26.4	–	3.2	–	–	–
	39.7	17.7	2.9	5.6	24.4	–	4.6	–	1.7	–
	34.4	15.4	2.0	6.2	30.8	–	4.5	–	2.2	–
Lim *et al.* (2019)	50.7	11.6	2.7	3.0	26.6	0.3	2.2	–	2.1	–
Kang *et al.* (2019)	40.0	14.0	2.7	2.3	33.0	–	4.1	0.5	–	–
Kong *et al.* (2019)	42.7	19.2	3.3	5.2	23.9	–	1.8	–	1.4	–
Cikmit *et al.* (2019)	41.0	14.0	2.6	2.3	33.0	–	3.0	0.4	–	–
Zhang *et al.* (2019)	44.0	12.9	3.0	4.1	19.3	0.4	2.2	1.2	1.7	
Librandi *et al.* (2019)	51.0	15.0	3.1	3.5	20.0	–	3.3	–	1.8	–

Reference	*Percentage oxide composition*									
	CaO	*SiO_2*	*Al_2O_3*	*MgO*	*FeO/Fe_2O_3*	*SO_3*	*MnO*	*TiO_2*	*P_2O_5*	*Free CaO*
Lim *et al.* (2020)	43.1	9.9	2.3	2.5	22.6	0.3	1.9	0.4	1.8	–
Zalnezhad and Hesami (2020)	55.6	10.1	1.1	1.1	12.3	–	3.8	3.1	2.8	0.4
Balaguera and Botero (2020)	41.7	8.5	0.3	1.9	29.5	0.7	8.7	0.2	7.1	
Ma *et al.* (2020)	36.9	11.1	3.0	12.1	30.9	–	2.4	–	1.8	–
Cui *et al.* (2021a)	36.6	16.0	3.1	6.0	27.6	–	5.4	–	2.5	–
Lai *et al.* (2021)	36.5	10.6	3.6	8.4	17.0	0.5	2.5	1.0	1.2	–
Sun *et al.* (2021)	40.0	15.8	9.8	4.5	23.7	–	–	–	–	–
Yang *et al.* (2021)	45.9	18.2	1.5	5.8	23.9	–	–	–	–	–
Swathi *et al.* (2021)	52.3	14.8	2.8	2.7	22.9	0.4	0.8	0.7	2.2	–
Andrade *et al.* (2021)	36.8	14.6	3.7	5.5	32.2	0.3	3.7	0.5	1.6	–
Li *et al.* (2022)	38.9	19.6	7.0	6.6	16.9	0.4	1.8	0.9	1.2	–
Zhao *et al.* (2022)	35.8	20.0	3.0	8.5	20.3	–	2.2	–	–	–

Table 2.5: Chemical composition of EAF steel slag from reviewed literature.

Reference	*Percentage oxide composition*									
	CaO	*SiO_2*	*Al_2O_3*	*MgO*	*FeO/Fe_2O_3*	*SO_3*	*MnO*	*TiO_2*	*P_2O_5*	*Free CaO*
Fakhri and Ahmadi (2017)	40.0	16.0	5.0	5.0	27.0	–	1.0	–	2.0	0.2
Goli *et al.* (2017)	25.6	18.7	2.8	7.5	35.2	–	0.3	1.6	–	–
Masoudi *et al.* (2017)	39.4	17.3	4.2	5.7	25.3	0.6	–	–	–	–
Qazizadeh *et al.* (2018)	38.9	17.5	4.0	5.0	25.8	0.5	2.3	2.1	1.5	–
Abd El-Azim *et al.* (2019)	32.0	19.5	8.9	8.7	27.9	–	1.5	0.7	0.6	–
Alinezhad and Sahaf (2019)	28.0	20.5	4.9	5.7	28.4	0.2	0.4	0.7	0.5	–
Pattanaik *et al.* (2019)	30.7	12.8	12.0	7.7	31.1	–	0.5	–	0.4	–
Zhang *et al.* (2019)	38.0	15.5	4.3	3.5	28.2	0.7	3.6	0.8	1.8	–
Rooholamini *et al.* (2019)	33.3	19.5	4.9	4.3	25.9	2.3	–	1.1	0.4	–
Pomaro *et al.* (2019)	30.3	14.6	10.2	3.0	33.3	–	4.3	–	–	–
Sern *et al.* (2019)	30.0	17.3	4.7	5.4	27.3	–	5.0	0.8	1.1	–
Ameli *et al.* (2020)	25.6	18.7	2.8	7.5	35.2	–	0.3	–	–	–

Reference	*Percentage oxide composition*									
	CaO	SiO_2	Al_2O_3	*MgO*	FeO/Fe_2O_3	SO_3	*MnO*	TiO_2	P_2O_5	*Free CaO*
Balaguera and Botero (2020)	25.1	12.2	1.6	7.7	38.5	0.7	5.9	0.4	0.6	–
	30.9	13.4	2.7	2.8	37.9	0.7	4.1	0.5	1.4	–
Papachristoforou *et al.* (2020)	31.7	17.1	6.1	2.0	36.1	–	6.3	–	–	–
Roslan *et al.* (2020)	16.9	26.4	4.8	1.9	43.4	–	2.7	–	–	–
Abd El-Hakim *et al.* (2020)	33.0	13.1	5.5	5.0	36.8	0.1	4.2	0.6	0.7	–
Ziaee and Behnia (2020)	27.9	21.2	5.5	5.7	25.1	0.3	0.4	0.7	0.5	–
Motevalizadeh *et al.* (2020)	33.3	19.5	4.9	4.3	25.9	–	–	–	–	–
Keymanesh *et al.* (2021)	43.0	18.7	2.8	7.5	35.2	–	0.3	1.6	–	0.4
Zakaria *et al.* (2021)	34.1	21.4	5.9	2.4	26.9	–	6.6	0.6	–	–
Andrade *et al.* (2021)	27.4	19.0	6.5	5.6	33.5	0.3	4.0	0.8	1.1	–
Pai *et al.* (2022)	19.6	22.6	12.8	0.2	40.7	–	0.1	–	0.6	–
Cristelo *et al.* (2022)	26.7	20.3	8.9	4.3	32.3	0.3	3.3	–	–	–

The weightage of iron oxide (FeO/ Fe_2O_3) present in the BOF steel slag depends on the efficiency of the furnace and can be as high as 33%. Higher the efficiency of the BOF, lower will be the percentage of iron oxide present in the slag. The silica (SiO_2) content in BOF steel slags ranges from 8.5 to 20.0%, while Al_2O_3 and MgO vary in the ranges of 0.3–9.8% and 1.1–12.1%, respectively. Free lime content was also observed in BOF steel slag which may lead to volumetric instability (discussed later in Section 2.4.5).

EAF steel slags have a chemical composition quite alike to that of BOF steel slags. The EAF process of steelmaking is basically a scrap steel recycling process and so the slag chemical composition substantially depends on the properties of the recycled steel. The major chemical constituents of EAF steel slags can vary when compared to BOF steel slags. The prime chemical constituents – CaO, FeO (and Fe_2O_3), SiO_2, Al_2O_3, and MgO are reported in the ranges of 16.9–43.0%, 25.1–43.4%, 12.2–26.4%, 1.6–12.8%, and 0.2–7.7%, respectively. Minor impurities such as MnO, Ti_2O_5, P_2O_5, and SO_3 are also present in trace amounts depending on the properties of the scrap steel used in the recycling process. Low percentages of free lime content have been reported in the case of EAF steel slag unlike BOF steel slag.

2.4.4 Physical characterisation of steel slag

Steel slags possess a distinct vesicular surface morphology with visible surface pores developed due to the expulsion of gaseous matter during the cooling process. The basic physical, mechanical, and morphological properties of both BOF and EAF steel slags are quite comparable to that of natural crushed aggregates. The following section discusses the common physical properties of both steel slags and compares it with conventional road making aggregates.

Specific gravity: Aggregate specific gravity is a quality parameter to assess the denseness of an aggregate. Aggregates with a higher specific gravity are generally stronger than those with a lower specific gravity. Figure 2.2 compares the bulk specific gravities of BOF and EAF steel slag aggregates with conventional road making aggregates. Both steel slag aggregates reported considerably high bulk specific gravity values than corresponding natural aggregates. High bulk specific gravity values of steel slag aggregates indicate that they are comparatively stronger. The high bulk specific gravity values of the steel slag aggregates are mainly attributed to the presence high amount of iron oxide (Xue *et al.*, 2006; Pasetto and Baldo, 2011; Amelian *et al.*, 2018) as can also be seen from Tables 2.4 and 2.5.

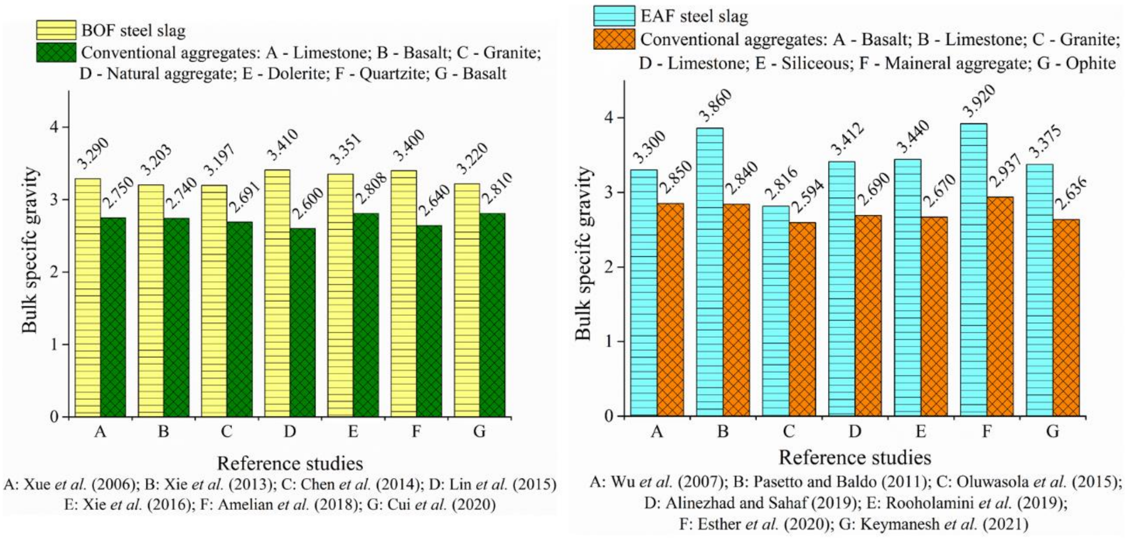


Figure 2.2: Bulk specific gravities of steel slag aggregates compared with conventional aggregates.

Water absorption: Aggregates with high water absorption potential are considered to be relatively weak and non-durable (susceptible to frosting under icy climatic conditions) (Holliday, 1997; O'Flaherty and Hughes, 2015). Figure 2.3 illustrates the water absorption values of BOF and EAF steel slag aggregates which are found to be relatively higher than their corresponding natural stone aggregates. Water absorption of both BOF and EAF steel slag were reported to be less than the maximum permissible value of 2.0% (barring a few studies). Water absorption of BOF steel slag aggregates were found to be about six and four times higher than corresponding basalt and granite aggregates respectively. Water absorption of EAF steel slags was found to be about fifteen and five times more than basalt and granite aggregates respectively.

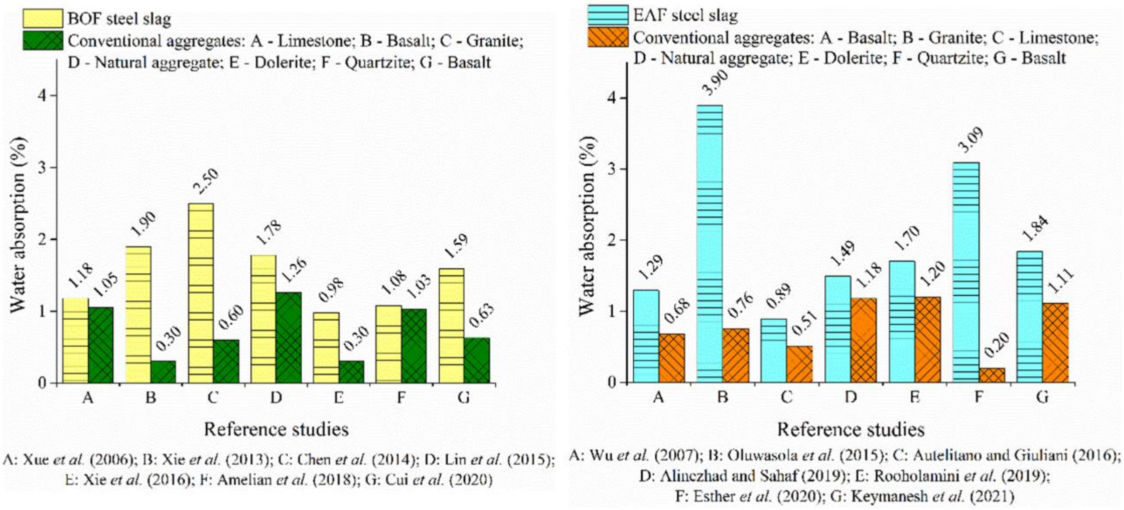


Figure 2.3: Water absorption of steel slag aggregates compared with conventional aggregates.

The relatively high water absorption of steel slag aggregates is due to its vesicular surface morphology which is a result of the expulsion of the entrapped air during slag cooling process. Steel slag aggregates reported an average water absorption of about 2.0% primarily due to rough (pitted) surface morphology that entraps the water in the surface pores. On the contrary, this pitted and vesicular surface texture of the steel slag aggregates also ensures better and enhanced bonding with asphalt binder. Studies cited in Figure 2.3 did not report any undesirable performance due to the high water absorption characteristics of the steel slag aggregates. In contrast, a better bonding with asphalt binder has been reported with both BOF and EAF steel slag aggregates than conventional natural aggregates.

Hardness: It is defined as the resistance offered by an aggregate against wear due to abrasive action. Figure 2.4 represents the hardness of BOF and EAF steel slag aggregates measured using the Los Angeles abrasion machine. The test measures the percentage abrasion loss of aggregates due to impact, attrition, and crushing between aggregate particles and abrasive charges (steel balls). The abrasion loss is denoted as Los Angeles abrasion value (LAAV). Apart from hardness, the test also gives an indirect measure of the aggregate toughness and strength. Most specifications recommend a maximum LAAV of 30% for aggregates to be used in surface courses. Aggregates with lower LAAV are expected to exhibit better mechanical strength and enhanced performance. Aggregates with high LAAV values often degrade during mixing and compaction operations thereby altering the desired aggregate gradation.

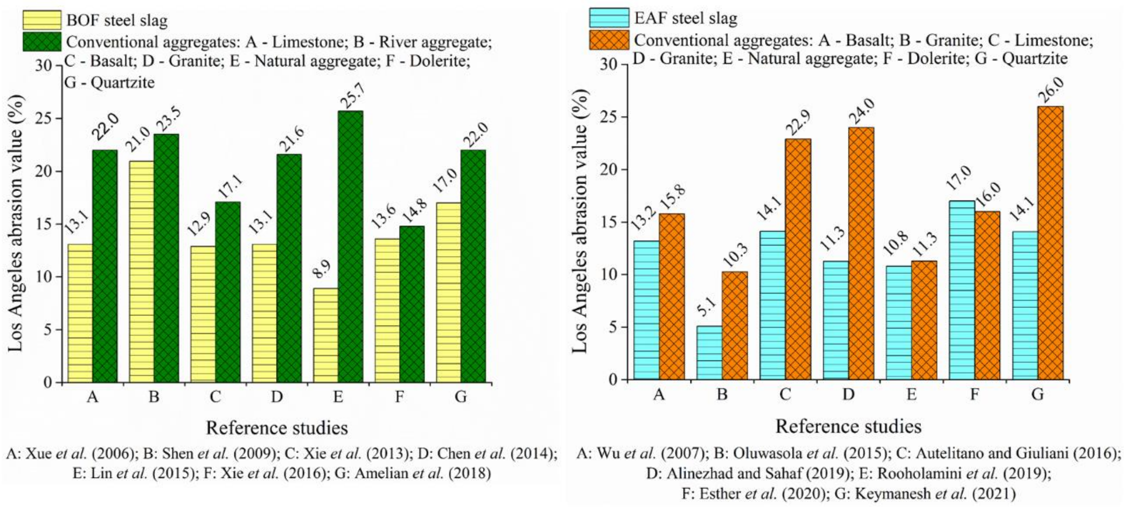


Figure 2.4: Los Angeles abrasion values of steel slag aggregates compared with conventional aggregates.

As observed from the literature, LAAVs of BOF and EAF steel slag aggregates were found in the range of 8.9–21.0% and 5.1–17.0% respectively. The LAAVs reported for both steel slag aggregates were considerably low than the conventional aggregate used in the respective studies. Thus, steel slag aggregates possess good strength, toughness and excellent resistance against abrasion. The results of slag physical properties show that steel slag aggregates form a possible alternative material for use in road making. A few studies have reported that BOF and EAF steel slags are about two to three times harder than natural stone aggregates (Xi *et al.*, 2006; Oluwasola *et al.*, 2015; Alinezhad and Sahaf, 2019).

Durability: Durability or soundness represents the resistance of an aggregate particle to disintegration when exposed to freezing (wetting) and thawing (drying) cycles. It is determined as the percentage loss in the mass of aggregates when exposed to subsequent freezing and thawing cycles using sodium sulphate or magnesium sulphate salts. Generally, the material specifications allow a maximum allowable mass loss of 12% using sodium sulphate while 18% is permissible in the case of magnesium sulphate. Sound and durable aggregates are preferred to uphold the integrity of an asphalt mix during its service life. The aggregate soundness values (ASV) obtained using sodium sulphate salt solution for BOF and EAF steel slag aggregates reported in previous studies are presented in Figure 2.5.

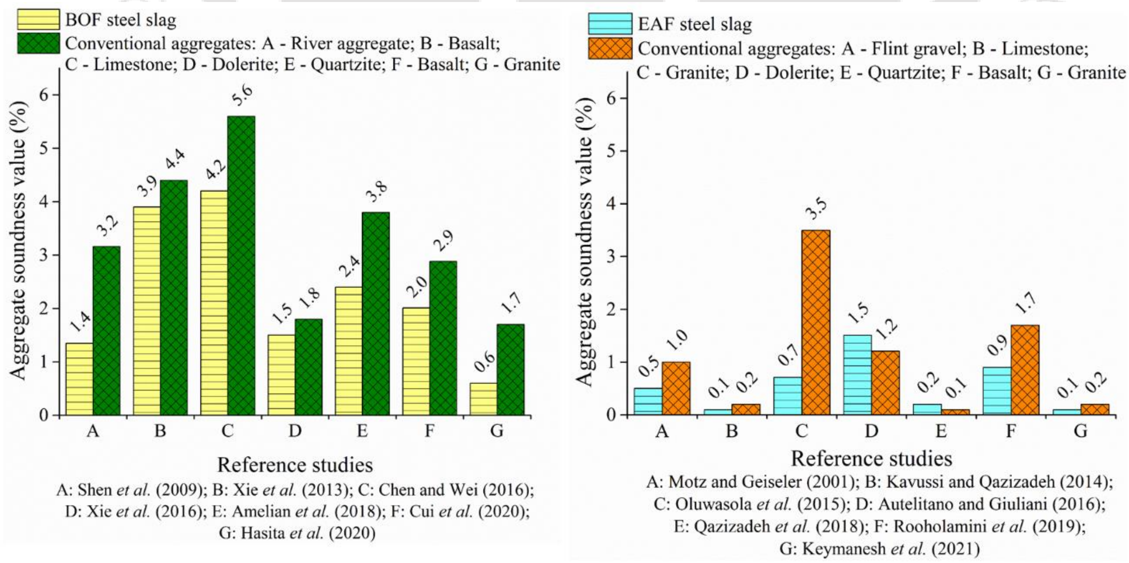


Figure 2.5: Aggregate soundness values of steel slag aggregates compared with conventional aggregates.

The ASVs reported in the figure clearly show that steel slag aggregates are more durable and sound than conventional natural aggregates. ASV of BOF steel slag aggregates is found to be as better as three times than granite aggregates while, EAF steel slag aggregates reported ASVs five times better than the granite aggregates. These lower ASVs values support the use of steel slag aggregates in road making.

Polished stone value: The polished stone value (PSV) test measures the aggregates resistance to polishing action similar to that of a vehicle tyre moving over a road surface. The PSV is closely related to resistance of aggregates to skidding and driving safety. PSV of aggregates helps to estimate the surface texture at a microscopic scale. Highly crucial road junctions like traffic intersections, pedestrian crossings, roundabouts, and level crossings demand aggregates with a minimum PSV of 65. The PSVs generally recommended for aggregates used in most highway projects are in the range of 55 to 65. Aggregates with PSV lower than 55 are not recommended for use in surface courses (British Pendulum Manual, 2000; O'Flaherty and Hughes, 2015). Figure 2.6 illustrates the PSVs of BOF and EAF steel slag aggregates as reported in various studies.

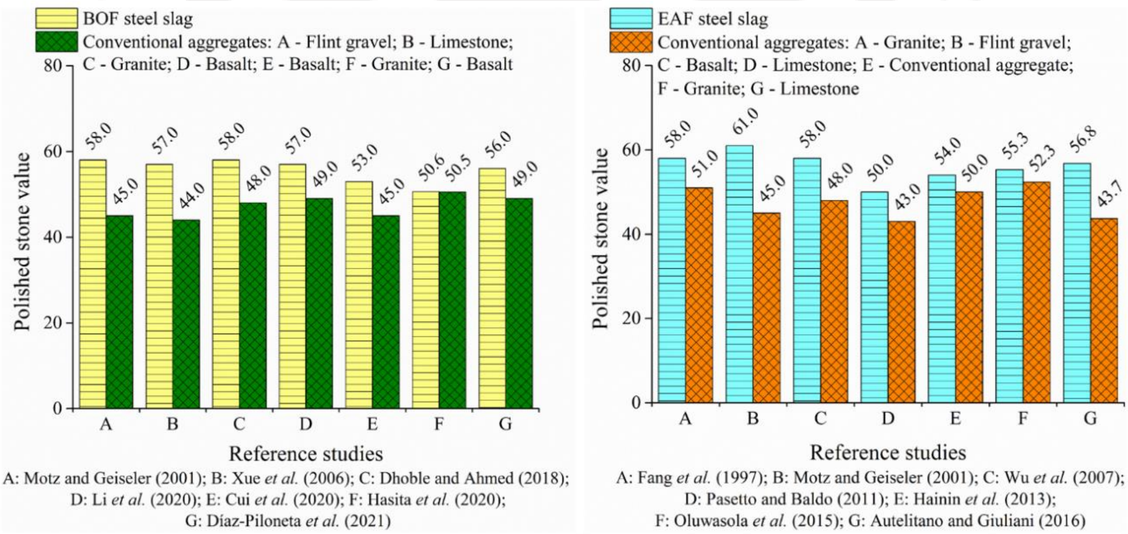


Figure 2.6: Polished stone values of steel slag aggregates compared with conventional aggregates.

It can be seen that all studies reported a higher PSV for steel slag aggregates than natural stone aggregates. This higher PSV is generally attributed to the presence of sharp surface morphology and overall hardness of the material (Kambole *et al.*, 2017). Both BOF and EAF steel slag aggregates have reported PSV of 50 and higher.

2.4.5 Volumetric expansion potential of steel slag

During the steelmaking process, lime and dolomite are mainly used as a fluxing agents to remove the impurities in the form of slag. This addition of lime or dolomitic fluxes results in the formation of free lime (f-CaO) or free MgO/periclase (f-MgO) in steel slags. The presence of f-CaO or f-MgO leads to volumetric instability of steel slag when exposed to moisture (Motz and Geiseler, 2001; Wang *et al.*, 2010). Volumetric stability of steel slag is a critical feature that needs to be carefully evaluated especially when slag is intended to be used as an aggregate for road construction. This is because on exposure to moist environmental conditions, f-CaO and f-MgO may react with the available moisture (H_2O) and convert to form portlandite ($Ca(OH)_2$) and brucite ($Mg(OH)_2$), respectively. Depending on the concentration of f-CaO or f-MgO present in the steel slag, the resulting increase in the volume of the slag aggregates may lead to disintegration and loss of the strength of the layer. The amount of f-CaO or f-MgO present in steel slag depends on the rate of cooling of the molten slag material. Slow cooling rate enhances the concentration of f-CaO or f-MgO (Kambole *et al.*, 2017). Therefore, for application of steel slag in roadmaking, it is preferable to use steel slags with a higher rate of cooling.

The problem concerning the volumetric expansion of steel slag can be remedied by proper conditioning or weathering the steel slag prior to its application. This process is termed as ageing and is performed by exposing the slag to open-air environmental conditions with optional spraying of water to accelerate the hydration process. The period required for complete hydration of the f-CaO or f-MgO varies from slag to slag and depends on the initial concentration of f-Cao/f-MgO. Table 2.6 lists the different ageing periods recommended by studies prior to application of slags in road construction. The most common test method adopted to evaluate the volumetric instability of steel slag aggregates is ASTM D4792 (2013) *"Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions"*. For use as aggregates in hot mix asphalts, a maximum permissible expansion of 1% is suggested by previous studies (FHWA, 1998; Wu *et al.*, 2007).

Table 2.6: Ageing duration of steel slag recommended in literature for volumetric stability.

Reference	*Ageing duration*
Australian Slag Association (2002)	One to three months
Sorlini *et al.* (2012)	Two to three months
Sasaki and Hamazaki (2015)	Minimum six months
Das *et al.* (2007)	Nine to twelve months
Federal Highway Administration (1998)	Up to eighteen months

2.4.6 Leaching potential of steel slag

Steel slags may comprise of certain heavy metals at concentrations which are not desirable and may be higher than those commonly observed in soils. This emphasises the need to assess the effect of their application on human health and environment. A pavement built using steel slag aggregates is in contact with the adjacent soil and there is a possibility that the pollutants (heavy metals), if present, in the steel slag aggregates may leach through the underlying soil and pollute the groundwater. Environmental assessment of the steel slag aggregates is thus important prior to the application in road making. The most common method adopted to evaluate the leaching potential of steel slag aggregates is the US-EPA SW-846 Test Method 1311 – Toxicity Characteristic Leaching Procedure (ASTM D5106, 2015). Geiseler (1996), Proctor *et al.* (2000), and Motz and Geiseler (2001) conducted studies to examine the leaching potential of BOF steel slag and reported no significant leaching of heavy metals. Similar studies with EAF steel slag have also been performed by Milačič *et al.* (2011) and Sorlini *et al.* (2012) and no significant environmental or health hazard were reported.

It can be concluded that steel slag (both BOF and EAF steel slags) meets all the requirements of road aggregates used in the construction of asphalt mixtures. Steel slag has reported comparable and somewhat better properties than conventional natural aggregates. Thus, addition of steel slag in the inventory of road making aggregates will reduce the pressure on the non-renewable natural aggregate resources and will help to address the challenges with its disposal and thus will be also a step towards sustainable road construction.

2.5 Studies on application of steel slag in asphalt mixtures

Applications of ferrous/iron or steel slags in road construction can be dated back to the first industrial revolution in the early 1800. The first reported slag road was constructed in England in 1813, followed by the USA in 1830 (https://nationalslag.org/history/). Several projects and studies have been carried out since then on the utilisation of slag in different pavement layers. As discussed earlier, steel slag usually meets all the physical and chemical requirements of road aggregates used for construction of pavement courses (asphalt courses). Numerous studies have been performed in the past concerning the properties of asphalt mixes fabricated with steel slag, especially considering mechanical behaviour, moisture susceptibility, rutting and fatigue resistance, drainability, skid resistance, and noise absorption. Table 2.7 summarises several such past studies and reports the asphalt mix properties found after the use of steel slag aggregates.

Table 2.7: Summary of literature on asphalt mixture properties with application of steel slags.

Reference	*Steel slag type*	*Mix type*	*Replacement*	*Conclusions*
Stock *et al.* (1996)	EAF	Surface dressing	–	10 to 15% higher skidding resistance.
Kandhal and Hoffman (1997)	–	–	Coarse, fine, and full replacement	Higher moisture resistance and about 20 to 35% higher Marshall stability. Partial replacement of steel slag (either coarse or fine) to natural aggregate was suggested.
Bagampadde *et al.* (1999)	–	–	100% coarse replacement 100% fine replacement	Mixes with 100% coarse SSA reported highest resistance to rutting and a high fatigue life.
Motz and Geiseler (2001)	BOF	–	50 and 100% coarse replacement	No significant difference in the abrasion and polishing behaviour of BOF mixes.
Xue *et al.* (2006)	BOF	SMA	100% coarse replacement	Improved dynamic stability, low temperature cracking, and fatigue cracking.
Asi *et al.* (2007)	–	Dense graded HMA	0, 25, 50, 75, and 100% coarse replacement	SSA reported improved tensile strength, rutting resistance, fatigue life, and RM. 75% SSA replacement was recommended.
Wu *et al.* (2007)	BOF	SMA	80% coarse replacement	Road sections laid with BOF slag reported an excellent abrasion and skidding resistance after two-years of service life.

Reference	*Steel slag type*	*Mix type*	*Replacement*	*Conclusions*
Ahmedzade and Sengoz (2009)	–	Dense graded HMA	100% coarse replacement	Better resistance to permanent deformation, moisture damage, higher MQ, ITS, and creep stiffness.
Pasetto and Baldo (2010)	EAF	Dense graded HMA	100% coarse replacement	7-10% higher TSR, and 40-60% higher stiffness modulus.
Pasetto and Baldo (2011)	EAF	Dense graded HMA	100% coarse replacement	Higher resistance to permanent deformation and increased fatigue life.
Liapis and Likoydis (2012)	EAF	25 mm thin skid-resistant course	–	Increased skid resistance and macrotexture depth after 30 and 41 months of traffic.
Behnood and Ameri (2012)	–	SMA	100% coarse replacement 100% fine replacement	Mixtures with steel slag as coarse portions yielded the highest Marshall stability, MQ, ITS, TSR, RMS, RM, and resistance to permanent deformation followed by mixtures with steel slag as fine portions.
Xie *et al.* (2012)	BOF	–	100% coarse replacement	Higher moisture resistance and RM.
Arabani and Azarhoosh (2012)			100% coarse replacement 100% fine replacement	Mix prepared using SSA as CA and RCA as FA, dacite as a filler reported the highest MQ, RM, and fatigue life.

Reference	*Steel slag type*	*Mix type*	*Replacement*	*Conclusions*
Sorlini *et al.* (2012)	EAF	Dense graded HMA	40% coarse replacement	Marshall stability and flow values of both control and EAF slag mix were comparable.
Xie *et al.* (2013)	BOF	–	100% coarse replacement	Bonding between asphalt binder and BOF steel slag aggregates was almost double the bonding between asphalt binder and basalt aggregate. BOF slag mixes also reported improved rutting and moisture resistance.
Ameri *et al.* (2013)	EAF	Dense graded HMA	100% coarse replacement 100% fine replacement 100% replacement	RM of all mixes were equivalent, flow number and ITS of coarse EAF mix was higher, and moisture resistance of fine EAF mix was better.
Pandey and Jain (2013)	EAF	Dense graded HMA		Higher resistance to fatigue cracking, improved moisture susceptibility (TSR and RMS) and RM, 24% lower rut depth.
Kavussi and Qazizadeh (2014)	EAF	–	0, 25, 50, 75, and 100% coarse replacement	Fatigue life increased for every 25% coarse replacement.
Bessa *et al.* (2014)	–	–	–	SSA was the most resistant to polishing action compared to gneiss, phonolite, and granite.

Reference	*Steel slag type*	*Mix type*	*Replacement*	*Conclusions*
Chen *et al.* (2014)	BOF	–	–	Mixes with SSA reported a higher ITS and TSR than mixes with basalt and granite aggregates.
Lin *et al.* (2015)	BOF	–	–	BOF road section after two years of traffic and environmental actions reported higher ITS, TSR, RM, skid, and rutting resistance.
Chen *et al.* (2015)	BOF	Dense graded HMA	–	Coarse graded BOF mixes reported highest ITS, TSR, and creep resistance; while mid graded BOF mixes reported highest RM.
Ziari *et al.* (2015)	BOF		0, 25, 50, 75, and 100% coarse, fine, and complete substitution	Coarse substitution — highest stability, RM Fine substitution — highest fatigue life Complete substitution — highest ITS
Chen and Wei (2016)	BOF	DGAC and SMA	100% coarse replacement	DGCA-BOF mixes reported highest ITS and RM; while SMA-BOF mixes reported highest moisture and rut resistance. BOF mixes also reported better friction and polishing properties.

Reference	*Steel slag type*	*Mix type*	*Replacement*	*Conclusions*
Wen *et al.* (2016)	–	–	0, 20, 40, and 60% replacement	SSA resisted the damages by studded tires and reported higher dynamic modulus, flow, and better moisture and rut resistance.
Fakhri and Ahmadi (2017)	EAF	WMA	40% coarse replacement	SSA mixes reported highest ITS, and better resistance to moisture, rutting, and fatigue.
Masoudi *et al.* (2017)	EAF	WMA	100% coarse replacement	WMA mixture with SSA exhibited a higher short and long-term aged Marshall stability, ITS, and RM compared to HMA mixtures.
Amelian *et al.* (2018)	BOF	WMA and HMA	100% coarse replacement	Mixture with SSA exhibited higher TSR, RM and rut resistance.
Qazizadeh *et al.* (2018)	BOF and EAF	Dense graded HMA	0, 25, 50, 75, and 100% coarse replacement	Fatigue life increased with SSA replacement. EAF SSA mixes reported higher fatigue life.
Alinezhad and Sahaf (2019)	EAF	Warm SMA	100% coarse replacement	Warm SMA mixes with SSA reported a lower fatigue life due to the stiffening effect of Sasobit and high stiffness of SSA.
Teixeira *et al.* (2019)	BOF	Dense graded HMA	25 and 50% coarse replacement	SSA mixes reported better skid, rutting, ravelling, and moisture resistance and were independent of level of expansion.

Reference	*Steel slag type*	*Mix type*	*Replacement*	*Conclusions*
Ziaee and Behnia (2020)	EAF	WMA	0, 25, 50, and 75% coarse replacement	SSA mixes required higher OBC and reported 343% increase in rut resistance and 17% increase in ITS.
Guo *et al.* (2020)	BOF	SMA	0, 30, 50, 70, and 100% coarse replacement	Mixes with 30% SSA replacement reported the highest resistance to long-term water damage.
Motevalizadeh *et al.* (2020)	EAF	Dense graded HMA and WMA	50 and 100% coarse replacement 50% fine replacement	Use of EAF SSA in WMA mixtures reported a positive synergic effect in reducing temperature susceptibility of asphalt fracture resistance at low-temperature compared with HMA.
Díaz-Piloneta *et al.* (2021)	BOF	Dense graded HMA	15% coarse replacement	MQ increased by 35% and carbon emission reduced by more than 14%.
Zhao *et al.* (2021)	BOF	Dense graded HMA and SMA	100% fine replacement	High-temperature stability and low-temperature crack resistance of the mixes improved.

Note: 'BOF' stands for 'basic oxygen furnace'; 'EAF' stands for 'electric-arc furnace'; 'HMA' stands for 'hot mix asphalt'; 'DGAC' stands for dense graded asphalt mix'; 'SMA' stands for 'stone matrix asphalt'; 'WMA' stands for stone matrix asphalt'; 'MQ' stands for 'Marshall quotient'; 'ITS' stands for 'indirect tensile strength'; ' TSR' stands for 'tensile strength ratio'; 'RM' stands for 'resilient modulus'; 'RMS' stands for 'retained Marshall stability'; 'SSA' stands for 'steel slag aggregate'; 'CA' stands for 'coarse aggregate'; 'FA' stands for 'fine aggregate'; 'RCA' stands for 'recycled coarse aggregate'; 'OBC' stands for 'optimum binder content'.

The findings of Table 2.7 show that both BOF and EAF steel slags have been successfully applied in conventional dense graded asphalt mixes. Replacement of coarse fraction of natural stone aggregate with steel slag aggregate has shown improvement in the performance of conventional asphalt mixes. Improvement in Marshall parameters (stability and flow), moisture susceptibility — tensile strength ratio and retained Marshall stability, rutting resistance, fatigue life, mix strength — resilient modulus and dynamic stability, and low temperature cracking have been reported with the use of steel slag aggregates. Also, use of steel slag aggregate as either coarse or fine fraction replacement has been recommended in place of complete replacement of both coarse and fine fraction aggregates by several studies cited in Table 2.7.

2.6 Studies on application of steel slag in OGAFC mixtures

Unlike conventional asphalt surface courses, use of steel slag aggregates in OGAFC mixes is relatively new and only limited studies are available to date. Li *et al.* (2007) found that for any OGAFC section, mixes prepared with steel slag aggregates exhibited the highest skid resistance. Shen *et al.* (2009) used BOF steel slag in preparation of OGAFC mixes with 0, 25, 50, 75, and 100% replacement of coarse natural aggregates. They found that 100% BOF steel slag replacement resulted in the highest stability and skid resistance. Also, for 100% BOF steel slag replacement, highest resistance to ravelling, moisture damage, and rutting was reported. Wang and Wang (2011) prepared OGAFC mixes with EAF steel slag (100% replacement of both coarse and fine fraction) and evaluated the mixes for rutting and moisture resistance. EAF mixes were found to be three times more rut resistant but were also more susceptible to moisture due to the presence of high free lime. Fang *et al.* (2013) also replaced 100% natural aggregates (both coarse and fine fractions) with steel slag and found a 2 dB reduction in noise level and 12% increase in frictional performance compared to friction courses prepared with granite aggregates. A high resistance to rutting and moisture damage was also reported for steel slag mixes. Hainin *et al.* (2014) replaced the coarse fraction of OGAFC mixes with EAF steel slag and observed about two and three times improvement in its resilient modulus and rut resistance. However, mixes with EAF steel slag reported about 50% decrease in permeability.

Pattanaik *et al.* (2018a, 2018b, 2019, 2020, 2021) conducted a series of studies on the utilisation of EAF steel slag in OGAFC mixes. They replaced the coarse fraction of natural stone aggregates in five percentage replacements – 0, 25, 50, 75, and 100% and examined the mix design parameters, moisture susceptibility, permeability, skid resistance, and performance. They concluded that properties of OGAFC mixes improved with replacement percentage of EAF steel slag till 100% replacement. A 75% replacement of coarse natural aggregate with EAF steel slag was reported as the optimum replacement percentage.

Skaf *et al.* (2019) prepared OGAFC mixes with 100% EAF steel slag (both coarse and fine aggregate replacement) and reported improved stability, tensile strength, microtexture, macrotexture, and dynamic stability. Use of steel slag also led to a lower rut depth. Wan *et al.* (2019) utilised steel slag aggregates in the preparation of OGAFC mixes and reported improved induction heating performance, durability, and ice and snow melting efficiency. Chen *et al.* (2019) performed life cycle cost analysis of steel slag incorporated OGAFC road sections and confirmed cost savings of 23 percent under low (haul distance 0-60 km) and medium (haul distance 60-120 km) price ranges compared to conventional OGAFC sections (considering the average design life of an OGAFC section as 6.9 years). OGAFC mixes with steel slag reported cost savings compared to conventional OGAFC mixes under high (haul distance 120-180 km) price ranges when its service life was more than eight years. Incorporation of steel slag in OGAFC mixes reported a 92% chance of being more cost effective. Chai *et al.* (2020) prepared OGAFC mixes using styrene-butadiene-styrene (SBS) polymer modified bitumen, crumb rubber, and basalt fibre. Basalt and crumb rubber modified steel slag incorporated OGAFC mixes reported the best results for Marshall stability, water stability, and low-temperature crack resistance.

Cui *et al.* (2021b) prepared OGAFC mixes by replacing the coarse fraction with BOF steel slag and reported significant improvement in stone-on-stone contact and load bearing capacity. Lou *et al.* (2021) studied the self-healing properties of OGAFC mixes prepared with 0, 20, 40, 60, 80, and 100% steel slag by replacing the 9.5–4.75 mm fraction of limestone aggregate. The mix with 80% steel slag reported the best micro-crack healing properties corresponding to a 40 second healing period. Preti *et al.* (2021) used high surface area (HSA) hydrated lime as filler in preparation of OGAFC mixes with steel slag aggregate as both coarse and fine aggregate and found that HSA hydrated lime increased the fracture energy of OGAFC mixes prepared with steel slag aggregates. Yang *et al.* (2021) reported that BOF steel slag incorporated OGAFC mixes could remove about 25–60% of zinc and 57–79% of copper from the rainwater runoff.

2.7 Conclusions and research gaps

OGAFC is a special-purpose uniformly graded functional (non-structural) asphalt course laid over the surface of an impermeable pavement with adequate cross slope to rapidly drain-off the surface water to the adjacent day-lighted edges. Prominent advantages of OGAFC include absence of water film during rains, reduction in splash and spray of rainwater, reduced risk of hydroplaning, reduce glare, improved visibility of pavement markings during wet weather conditions, and reduced noise. It provides a significant advantage in terms of improved traffic safety due to enhanced frictional characteristics achieved with its porous skeleton structure, especially during wet/ inclement weather conditions.

The open skeleton structure of an OGAFC is achieved by adopting a predominantly single-sized coarse aggregate gradation with little fine content. The lack of fines makes the mixes susceptible to binder draindown and ravelling. Studies conducted with the use of modified binders (such as polymer modified bitumen, crumb rubber modified bitumen, and high viscosity bitumen), have reported improvement in binder draindown and ravelling resistance of OGAFC mixes. Several studies have also recommended the use of fibres (such as cellulose fibre, mineral fibre, date-palm fibre, textile fibre, polyester fibre, polyethylene fibre, basalt fibre, and glass fibre) to reduce the binder draindown potential of OGAFC mixes. The coarse aggregate skeleton of an OGAFC is responsible to transmit the wheel load of a vehicle to the underlying layer, and to do so, OGAFC requires good quality aggregates (in terms of shape and strength compared to conventional dense graded asphalt mixes) and a gradation with proper stone-on-stone contact. Studies have recommended the use of *VCA*-ratio (VCA_{mix}/VCA_{DRC}) criterion of less than unity to ensure a proper stone-on-stone contact.

In terms of the drainage properties of OGAFC mixes, porosity or the volume of inter connected air voids is considered an important parameter and is found to be quite well related to the permeability of the mix. Clogging is a prime concern reported with OGAFC mixes and is dependent on the aggregate size/gradation used. Particle-related clogging, stripping-related clogging, and deformation-related clogging are the three main clogging phenomena generally reported with OGAFC mixes. Regular maintenance operations (vacuum cleaning and flushing) are found to restore and maintain the permeability of an OGAFC mix well above the minimum requirement. Further, wet weather road safety of OGAFC mixes were found to be superior than conventional dense graded asphalt courses and stone matrix asphalt mixes. Surface characteristics like micro and macrotexture plays a vital role in the wet weather safety. Frictional properties of OGAFC mixes were reported to decrease with an increase in the water film thickness; however, this decrease was very less compared to other traditional surface courses. OGAFC mixes were found to be less susceptible to polishing action by the vehicle wheels.

Ravelling, ageing, and moisture induced damages are the most prominent distresses reported with OGAFC. Use of a high asphalt film thickness (higher binder dosage) and stiffer graded binders (modified binders) is reported to make OGAFC mixes more durable. Use of additives (such as hydrated lime, anti-stripping agents, and several fibres) have reported to improve the moisture resistance of OGAFC mixes. Use of good quality aggregates, i.e., strong aggregate with basic nature have reported to enhance the ravelling and moisture resistance of OGAFC mixes. Usually, OGAFC mixes are considered as functional layer and their structural contribution is considered quite low than conventional dense graded asphalt mixes. Use of coarse graded strong aggregates, modified binders, and fibres have reported to improve the rutting and cracking resistance, fracture life, and resilient modulus of OGAFC mixes.

OGAFC mixes have been gaining popularity due to the associated advantages but the requirement of higher binder dosage, stiffer binder, fibres, and good quality aggregates makes it economically unpopular. Utilisation of steel slag aggregates as replacement to natural stone aggregates can somewhat reduce the cost of OGAFC mixes and make it economically more viable. Use of steel slag in OGAFC mixes will also result in several other socio-economic benefits. Based on the furnace used for the conversion of iron to steel, steel slag is classified as — basic oxygen furnace (BOF) steel slag and electric-arc furnace (EAF) steel slag. Both steel slag aggregates have reported comparable and somewhat better physical, chemical, and morphological properties compared to conventional road aggregates. The characterisation of both slags revealed distinct differences in their properties. Both BOF and EAF steel slag have been used in several conventional asphalt mixes as a partial and full replacement to natural stone aggregate. Studies conducted with either coarse or fine fraction replacement with steel slag aggregates have reported improved Marshall stability, tensile strength, frictional properties, rutting and cracking resistance, fracture life, and resilient modulus. Complete replacement of both coarse and fine fraction with steel slag is not recommended.

Limited studies have been conducted on the use of steel slag aggregate in preparation of OGAFC mixes. Use of steel slag in OGAFC mixes reported better resistance to ravelling, moisture induced damages, and frictional properties. Steel slag aggregates have also reported to enhance the self-healing properties of OGAFC mixes. Studies have also reported improved noise absorption properties with the use of steel slag aggregates. Performance properties in terms of rutting resistance and fatigue life have also been reported to improve with the application of steel slag aggregates.

Based on the above conclusions of the literature review, the following gap areas are identified in the current research field:

1. Most studies governing the use of steel slag aggregate in OGAFC mixes have been performed using EAF steel slag and less studies are available with BOF steel slag.
2. Limited studies have been performed to analyse the effect of steel slag on the clogging and de-clogging behaviour of OGAFC mixes.
3. Particle-related clogging, stripping-related clogging, and deformation-related clogging need to be assessed in details with consideration to the effect of incorporation of different contents of steel slag aggregates in OGAFC mixes.
4. Frictional characteristics of OGAFC mixes under different surface conditions need to be examined. Also, the effect of polishing action on steel slag incorporated OGAFC mixes needs to be evaluated in detail.

5. OGAFC mixes are more prone to moisture damages due to the continuous exposure to rainwater runoff and are to be evaluated under harsher moisture conditioning environments, compared to the one used for conventional dense-graded HMA mixes. There is a need to examine the moisture susceptibility of OGAFC mixes under different environmental conditions.
6. The effect of freezing and thawing cycles on the functionality (permeability) of OGAFC mixes needs to be evaluated.
7. During the service life, OGAFC mixes may experience long-term binder draindown which may result in clogging of the pores in the lower section of the OGAFC course. The effect of long-term binder draindown on durability and functionality of the OGAFC mixes with BOF steel slag needs to be evaluated.
8. Performance properties, especially in terms of rutting resistance, cracking potential, fatigue life, and modulus properties needs to be evaluated with different modified binders to examine the effect of BOF steel slag replacement percentages on the OGAFC mix performance.

2.8 Summary

This chapter provided a detailed review of the existing state-of-the-art studies on the utilisation of steel slag aggregates in OGAFC mixes. The review covered studies on the design parameters, functionality, durability, and performance of OGAFC mixes. The chapter also reviewed studies corresponding to the application of steel slag aggregates in conventional dense graded asphalt mixes. Finally, studies on the application of steel slag in OGAFC mixes were explored and reviewed in details. Based on the literature review, research gaps were identified for formulation of objectives for this study.

Chapter 3: Experimental Programme and Methodology

3.1 General

This chapter presents a detailed description of the materials used and a comprehensive discussion of the experimental programme formulated to achieve the objectives of the study. The chapter starts with the basic characterisation of the materials (bituminous binders, aggregates, and stabilising additives) used in the study. Further, the chapter discusses the preparation/fabrication and design of open graded asphalt friction course (OGAFC) mixes with varying percentages of basic oxygen furnace (BOF) steel slag and the evaluation of volumetric and mix design parameters. Finally, the chapter provides a detailed explanation of the experimental protocols followed for measuring the functionality (drainability, clogging potential, and frictional characteristics); durability (moisture susceptibility and long-term draindown potential); and performance properties (rutting resistance under different forms of loading, cracking potential, fatigue life, stiffness modulus, and resilient modulus) of the BOF steel slag incorporated OGAFC mixes.

3.2 Materials

3.2.1 Bituminous binders

Bituminous binders are employed, in conjunction with mineral aggregates, for preparation of bituminous mixes that constitute the surface layer or the topmost layer of a flexible pavement. The properties of bituminous binders significantly impact the performance of OGAFC mixes particularly governing its binder draindown and ravelling potential. Compared to conventional dense graded bituminous mixes, OGAFCs demand stiffer grade of bitumen to minimise the downward movement of binders at elevated temperatures during their production, transportation and construction. Due to high air void content, they also demand binders that are less susceptible to ageing to have a higher resistance to ravelling. Moreover, as OGAFC mixes are usually applied in areas of high rainfall and remain in contact with water for longer duration, they have need of binders that form a stronger bond with aggregates to reduce the moisture damage/stripping of the binder film. Neat (or virgin) binders are generally considered incapable to adequately perform under such adverse environmental conditions and therefore OGAFC mixes are typically prepared using modified bitumen binders. Bituminous binders are modified with different additives/stabilisers such as polymers (styrene-butadiene-styrene, ethylene vinyl acetate, ethylene terpolymer, *etc.*) and waste rubber (crumb rubber, ethylene propylene diene monomer, *etc.*). In the last two decades, modified bitumen has gained a vast worldwide acceptance in the application of OGAFC mixes.

In this study, a polymer modified bitumen (PMB) and a crumb rubber modified bitumen (CRMB) were used for the preparation of OGAFC mixes. Both PMB and CRMB binders were obtained from a commercial manufacturer M/s TikiTar Industries (Gujarat, India). As per the manufacturer's information, PMB and CRMB binders were prepared by wet blending ethylene terpolymer (ETP) and crumb rubber particles, respectively with a viscosity grade 30 (VG 30) binder as the base bitumen. The physical properties of the PMB and CRMB binders were tested in accordance with IS 15462 (2004) and the test results are listed in Tables 3.1 and 3.2, respectively.

Table 3.1: Physical properties of polymer modified bitumen (PMB 40).

Property	*Requirement for PMB 40*	*Test results*
Tests on neat bitumen		
Penetration at 25°C, 0.1 mm, 100 g, 5 s	30 – 50	42
Softening point (R&B), °C	Min. 60	71
Flash point, COC, °C	Min. 220	>220
Elastic recovery of half thread in ductilometer at 15°C, %	Min. 70	76.5
Separation difference in softening point, R&B, °C	Max. 3	1.9
Viscosity at 150°C, poise	3 – 9	7.78
Tests on RTFOT residue		
Loss in weight, %	Max. 1	0.2
Increase in softening point, °C	Max. 5	2.8
Reduction in penetration of residue at 25°C, %	Max. 35	34
Elastic recovery of half thread in ductilometer at 25°C, %	Min. 50	74.5
Rheological properties		
Temperature for $G^*/\sin\delta$ = 1.0 kPa (original binder), °C	—	76.4
Temperature for $G^*/\sin\delta$ = 2.2 kPa (RTFOT residue), °C	—	77.6
Temperature for $G^*\sin\delta$ = 5.0 MPa (PAV residue), °C	—	19.8

Note: PMB=polymer (elastomeric type) modified bitumen; Max.=maximum; Min.=minimum; R&B=ring and ball; COC=Cleveland open cup; RTFOT=rolling thin film oven test; G=complex modulus; δ=phase angle; PAV=pressure aging vessel*

The test results indicate that the PMB binder conforms to grade 40 (PMB 40) while the CRMB binder conforms to grade 60 (CRMB 60). A PMB 40 grade bitumen corresponds to a PMB binder with a penetration value between 30 and 50 while a CRMB 60 grade bitumen corresponds to a CRMB binder with a minimum softening point of 60°C. The mixing and compaction temperatures for the two types of binder used in this study were selected as per the manufacturer's recommendation and are respectively 170°C and 160°C for the PMB binder and 175°C and 165°C for the CRMB binder.

Table 3.2: Physical properties of crumb rubber modified bitumen (CRMB 60).

Property	*Requirement for CRMB 60*	*Test results*
Tests on neat bitumen		
Penetration at 25°C, 0.1 mm, 100 g, 5 s	Max. 50	31
Softening point (R&B), °C	Min. 60	70.6
Flash point, COC, °C	Min. 220	>220
Elastic recovery of half thread in ductilometer at 15°C, %	Min. 50	72.5
Separation difference in softening point, R&B, °C	Max. 4	2.5
Viscosity at 150°C, poise	3 – 9	8.12
Tests on RTFOT residue		
Loss in weight, %	Max. 1	0.4
Increase in softening point, °C	Max. 5	3.65
Reduction in penetration of residue at 25°C, %	Max. 40	31.3
Elastic recovery of half thread in ductilometer at 25°C, %	Min. 35	68.5
Rheological properties		
Temperature for $G^*/\sin\delta$ = 1.0 kPa (original binder), °C	—	79.1
Temperature for $G^*/\sin\delta$ = 2.2 kPa (RTFOT residue), °C	—	81.7
Temperature for $G^*\sin\delta$ = 5.0 MPa (PAV residue), °C	—	19.4

Note: CRMB=crumb rubber modified bitumen; Max.=maximum; Min.=minimum; R&B=ring and ball; COC=Cleveland open cup; RTFOT=rolling thin film oven test; G=complex modulus; δ=phase angle; PAV=pressure aging vessel*

3.2.2 Aggregates

The requirements of aggregates for preparation of OGAFC mixes are quite diverse than traditional dense graded hot mix asphalt (HMA). OGAFC mixes are prepared predominantly using coarse aggregates and a little amount of fines to maximise the voids space. The properties of the coarse aggregates chiefly govern the functionality, durability and performance of OGAFC mixes. Compared to traditional dense graded HMA, physical and morphological requirements for coarse aggregate used in OGAFC mixes are typically higher in terms of strength and shape. Also, as the skeleton structure of OGAFC mixes permits free flow of rainwater runoff through the network of interconnected voids, they are more susceptible to moisture induced damages and hence, demand aggregates with good adhesion capabilities with bitumen. In this study, one source of conventional natural stone aggregate was used as the primary aggregate along with one source of basic oxygen furnace (BOF) steel slag aggregate to examine the potential of BOF steel slag as a secondary aggregate for OGAFC mixes.

Crushed natural stone aggregates were collected from a nearby stone crushing plant, while the BOF steel slag was obtained from the Steel Authority of India Limited (SAIL) plant in Durgapur (West Bengal, India). From both the sources, aggregates conforming to the size corresponding to OGAFC mixes were sieved out as per the gradation requirements. Figures 3.1 and 3.2 illustrate the processing and collection of natural stone aggregate and BOF steel slag, respectively.

Figure 3.1: Processing and collection of natural stone aggregates– (a) aggregate crushers, (b). aggregate screening, (c). aggregate stockpiles, and (d). transportation of aggregates.

Figure 3.2: Processing and collection of BOF steel slag – (a) transfer of molten slag, (b) disposal of molten slag, (c) water spraying over molten slag, (d) water cooling process, (e) cooled steel slag, and (f) slag stockpiles.

3.2.2.1 Chemical characterisation of aggregates

The metal oxide composition of natural and BOF steel slag aggregates was quantified using a PANalytical Axios Sequential X-ray Fluorescence (XRF) Spectrometer. It is a non-destructive test that quantifies the elemental composition of a material by capturing the secondary (or fluorescent) X-rays emitted by the material when excited by a source of primary X-ray. The captured fluorescent X-rays possess fingerprints corresponding to specific elements and thus the chemical composition of the material is qualitatively and quantitatively analysed. The obtained concentrations of oxides in both aggregate types are reported in Table 3.3. CaO, FeO (or Fe_2O_3), and SiO_2 were the principal oxides found in both the aggregates. Natural stone aggregate reported a very high concentration of SiO_2 while the BOF steel slag had a significant concentration of CaO and FeO (or Fe_2O_3). The CaO/SiO_2 ratio, which represents aggregates' basicity — a characteristic of the alkalinity of the aggregate, was found to be considerably higher for BOF steel slag compared to natural stone aggregate.

A higher basicity generally contributes to a good adhesive bond with the weakly acidic asphalt binder (Pasetto and Baldo, 2011; Xie *et al.*, 2012). Aggregates with higher basicity are usually termed alkaline aggregates and are characterised by a high amount of alkali content and a lower amount of silica content and thus exhibit a hydrophobic nature with a relatively lower affinity toward water (Kandhal, 2016). The available calcium in alkaline aggregates associates strongly with the acidic functional groups in asphalt binders (such as carboxylic acids) to form carboxylate salts that are not easily dissolved in water (Yoon and Tarrar, 1988).

Table 3.3: Chemical characterisation of natural stone aggregate and BOF steel slag.

Chemical composition	*Natural stone aggregate*	*BOF steel slag*
SiO_2	50.01	12.04
Al_2O_3	16.03	2.31
FeO or Fe_2O_3	11.63	26.70
MnO	0.16	2.39
MgO	2.35	2.41
CaO	8.10	45.10
Na_2O	2.69	0.27
K_2O	4.25	0.15
TiO_2	1.72	0.60
P_2O_5	0.76	1.29
SO_3	-	0.10
Basicity (CaO/SiO_2)	0.16	3.75

The basicity of the alkaline aggregates is counterbalanced by the acidic functional group of asphalt binders that results in the formation of new species (carboxylate salts), enhancing the adhesive bond between the aggregate and the asphalt binder. It has been reported that acidic aggregates exhibit the weakest adhesive properties, followed by weakly alkaline aggregates, and highly alkaline aggregates possess the strongest adhesion with asphalt binder (Liu *et al.*, 2020a). It is attributed to highly positively charged alkaline minerals on the surface of strong alkaline aggregates that are more attracted towards asphalt binders than acidic and weakly alkaline aggregates. Steel slag with a high percentage of Ca^{2+} ions is a strongly alkaline aggregate and thus expected to possess a good adhesion with asphalt binders.

3.2.2.2 Physical characterisation of aggregates

The obtained crushed natural stone aggregate and BOF steel slag were evaluated for their physical properties in terms of bulk specific gravity, water absorption, shape characteristics (angularity number, particle index, flaky and elongated particles, and fracture faces), and strength parameters (hardness, toughness, strength and durability). As coarser fraction of BOF steel slag aggregates was used as replacement of natural aggregates, fine aggregate angularity (uncompacted voids content) and sand equivalent test were conducted for natural aggregates only. The obtained test results for natural stone aggregate and BOF steel slag are listed in Table 3.4.

BOF steel slag had a higher specific gravity compared to the natural stone aggregate due to considerably higher concentration of iron oxide (FeO or Fe_2O_3) and dense structural integrity. Aggregates with higher specific gravity are generally characterised as strong aggregates (Langer, 1988; Aydilek, 2015). The water absorption values for both aggregates were below the maximum permissible value of 2.0% as specified for dense graded bituminous mixes. However, the water absorption value for BOF steel slag was quite higher than that for natural stone aggregate. The high water absorption value of BOF steel slag is attributed to its porous and rough surface morphology and is also considered as a positive characteristic since it may help in achieving a better bonding with asphalt binder (Kambole *et al.*, 2017). In terms of shape parameters evaluated through angularity number, particle index (angularity coefficient), combined flakiness and elongation index, and percent fractured faces, BOF steel slag exhibited adequate and good shape characteristics which are quite comparable to the natural stone aggregates used in the study.

Table 3.4: Physical properties of natural stone aggregate and BOF steel slag.

Property	*Test methods*	*Requirement (ASTM D7064)*	*Natural stone aggregate*	*BOF steel slag*
Bulk specific gravity	ASTM C127	NA	2.958	3.268
Water absorption (%)	ASTM C127	Max. 2	0.45	1.97
Angularity number	IS 2386 (P-1)	NA	9	11
Particle index (%)	ASTM D3398	NA	12.60	15.90
Flat and elongated particles (%)	IS 2386 (P-1)	Max. 20	18.50	11.08
Percentage fractured faces	ASTM D5821			
i. one fractured face		Min. 95	98.0	96.75
ii. two fractures faces		Min. 90	95.7	91.53
Aggregate abrasion value (%)	ASTM C131	Max. 30	19.47	12.20
Aggregate impact value (%)	IS 2386 (P-4)	NA	15.82	17.45
Aggregate crushing value (%)	IS 2386 (P-4)	NA	19.77	17.73
Aggregate soundness value (%)	IS 2386 (P-5)	NA	3.30	1.38
Uncompacted voids content (%)	ASTM C1252	Min. 40%	41.40	-
Sand equivalent (%)	ASTM D2419	Min 45%	55	-

Note: NA=not applicable, Max.=maximum, Min.=minimum

The hardness, toughness, strength, and durability properties of both aggregates were compared through Los Angeles abrasion value (LAAV) test, aggregate impact value (AIV) test, aggregate crushing value (ACV) test, and aggregate soundness value (ASV) test (using sodium sulphate (Na_2SO_4) salt solution), respectively. BOF steel slag demonstrated better LAAV, AIV, ACV, and ASV than natural stone aggregate indicating that BOF steel slag exhibits better hardness, toughness, strength, and durability. The higher strength properties exhibited by BOF steel slag are attributed to the presence of higher FeO (or Fe_2O_3) concentration and denser packing of mineral structures. Further, the fine fraction of the natural stone aggregate was evaluated for fine aggregate angularity or uncompacted voids content (aggregate fraction size 2.36–0.150 mm) and sand equivalent value (aggregate fraction size smaller than 4.75 mm). It was observed that the fine fraction of aggregate meets the minimum requirements specified by ASTM D7064 (2013).

Both natural stone aggregate and BOF steel slag were also examined for surface morphology using a field emission scanning electron microscope (FESEM). Figure 3.3 illustrates the FESEM micrographs of both aggregates captured at magnification scales of 10.0 KX and 3.0 KX.

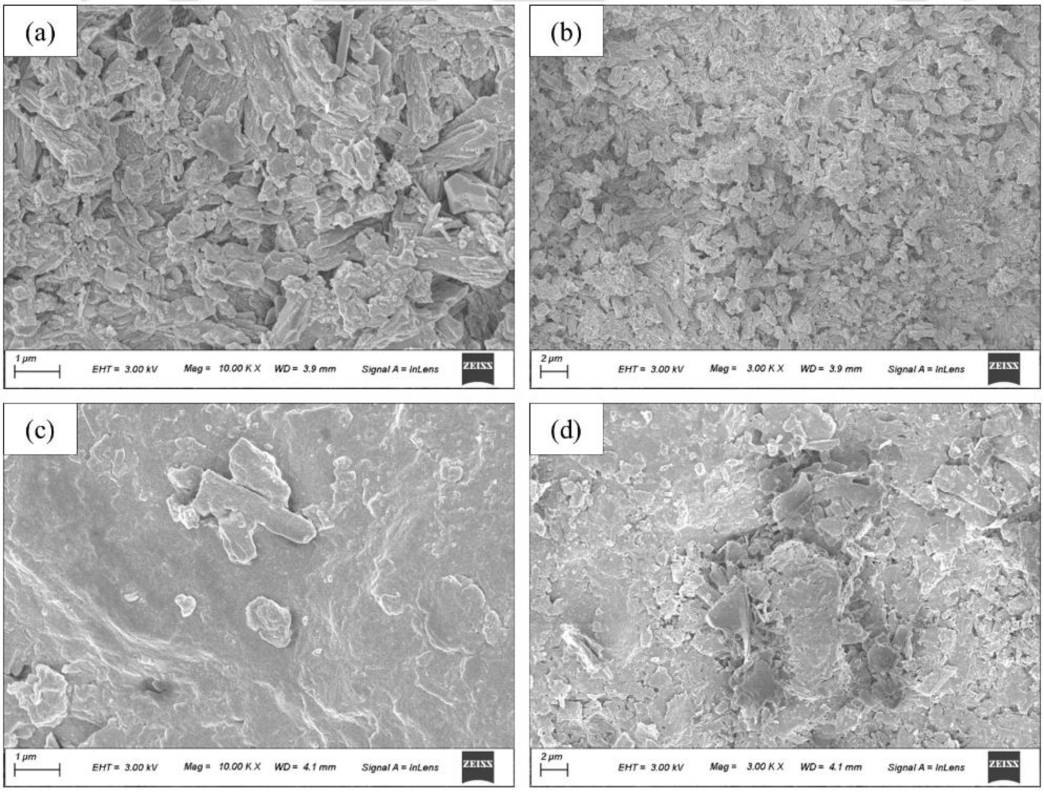


Figure 3.3: FESEM micrographs of – (a) BOF steel slag at 10.0 KX, (b) BOF steel slag at 3.0 KX, (c) natural stone aggregate at 10.0 KX, and (d) natural stone aggregate at 3.0 KX.

The micrographs indicate that BOF steel slag yields a diverse and complex texture compared to the natural aggregates. It is seen that the surface morphology of steel slag is uneven (rough) and consists of surface cavities/pores (mainly formed during the cooling of molten slag). The surface of steel slag shows the presence of pitted and vesicular surface morphology. Such surface features, along with the formation of new species through surface chemical reactions and asphalt binder sorption onto the mineral surface, are expected to enhance the binding properties of the slag with asphalt binder (Shen *et al.*, 2018).

3.2.2.3 Volumetric expansion potential of BOF steel slag aggregates

Due to the use of lime and dolomite as a fluxing agent in the conversion of pig iron to steel, steel slags are often reported to exhibit free lime (f-CaO) and free periclase (f-MgO) higher than desirable quantities. When BOF steel slag particle are used for road making activities, the available f-Cao and f-MgO present in BOF steel slag reacts with the atmospheric moisture and hydrates to portlandite ($Ca(OH)_2$) and brucite ($Mg(OH)_2$), respectively. The volume of portlandite and brucite are comparatively higher than lime and periclase and thus its conversion leads to particle disintegration and loss of strength. Therefore, it is undesirable to use steel slag aggregates with high volumetric expansion/ swelling potential in road making activities.

The volumetric expansion potential of a steel slag depends on the type of cooling process (crystallisation of molten steel slag) adopted in cooling the molten slag in the steel making industry — air cooled or water cooled. Water cooled steel slags are reported to have substantially less potential of volumetric expansion than air cooled steel slags. Further ageing of the steel slag in open air also reduces the volumetric potential of the slag (da Silveira *et al.*, 2004; Sorlini *et al.*, 2012; Sasaki and Hamazaki, 2015). The BOF steel slag used for the study was a water cooled slag and was about two-weeks old when collected from the SAIL plant (Durgapur, India). Further, the steel slag was allowed to age in open air for about a year (in the IIT Guwahati premises) prior to its application in the study.

The volumetric expansion of the steel slag was examined through ASTM D4792 (2013) specification at three time intervals after its production — one-month, one-year, and two-years. The variation of the expansion potential of the BOF steel slag with ageing period is presented in Figure 3.4. It was observed that the volumetric expansion after 7-days of hydration was well within the maximum permissible value of 1.0% (Wu *et al.*, 2007) under all three ageing periods. Also, after a year of ageing, the volumetric expansion was observed to reach a steady value. Therefore, it was concluded that the BOF steel slag used in the study is feasible to be used in road making operations and that its volumetric expansion would not cause any hindrance in its future performance.

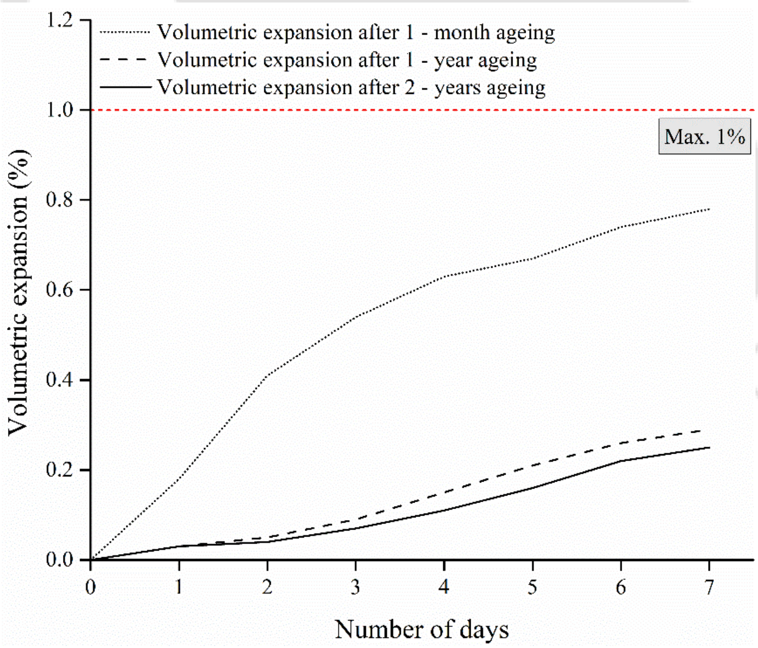


Figure 3.4: Volumetric expansion of BOF steel slag.

3.2.2.4 Leaching potential of BOF steel slag aggregates

Steel slag aggregates may comprise of heavy metals at concentrations higher than that reported in most common soils. This emphasises the necessity to examine the probable environmental hazards and health risks associated with the application of steel slag. A road pavement prepared using steel slag aggregates may leach harmful metals into the groundwater. Therefore, it is important to examine steel slag used in road making operations for its leaching potential.

The BOF steel slag used in the study was evaluated for its potential for leaching as per toxicity characteristics leaching procedure (TCLP) test method EPA SW846 1311 (1992) recommended by the United States Environmental Protection Agency (USEPA). In this method, steel slag was exposed to an acidic environment (pH of 4.93±0.05) to enhance its potential for leachate generation. The acidic environment was developed by adding 5.7 mL glacial acetic acid (CH_3COOH) to 500 mL distilled water to which another 64.3 mL 1-N sodium hydroxide (NaOH) was added to attain a pH of 4.33±0.05. This acidic solution was diluted and stored in a one-litre reagent bottle for further use. In a conical flask, 5 g of powdered BOF steel slag (<200 µm) was added to 100 mL acidic solution and required volume of 1-N NaOH was used to attain the target pH of 4.93±0.05. The conical flask was then placed in a mechanical shaker operating at a speed of 30±2 rpm for 18 hours after which it was placed in a centrifuge rotating at 10,000 rpm for 5 minutes. The sample was then filtered through a Whatman 42 filter paper and stored at 4°C for further analysis through atomic absorption spectroscopy (AAS) test to detect the presence of heavy metals. The results of the TCLP test solution after subjection through the AAS test are listed in Table 3.5. The results indicate that the obtained concentration of heavy metals were within the permissible limit for drinking water when compared with the recommended values specified in IS 10500 (2012). It was concluded that the BOF steel slag used in this study showed no sign of leaching of any heavy metal, and therefore could be considered safe for use in OGAFC mixes.

Table 3.5:Toxicity characteristic leaching procedure (TCLP) test results.

Element	*Permissible limit (mg/L) as per IS 10500 (2012)*	*TCLP leaching concentration (mg/L)*
Magnesium (Mg)	100	19.3
Aluminium (Al)	0.2	0.048
Silica (Si)	NA*	1.13
Calcium (Ca)	200	103.4
Vanadium (V)	0.25	0.144
Chromium - total (Cr)	0.05	0.024
Manganese (Mn)	0.3	0
Iron (Fe)	0.3	0
Cobalt (Co)	0.05	0
Nickel (Ni)	0.02	0.003
Copper (Cu)	1.5	0.101
Zinc (Zn)	15	0.329
Selenium (Se)	0.01	0
Cadmium (Cd)	0.003	0.002
Mercury (Hg)	0.001	0
Lead (Pb)	0.01	0.008

Note: "NA" stands for "Not Applicable"

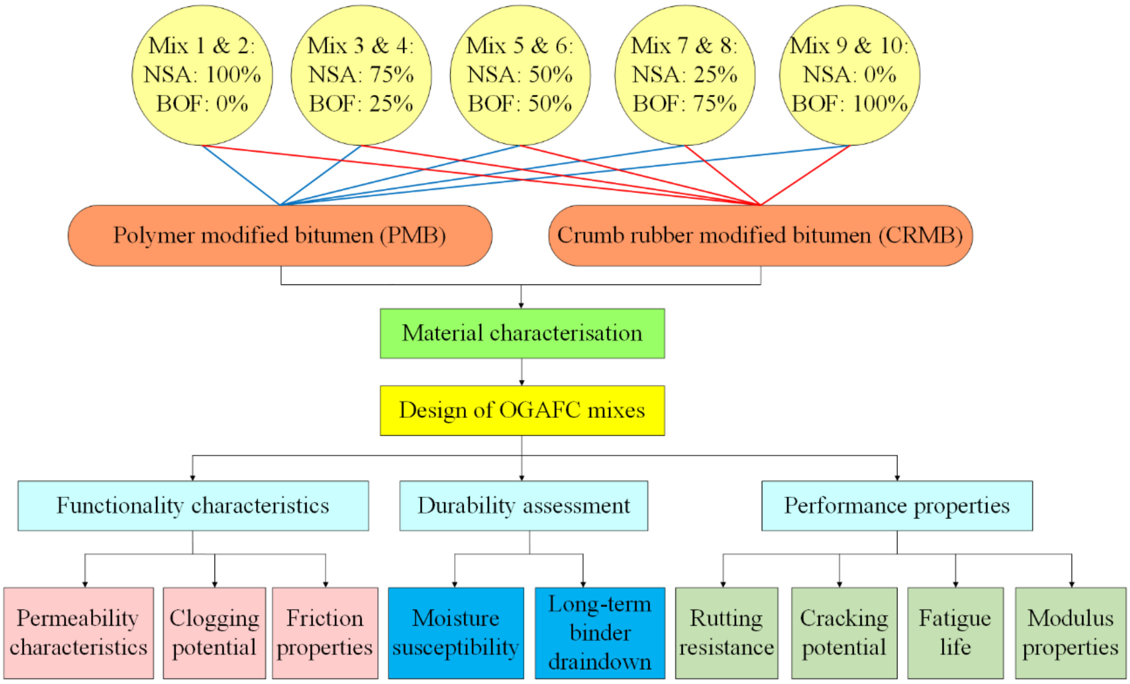
3.2.3 Stabilising additive

OGAFC mixes predominantly comprise of single sized coarse aggregates with small fraction of fine aggregates/filler and also demand a high amount of binder content than the traditional asphalt mixes. The low fine fraction and high binder content makes the OGAFC mixes prone to binder draindown at elevated temperatures. The binder draindown is the downward migration of asphalt binder under the force of gravity at elevated operational temperatures. It is observed during the mixing, hauling and laying stages of OGAFC preparation and construction. Binder draindown results in non-homogeneous heaps (piles) of OGAFC mixes with a binder gradient resulting in road sections with variable binder contents. The sections with higher binder content may result in over compaction leading to lower air voids and a subsequently lower permeability while the sections with lower binder content may show premature ravelling due to lower compaction and relatively higher air voids. In order to negate the binder draindown and to maintain the homogeneity of the OGAFC sections, ASTM D7064 (2013) recommends the use of stabilising agents (additives) which increase the overall stiffness of the binder and also prevent its downward migration. One type of organic cellulose fibre obtained from the Organo Chemical Industries (Mumbai, India) was used as stabilising additive in this study to minimise the draindown potential of the OGAFC mixes. The cellulose fibre was added to the heated aggregates (dry mixing) at a dosage of 0.3% by weight of the mixture. Figure 3.5 illustrates the naked eye view of the cellulose fibres used for the study.

Figure 3.5: Cellulose fibre used for the study.

3.3 Experimental plan

The present study aims to evaluate the effect of varying percentage substitution of BOF steel slag and different binder types on the mix design parameters, functionality, durability, and performance of OGAFC mixes. Figure 3.6 illustrates the overview of the experimental plan adopted in this study. The following sections discuss in details the test procedures and test parameters considered for the evaluation of the mix design parameters, functionality, durability, and performance of OGAFC mixes.



Note: 'NSA' stands for natural stone aggregate, 'BOF' stands for basic oxygen furnace steel slag, and 'OGAFC' stands for open graded asphalt friction course.

Figure 3.6: Experimental plan of the study.

3.4 Design of OGAFC mixes

3.4.1 Selection of aggregate gradation

OGAFC mixes demand special type of aggregate skeleton that permits flow of rainwater runoff through a network of interconnected voids while maintaining the structural integrity. A highly porous aggregate skeleton (with low fines content) enhances the functionality (drainage properties) of OGAFC mixes but may raise concerns related to the durability (ravelling potential); while an OGAFC mix with relatively higher fine content improves its durability but reduces its functionality. The aggregate gradation should be so selected that there is a balance between the functionality and durability of the mix. For this study, the mid-value aggregate gradation recommended by ASTM D7064 (2013) was selected and is shown in Figure 3.7 with the specified upper and lower limits. As can be inferred from the figure, the selected gradation is quite a uniform-gradation with a high coarse fraction and a small fraction of fine aggregates. Specifically, the selected gradation comprises of 92.5% coarse aggregates (greater than 2.36 mm size) and only 7.5% fine aggregates (less than 2.36 mm size).

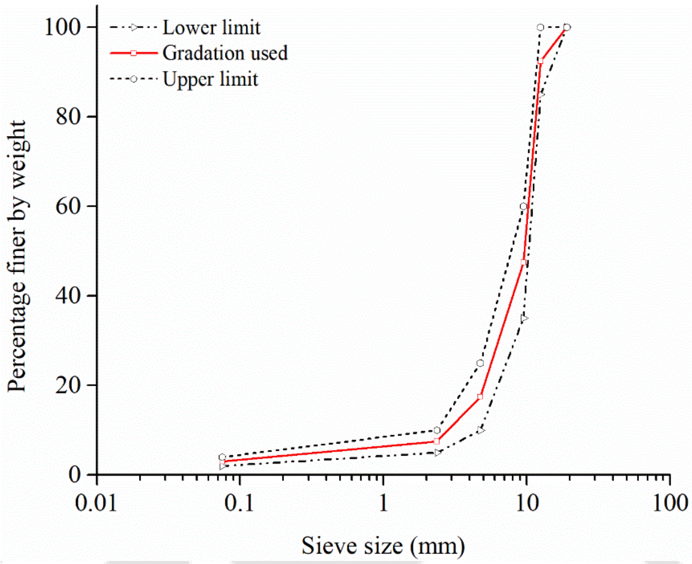


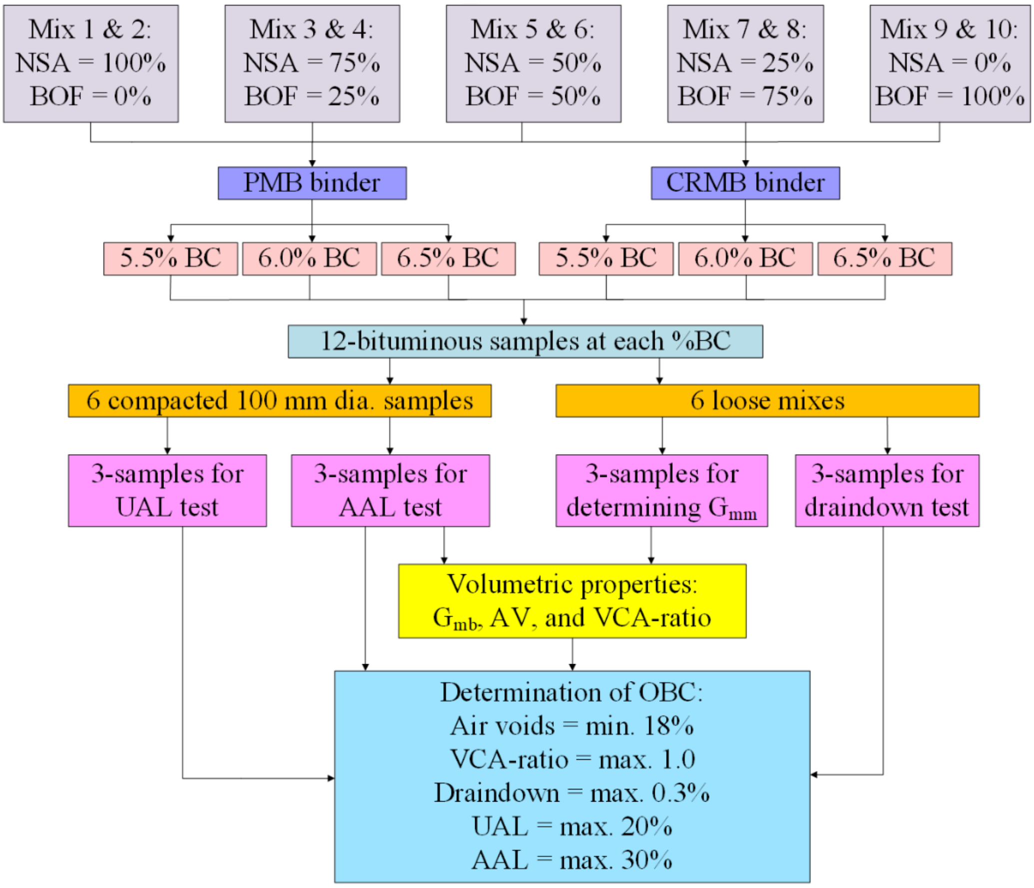
Figure 3.7: OGAFC gradation used in the study.

3.4.2 Preparation of OGAFC specimens

For preparation of OGAFC mixes, blended aggregate batches of 1000 g size corresponding to the selected aggregate gradation (by weight) were prepared in the laboratory. OGAFC mixes with BOF steel slag were fabricated by replacing the coarse aggregate fraction (greater than 2.36 mm) of the aggregate gradation in five replacement percentages — 0, 25, 50, 75, and 100 by weight of the total aggregate. A total of ten different OGAFC mixes (two binder types (PMB and CRMB) × five steel slag replacements) were evaluated in this study. For determination of the optimum binder content (OBC) for each of the ten mixes, OGAFC specimens were prepared at three trial binder contents – 5.5%, 6.0% and 6.5% by weight of mixture. During the preparation of the OGAFC specimens, both aggregates and binder were first pre-heated to the mixing temperature (170°C for PMB and 175°C for CRMB) and then mixed thoroughly in an isomantle along with the incorporation of cellulose fibre. Cellulose fibre was added at a dosage of 0.3% by weight of the mixture to the pre-heated aggregates to minimise the binder draindown. The bitumen coated loose OGAFC mixes were then subjected to short-term ageing in a forced draft oven at their respective compaction temperatures (160°C for PMB and 165°C for CRMB) for a duration of 2 hours. Following the short-term ageing, the loose mixes were then compacted by applying 50 Marshall impact compactor blows on each side of the specimen. ASTM D7064 (2013) recommends the use 50 gyrations of Superpave gyratory compactor (SGC) or any other mode of compaction providing an equivalent amount of compaction for the preparation of OGAFC mixes. Previous studies have shown that 50 Marshall impact compactor blows on both faces of an OGAFC specimen provides nearly similar compaction compared to 50 gyrations in an SGC (Mallick *et al.*, 2000; Watson *et al.*, 2003; Alvarez *et al.*, 2006). Therefore, Marshall method of compaction was used in this study. The compacted specimens were allowed to cool overnight inside the Marshall moulds and were extruded out once they attained ambient room temperature. Figure 3.8 illustrates the batching, mixing and compaction of OGAFC mixes in the laboratory.

Figure 3.8: Preparation of OGAFC mixes: (a). Batching of aggregates, (b). Mixing of OGAFC samples, and (c). Compaction of OGAFC samples.

At each trial binder content, twelve replicates (six loose mixes and six compacted specimens) were prepared. Three loose mixes were examined for binder draindown and three for the determination of the theoretical maximum specific gravity as per ASTM D6390 (2017) and ASTM D6857 (2018), respectively. The six Marshall compacted specimens were used for the assessment of volumetric properties and ravelling under both unaged and aged conditions through the Cantabro abrasion loss test. The details of the test procedures adopted for evaluation of the mix design parameters are discussed in the subsequent sections. The experimental plan (flowchart) selected for performing the design of the OGAFC mixes with five BOF steel slag replacement percentages and two modified binders is presented in Figure 3.9.



Note: 'NSA' stands for natural stone aggregate, 'BOF' stands for basic oxygen furnace, 'PMB' stands for polymer modified bitumen, 'CRMB' stands for crumb rubber modified bitumen, 'BC' stands for binder content, 'UAL' stands for unaged abrasion loss, 'AAL' stands for aged abrasion loss, 'G_{mm}' stands for theoretical maximum specific gravity, 'G_{mb}' stands for bulk specific gravity, 'AV' stands for air voids, 'VCA' stands for voids in coarse aggregate, 'max.' stands for maximum, and 'min.' stands for minimum.

Figure 3.9: Flowchart for design of OGAFC mixes.

3.4.3 Bulk specific gravity

Conventionally, the bulk specific gravity of compacted dense graded bituminous specimens is determined following the water displacement methodology (ASTM D2726, 2019). It is also the most accepted technique to evaluate the bulk specific gravities during various quality control (QC) and quality assurance (QA) operations of dense graded bituminous mixes. However, for OGAFC mixes, it is not freasible to evaluate the bulk specific gravities of compacted specimens using this technique as it is quite difficult to obtain the saturated surface dry (SSD) weights due to the high percentage of interconnected voids. For OGAFC specimens, the most commonly accepted methodology to evaluate the bulk specific gravity is through geometric measurement (dimensional analysis) specified in ASTM D3203 (2017). Many researchers have adopted this methodology (Tsai *et al.*, 2012; King *et al.*, 2013) and the same was used in this study for bulk specific gravity determination of compacted OGAFC mixes.

Dimensional analysis comprises the determination of weight of the dry specimen in air and the geometrical measurement of the volume of the specimen using its average diameter and height. Figure 3.10 shows diameter and height (measured at 120° apart) being measure for an OGAFC specimen using a digital Vernier calliper. The average of these readings were used to compute the bulk volume (V in cm^3) of the compacted samples. The bulk specific gravity of the specimen was then computed by dividing the dry weight (M in g) of the compacted specimen in air with the obtained bulk volume using Equation (3.1):

$$G_{mb} = \frac{M}{V} \tag{3.1}$$

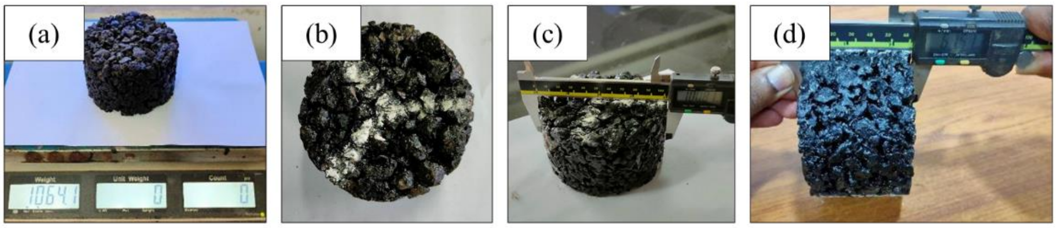


Figure 3.10: Dimensional analysis of OGAFC specimens: (a) weight, (b) 120° lines, (c) diameter, and (d) height.

3.4.4 Air voids content

Air voids are tiny air pockets or airspaces found in the aggregate skeleton formed within the coated aggregate particles of a compacted asphalt mix. Air void content is the primary parameter controlling the drainability/permeability of an OGAFC mixture and is quantified as the percent of the volume of air in the mixture. It is calculated using Equation (3.2):

$$V_a(\%) = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100 \tag{3.2}$$

where, V_a is the air voids content of the compacted asphalt mix in percent, G_{mm} is the theoretical maximum specific gravity of the mixture, and G_{mb} is the bulk specific gravity of the compacted specimen. The theoretical maximum specific gravity (G_{mm}) of the mix was evaluated in accordance with ASTM D6857 (2018). Loose asphalt mix was vacuum sealed using a CoreLok vacuum chamber and its theoretical maximum specific gravity was determined by the vacuum sealing method presented in Figure 3.11.

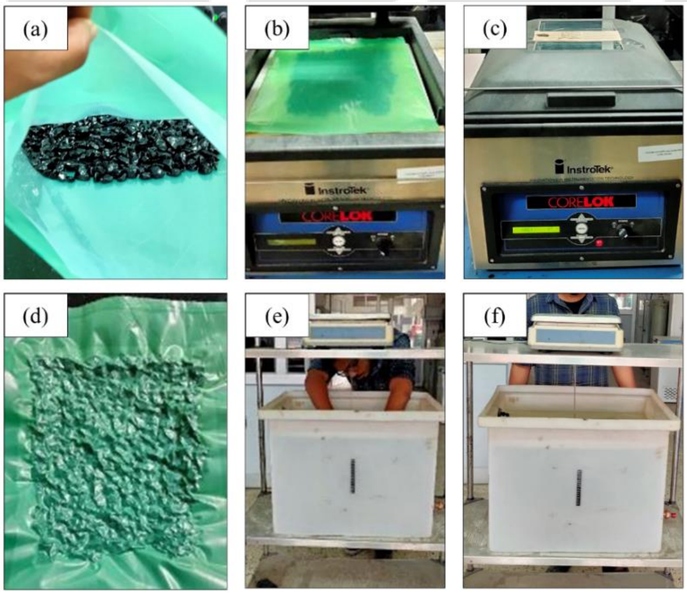


Figure 3.11: Determination of theoretical maximum specific gravity: (a) placing of loose asphalt mix in CoreLok bag, (b) aligning of Corelok bag, (c) vaccum sealing, (d) sealed loose asphalt mix, (e) removal of air pockets, and (f) weight under water.

3.4.5 Stone-on-stone contact

Stone-on-stone contact criterion is an important design requirement for OGAFC mixes and helps to ensure adequate resistance to ravelling and permanent deformation. The coarse aggregate fraction of the aggregate skeleton of the OGAFC mixture is responsible to provide adequate stone-on-stone contact to withstand the traffic loads. Figure 3.12 illustrates the stone-on-stone contact observed in an OGAFC cross-section and compares it with the cross-section of a conventional dense graded hot mix asphalt. A proper stone-on-stone contact can be seen in case of OGAFC mixture, while the coarse aggregates in dense graded hot mix asphalt appears to float in the matrix of fine aggregates.

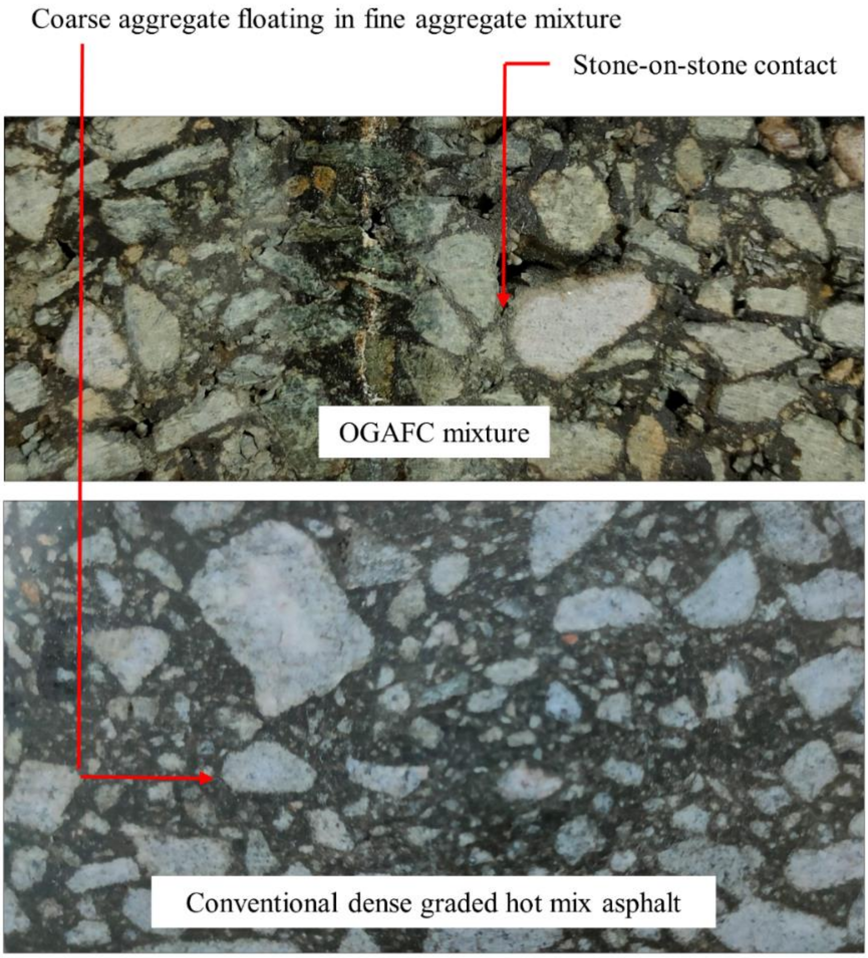


Figure 3.12: Sectional views illustrating the difference in stone-on-stone contact between OGAFC and conventional dense graded HMA specimen.

The stone-on-stone contact condition of the OGAFC mixes was evaluated by comparing the voids in the coarse aggregate size fraction greater than 4.75 mm of a compacted mix (VCA_{mix}) to the voids of the same aggregate fraction under dry-rodded condition (VCA_{DRC}) (Kandhal, 2002). The dry-rodded condition was established in accordance with the ASTM C29 (2017) specifications. VCA_{mix} and VCA_{DRC} were calculated using Equations (3.3) and (3.4), respectively. Figure 3.13 provides schematic illustration of the calculation of VCA_{mix} and VCA_{DRC}.

$$VCA_{mix}(\%) = \frac{G_{CA} - (G_{mb} \times P_{CA})}{G_{CA}} \times 100 \tag{3.3}$$

$$VCA_{DRC}(\%) = \frac{(G_{CA} \times \gamma_w) - \gamma_S}{G_{CA} \times \gamma_w} \times 100 \tag{3.4}$$

where, G_{CA} = bulk specific gravity of coarse aggregate; G_{mb} = bulk specific gravity of compacted OGAFC mix; P_{CA} = percent of aggregate fraction greater than 4.75 mm size in the mixture; γ_w = density of water; and γ_s = bulk density of coarse aggregate fraction in dry-rodded condition.

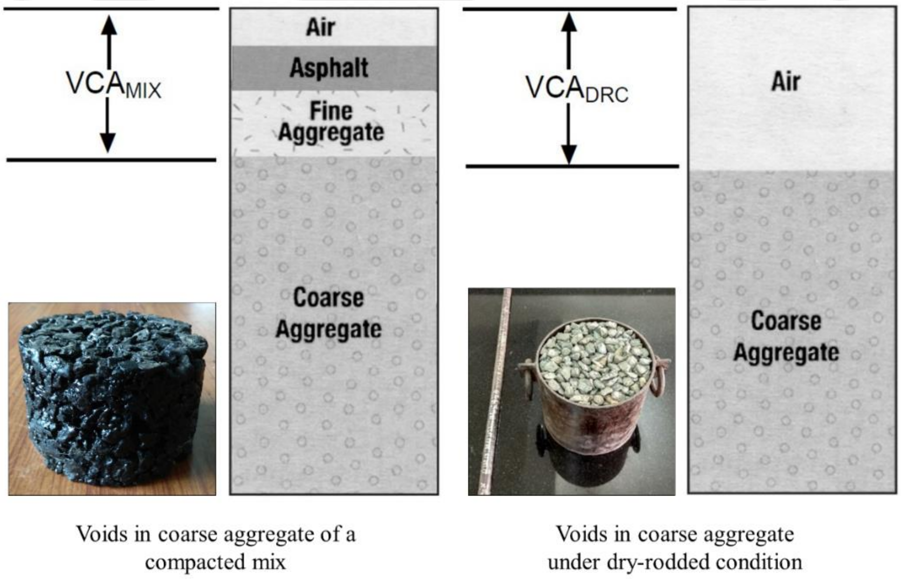


Figure 3.13: Schematic illustration of VCA_{mix} and VCA_{DRC} (Kandhal, 2002).

The stone-on-stone contact condition was ensured when the *VCA-ratio* is below 1.0 and was computed using Equation 3.5. A lower value of the ratio signifies a better stone-on-stone contact.

$$VCA\ ratio = \frac{VCA_{mix}}{VCA_{DRC}} \tag{3.5}$$

3.4.6 Binder draindown

Binder draindown is the downward migration of asphalt binder present around the aggregate surface, during production, transportation, and construction of an OGAFC mix. The low fine content in OGAFC mix may not provide the required holding strength or adequate stiffness to the asphalt mastic, and the high air void content may further ease its downward movement. Stabilising additives like cellulose fibres are often used to provide the desired cohesive strength to the asphalt mastic and mitigate the binder draindown. Further, modified binders are preferred over neat (unmodified) binders for preparation of OGAFC mixes as they are comparatively stiffer and resist the downward movement of binders at elevated temperatures. For illustration purpose, to represent the binder draindown in OGAFC mixes, a loose OGAFC mixture was prepared using a neat viscosity grade 30 (VG-30) binder and no additives (cellulose fibre). The lower stiffness and absence of cellulose fibre resulted in the separation of asphalt from the mixture which can be clearly observed in Figure 3.14. This results in a non-homogeneous mixture with variable binder contents with higher susceptibility of the mix to ravelling and moisture induced damage.

Figure 3.14: Binder draindown observed in OGAFC mixes.

Under the experimental program of this study, loss of binder or binder draindown of the OGAFC mixtures prepared with modified binders and cellulose fibre, was measured as per ASTM D6390 (2017). In the test, loose OGAFC mixtures were prepared and placed on an IS 6.3 mm sieve (6.3 mm mesh opening) in a forced draft oven at a temperature 10°C higher than the mixing temperature for 1 hour, and the binder or asphalt mastic draindown through the basket opening was computed using Equation (3.6). A maximum of 0.3% (by total weight of mixture) of draindown is permissible per ASTM D7064 (2013) guidelines. Figure 3.15 illustrates the methodology adopted for computation of the binder draindown adopted in the study.

$$Draindown\ (\%) = \frac{W_4 - W_3}{W_2 - W_1} \times 100 \qquad (3.6)$$

where W_1 = weight of wire basket; W_2 = weight of sample and wire basket; W_3 = weight of tray; and W_4 = weight of tray after being kept for 1 hour in the oven.

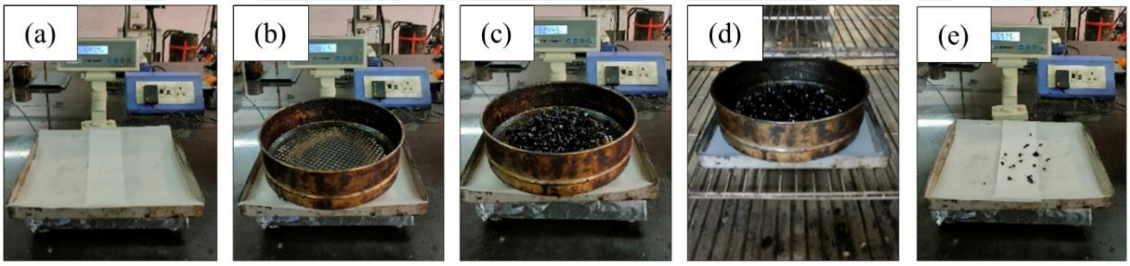


Figure 3.15: Binder draindown determination: (a) weight of tray, (b) weight of tray + sieve, (c) weight of empty tray + sieve + loose mix, (d) conditioning of loose mix, and (e) weight of draindown particle + tray.

3.4.7 Cantabro abrasion loss

Ravelling is a usually reported distress with OGAFC mixes. Greater air voids content, higher ageing and binder draindown potential of OGAFC mixes makes them vulnerable to ravelling. Ravelling is usually referred to as disintegration or loss of aggregate particles from the aggregate-asphalt matrix (Huber, 2000; Kandhal, 2016). During ravelling, the fine aggregate generally wears away first; followed by disintegration of larger fragments from the matrix. Over time the pavement possesses an uneven and jagged appearance. The Cantabro abrasion loss test is the most widely adopted test method to evaluate the ravelling potential of an OGAFC mixture. The test works on the principle of measuring the breakdown of compacted OGAFC specimens after being subjected to a specified number of revolutions in a Los Angeles abrasion drum. The test was conducted as per ASTM D7064 (2013) specifications where compacted OGAFC specimens were subjected to 300 revolutions in Los Angeles abrasion drum at a speed of 30 revolutions per minute (Figure 3.16) with no abrasive charge at a temperature of 25±1°C. The abrasion loss was measured as percentage weight loss compared to the initial weight of the sample using Equation (3.7):

$$Abrasion\ \ loss\ \ (\%) = \frac{P_0 - P}{P_0} \times 100 \qquad (3.7)$$

where, P_0 and P are the mass of sample before and after the test, respectively. The test was performed under two ageing conditions — unaged and aged. Ageing of the OGAFC specimens was performed to simulate the loss in binding ability due to oxidative hardening of the binder. As OGAFC mixes have higher air voids content, they are expected to undergo ageing at a higher rate. In order to simulate the oxidative ageing of the mixtures, compacted OGAFC specimens were subjected to ageing in a forced draft oven at 60°C for a period of 168 hours (7 days) [This ageing protocol is recommended in ASTM D7064 (2013)]. The samples were then subjected to Cantabro abrasion loss test as described earlier. Figure 3.17 shows the samples of OGAFC mixes fabricated with 25% BOF steel slag and prepared using PMB and CRMB binders at three bitumen contents (5.5%, 6.0%, and 6.5%) after being subjected to unaged and aged Cantabro abrasion loss tests.

Figure 3.16: Los Angeles abrasion drum used for Cantabro abrasion loss test.

Figure 3.17: Cantabro abrasion loss test specimens: (a) OGAFC samples prepared with 25% BOF steel slag, (b) unaged OGAFC samples after Cantabro abrasion loss test, and (c) aged OGAFC samples after Cantabro abrasion loss test.

3.4.8 Optimum binder content

For all OGAFC mixes, the optimum binder content was determined based on mix design parameter requirements stated by ASTM D7064 (2013). The desired/required OGAFC mix design parameters are listed in Table 3.6. The binder content at which an OGAFC mix satisfies all the design requirements is selected as the optimum binder content (OBC) of the mix.

Table 3.6: Requirements for selection of OBC for OGAFC mixes as per ASTM D7064 (2013).

Parameter	*Requirements/Limits*
Air voids content	Minimum 18%
Stone-on-stone contact	VCA-ratio < 1.0
Binder draindown	Maximum 0.3%
Unaged abrasion loss	Maximum 20%
Aged abrasion loss	Maximum 30%

3.5 Evaluation of functionality of OGAFC mixes with varying BOF steel slag content

Functionality mainly refers to the ability of an OGAFC mix to retain its useful properties/characteristics over time. OGAFC mixes are mostly designed as a functional layer to permit the lateral flow of rainwater runoff through the network of interconnected air voids and are laid over an existing impermeable dense graded asphalt course. An OGAFC layer provides a course with a high degree of permeability to negate hydroplaning and facilitate good frictional properties even during extreme wet weather conditions. In this study, the functionality of the OGAFC mixes was evaluated in terms of the drainage potential and frictional characteristics under different environmental conditions. In the following sections, the different test protocols and conditions considered to evaluate the drainability and frictional properties of OGAFC mixes are discussed in detail.

3.5.1 Permeability and clogging characteristics of OGAFC mixes

The drainability of an OGAFC mixture is characterised through permeability (also called hydraulic conductivity) and porosity. OGAFC mixes are designed for a high permeability and skid resistance to reduce the potential of hydroplaning, glare, and splash and spray of the rainwater runoff. The drainage benefits of an OGAFC layer are available until the void structure of these mixtures remains mobilised and allows free flow of the rainwater runoff. When these voids get clogged, the interconnectivity is disrupted and OGAFC mixtures may begin to behave like conventional dense-graded surfaces, and the associated advantages of OGAFC cease to exist. Therefore, evaluation of clogging characteristics of OGAFC mixes is of prime importance so that they continue to serve the designed functional purpose. Clogging is predominantly attributed to three distinct phenomena — particle-related clogging, stripping-related clogging, and deformation-related clogging. Particle-related clogging is associated with the intrusion of dirt and pollutants (for example, debris, detritus, ravelled off small aggregate particles, by-products of vehicle tyres, *etc*.) in the voids of the OGAFC skeleton. Stripping-related clogging is related to obstruction by stripped off asphalt film due to moisture damage (stripping). Whereas deformation-related clogging is related to the reduction in the air voids content of OGAFC mixtures due to permanent deformation (rutting). Considering the unfavourable effect of clogging, an investigation of the influence of different forms of clogging on the drainability of OGAFC mixtures is of paramount importance.

The three clogging mechanisms — particle-related clogging (due to intrusion of foreign material like sand), stripping-related clogging (due to deposition of stripped off bitumen-fines mortar in the mix structure), and deformation-related clogging (reduced drainability as a mixture undergoes permanent deformation) were evaluated in this study. Evaluation of particle-related clogging was done using surface clogging and de-clogging processes allowing the determination of initial and secondary clogging rates for the OGAFC mixes. For stripping-related clogging, the mixes were subjected to a moisture conditioning procedure and then evaluated for permeability and porosity. Dynamic creep test was employed to simulate clogging due to permanent deformation.

For evaluation of the drainability characteristics of the BOF steel slag incorporated OGAFC mixes with modified binders, compacted OGAFC specimens were prepared at 6.0% binder content (by weight of mixture) using a uniform compaction effort of 50 Marshall blows on both sides of the specimens to attain the desired target air voids content of the mix. Several researchers in the past have used the concept of equal compactive effort for evaluation of drainage properties of OGAFC mixes (Pattanaik *et al.*, 2018a; Skaf *et al.*, 2019; Chai *et al.*, 2020). The flow chart for the evaluation of drainability and clogging potential of the OGAFC mixes is presented in Figure 3.18.

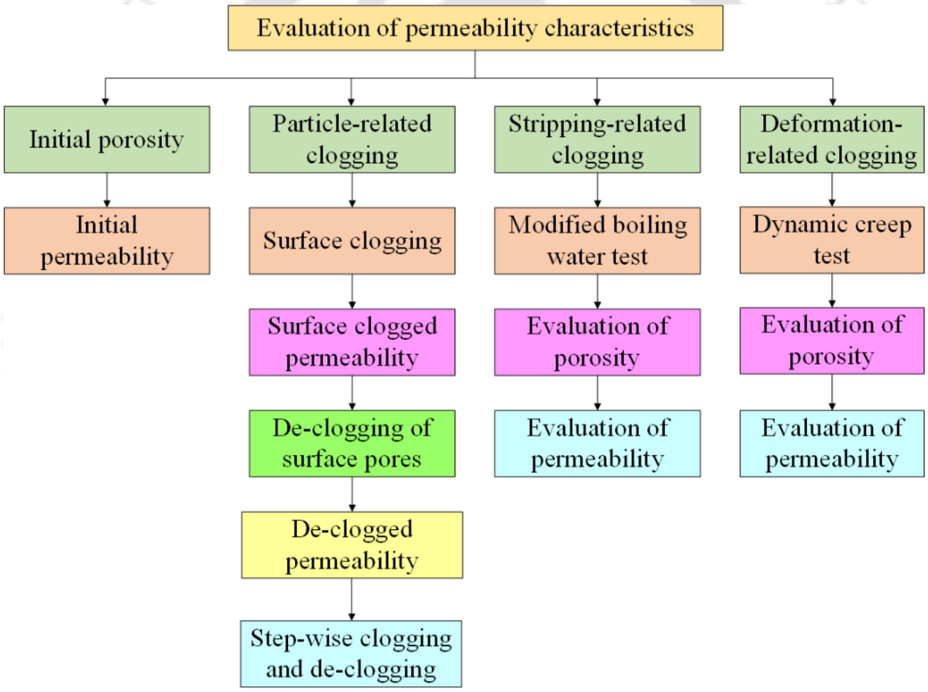


Figure 3.18: Flowchart for evaluation of drainability of OGAFC mixes.

3.5.1.1 Initial porosity and permeability

Porosity (*n*) or water permeable air voids in a compacted asphalt mix specimen is the network of interconnected air voids allowing free flow of water through its aggregate skeleton structure. Total air voids in a compacted specimen consist of both permeable and impermeable voids, while porosity represents the percentage of permeable/interconnected air voids. For drainage through an OGAFC mixture, water will infiltrate through the interconnected air voids and cannot access the voids which are impermeable in nature. Being related to the flow of water through an OGAFC mix, porosity is therefore more relevant for OGAFC compared to the total air void content. Porosity of the OGAFC specimens was measured through the vacuum sealing method specified in ASTM D7063 (2018) using the CoreLok device (Figure 3.19) and computed using Equation (3.8):

$$n = \frac{G_{ma} - G_{mb}}{G_{ma}} \times 100\% \tag{3.8}$$

where, n is the porosity of specimen in percent, G_{ma} and G_{mb} are the apparent and bulk specific gravities of the specimen, respectively.

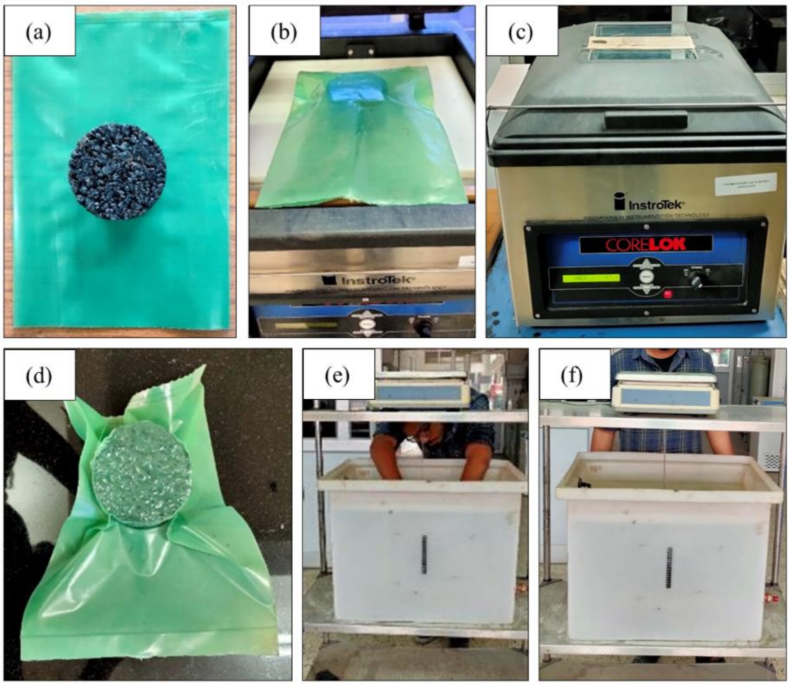


Figure 3.19: Determination of porosity using CoreLok test: (a) compacted OGAFC specimen and CoreLok bag, (b) aligning of Corelok bag with specimen, (c) vaccum sealing, (d) sealed OGAFC specimen, (e) removal of air pockets, and (f) weight under water.

Permeability (k) is a key functional characteristic of OGAFC mixes which determines the rate at which the porous structure will transport water under a given hydraulic gradient. Permeability for OGAFC mixtures is quite high compared to traditional dense graded asphalt mixtures due to the high degree of porosity. ASTM D7064 (2013) specifies a minimum permeability of 100 m/day for an OGAFC mix. In this study, the permeability of OGAFC specimen was measured in accordance with FDOT FM 5-565 (2015) standard using a falling head permeameter shown in Figure 3.20.

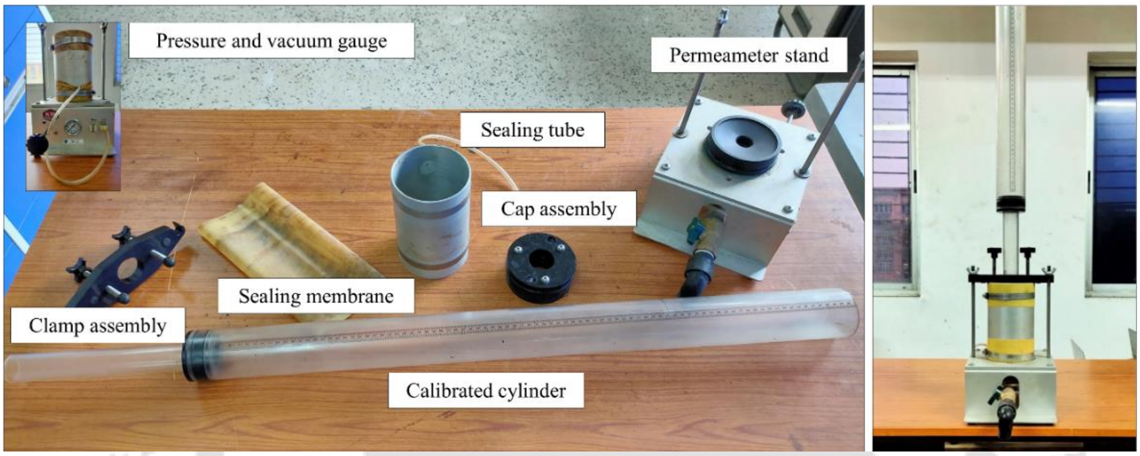


Figure 3.20: Falling head permeameter used in the study.

The permeameter comprised of a flexible latex wall which aids in sealing the sides of the cylindrical OGAFC specimen by maintaining an air pressure of 68.9±3.4 kPa. Before performing the test, the graduated stand-pipe was half-filled with water and the permeameter was rocked back, forth, and sideways to release any entrapped air. The stand-pipe was then completely filled and water was allowed to flow through the specimen by opening the outlet valve. The permeability of the OGAFC specimens was computed based on the Darcy's law using Equation (3.9):

$$k = \frac{aL \times ln(h_1/h_2)}{At} \times t_c \tag{3.9}$$

where, k (m/day) is the permeability of the OGAFC specimen, a (mm^2) is the cross-sectional area of stand-pipe, A (mm^2) and L (mm) are the cross-sectional area and height of the OGAFC specimen respectively, t (second) is the time required by the water to fall from an initial head of h_1 (mm) to a final head of h_2 (mm), and t_c is the temperature correction applied for water viscosity considering 20°C as standard testing temperature. Permeability measurements were conducted under saturated conditions and an OGAFC specimen was considered to be saturated when the difference between the first and third permeability reading was found to be within ±4.0%. The measured permeability was designated as the initial permeability (K_i). Three replicates of each OGAFC combination were considered for measuring porosity and permeability.

3.5.1.2 Particle-related clogging: Effect of clogging and de-clogging on drainage characteristics

Graded sand conforming to ASTM C778 (2017) was used to clog OGAFC specimens as per the procedure reported by Martin *et al.* (2014) and Pattanaik *et al.* (2018a). All OGAFC specimens were first wrapped with a packing tape along the curved surface with about 25 mm of the tape flushing above the top surface of the specimen as illustrated in Figure 3.21(a). Using a circular rubber slider, graded sand was smoothly and evenly spread over the surface of the specimen till all surface asperities were completely flushed with the clogging material (Figure 3.21(b)). The permeability of the surface clogged OGAFC specimens was measured using the flexible wall falling head permeameter (Figure 3.21(c)). This permeability represented the drainability characteristics of OGAFC mixtures under surface clogged condition and was denoted as K_{sc} (permeability after clogging of surface pores or the surface clogged permeability). After the measurement of the surface clogged permeability, the OGAFC specimens were left to dry at room temperature for 24 hours, following which de-clogging operations were carried out through the application of vacuum and by reverse flushing as illustrated in Figures 3.21(d) and 3.21(e), respectively. Subsequently, the permeability of the de-clogged OGAFC specimens were measured and denoted as K_{dc} (permeability after de-clogging operation or the de-clogged permeability).

The purpose of evaluating the de-clogged permeability was to find out the degree of permeability that could be restored through cleaning/maintenance operations.

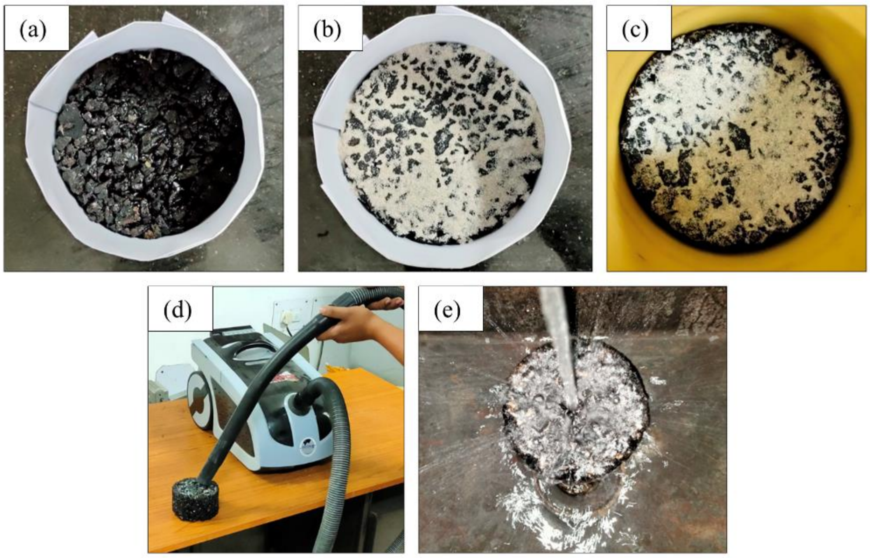


Figure 3.21: Clogging and de-clogging of OGAFC mix: (a). wrapping of OGAFC sample, (b). surface clogged OGAFC sample, (c). clogged OGAFC sample inside permeameter, (d). de-clogging by vacuum cleaning, and (e). de-clogging by reverse flushing.

To also understand the rate at which OGAFC mixes would clog with sequential addition of clogging material, a step-wise clogging was also performed. The de-clogged OGAFC specimens were re-clogged using 14 g batches of graded sand applied over the surface while the specimens were positioned inside the permeameter. Permeability was measured and reported after the addition of each batch of sand. The batch-wise addition of sand was continued till a steady permeability value was observed. During the entire process of the step-wise clogging, the OGAFC specimen was held inside the permeameter.

3.5.1.3 Stripping-related clogging: Effect of binder stripping on drainage characteristics

It is generally conceived that stripped off asphalt mastic from the aggregate surface, as a result of the action of moisture, may clog the voids of an OGAFC mix and thereby affect the drainability of OGAFC mixes. To replicate the stripping phenomenon in the laboratory and to understand its effect on the drainage characteristics, the compacted cylindrical OGAFC specimens were kept in boiling water at 100°C for 30 minutes (Figure 3.22(a)) and were then evaluated for porosity and permeability after attaining the room temperature. Similar test temperature and time for boiling water test have also been considered previously to simulate stripping of asphalt film (Chen *et al.*, 2014). The obtained porosity and permeability were compared with the control values (initial porosity and permeability) to evaluate the effect of stripping on drainage characteristics of the BOF steel slag incorporated OGAFC mixtures. For each OGAFC mix type (with varying steel slag content and modified binders), three replicates were prepared and used to evaluate the phenomenon of stripping-related cogging.

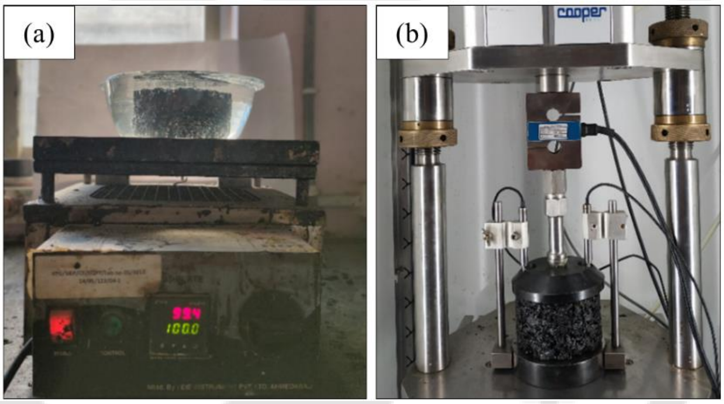


Figure 3.22: Evaliuation of the effect of moisture induced damage and permanent deformation on drainability of OGAFC mixes: (a). Stripping-related clogging, and (b). Deformation-related clogging.

3.5.1.4 Deformation related clogging: Effect of permanent deformation on drainage characteristics

Permanent deformation caused by dynamic vehicle loads may also reduce the drainability of an OGAFC layer due to restructuring and densification of the aggregate skeleton of the mix. To evaluate the extent of decrease in porosity and permeability of OGAFC mixtures with and without BOF steel slag aggregates under dynamic loading, cylindrical OGAFC specimens were subjected to a dynamic creep test in a universal testing machine (UTM) illustrated in Figure 3.22(b) and as per BS DD 226 (1996) specifications. Prior to the application of dynamic load, the test specimens were subjected to conditioning at the test temperature of 40°C for 4 hours. Post conditioning, a 10 kPa load was applied for 10 minutes to ensure a proper contact between the platen and the sample surface. Then, a dynamic load of 100 kPa was applied at 0.5 Hz frequency (1 second load and 1 second rest) for 10,000 cycles. After the test, the specimens were first brought to room temperature and then evaluated for porosity and permeability. Three replicates of each mix type were used to assess the deformation-related clogging of the OGAFC mixes.

3.5.2 Frictional characterisation of OGAFC mixes

Frictional characteristics of OGAFC mixes are of paramount importance to deliver the desired traffic safety both under dry and wet weather conditions during its service life. Driving safety is significantly improved by ensuring an adequate surface skid resistance (Kuttesch, 2004). A high percentage of road accidents is reported under wet weather conditions and one of the prime causes of these accidents is hydroplaning, accounting for about 13.5% of fatal accidents and 25% of the total road accidents globally (Kuemmel *et al.*, 2000). Application of OGAFC in different parts of the world have reported significant reduction in the number of road accidents and associated fatalities especially under wet weather conditions (Shimeno *et al.*, 1997; Kabir *et al.*, 2012). Like any other asphalt surface course, the skid resistance of OGAFC mixes is also reported to decrease with the appearance of water on its surface and this decrease is observed to decay further with increment in the water film thickness (Pattanaik *et al.*, 2017; Tan *et al.*, 2019). However, this decrease in the skid resistance due to the presence of water is not as significant as reported for dense graded asphalt courses, due to the high drainage potential of OGAFC mixes. When an OGAFC surface course gets clogged either due to particle-related clogging or due to deformation-related clogging (discussed in the previous sections), it reduces the drainage potential and may cause ponding of water on the surface. A high intensity rainfall (or runoff flow) on a clogged OGAFC course can result in ponding of water on the surface and may lead to hydroplaning. Even though several studies have been conducted on the skid resistance of OGAFC mixes under dry and wet surface conditions, studies exploring the frictional characteristics of OGAFC mixes under the possible ponding surface condition and its comparison with friction under dry surface condition are still limited.

Adhesion and hysteresis are the two main components of skid resistance (Kummer and Meyer, 1967; Croney and Croney, 1998). Adhesion is the component of skid resistance which results due to the contact between the vehicle tyre and the pavement surface; while hysteresis results from the deformation of the vehicle tyre due to the presence of surface asperities. Adhesion is related to the asperities in the aggregate (microlevel), while hysteresis is related to the irregularities of the overall mix structure (macrolevel). The concepts of both adhesion and hysteresis are illustrated in Figure 3.23.

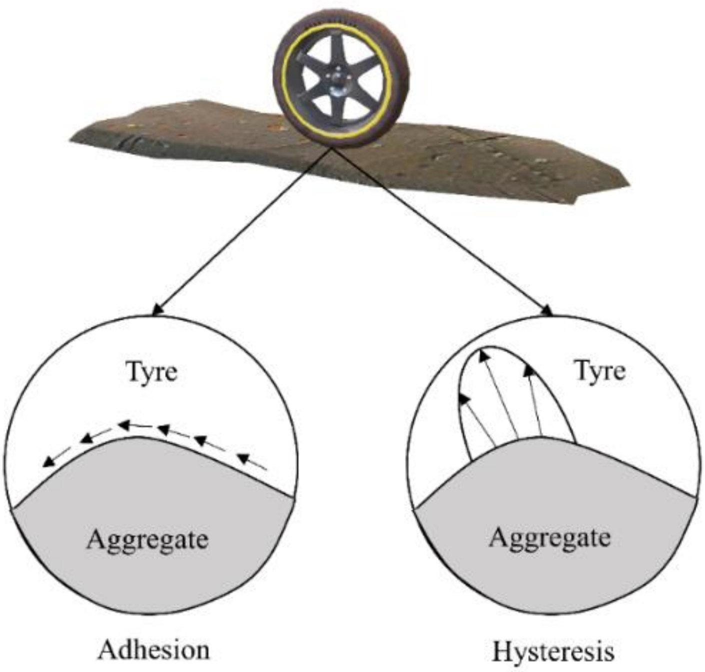


Figure 3.23: Adhesion and hysteresis components of skid resistance.

As seen in the figure, the adhesion component of friction is developed due to the resistance developed at the tyre-pavement interaction and is dependent on the microtexture, while the hysteresis component is a result of the bulk deformation of the vehicle tyre due to macrotexture asperities present in the pavement surface (Hall *et al.*, 2009). This study also determined adhesion and hysteresis components of the skid resistance of OGAFC mixes with BOF steel slag.

When an OGAFC course remains in service, the aggregates will be subjected to polishing and wearing off due to continuous traffic movements. Hence, another important aspect would be to determine the friction performance when the aggregates have undergone polishing/wearing. To understand frictional performance in the later service life of OGAFC mixes, aggregates were first polished in the laboratory through Los Angeles abrasion machine, and then OGAFC mixes were fabricated using these polished aggregates to check for frictional properties.

For the evaluation of the frictional characteristics, OGAFC square slabs of size 305×305×50 mm were prepared using a laboratory roller compactor (shown in Figure 3.24) at 6.0% binder content (by weight of the mix) for the target designed air void content. For each mix type, nine replicates of slab specimens were fabricated and a total of 90 slab specimens were used for the evaluation of the frictional characteristics under different surface conditions. Further, to examine the effect of polishing on aggregates, two levels of polishing were utilised and three replicates were prepared at each level of polishing. Therefore, 60 more square slab specimens were prepared to evaluate the effect of polishing on friction properties of the steel slag incorporated OGAFC mixes. The frictional characteristics of OGAFC mixtures were evaluated through British pendulum test, dynamic friction test, and sand patch test. The flowchart for the evaluation of frictional properties is presented in Figure 3.25.

Figure 3.24: Roller compactor for preparation of square slab specimens.

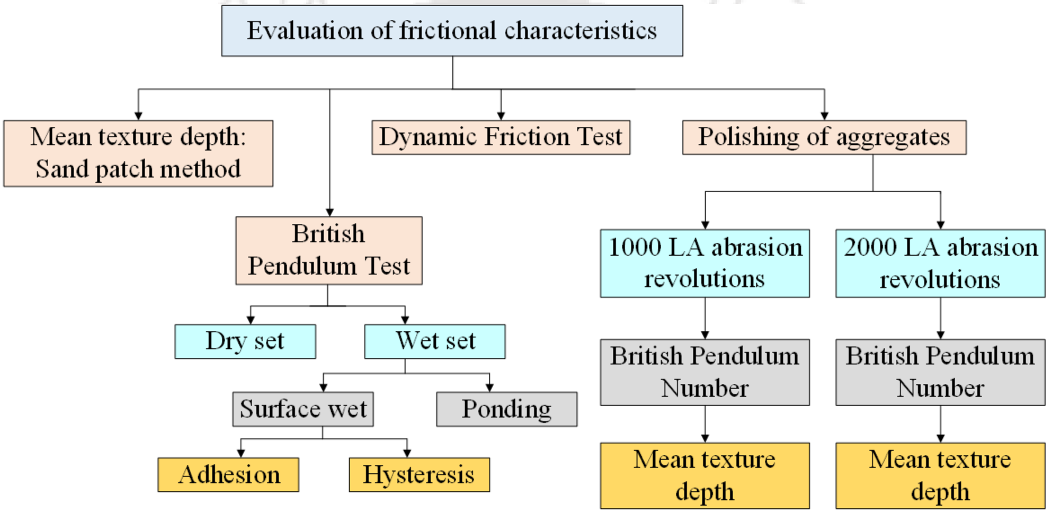


Figure 3.25: Flowchart for determination of frictional properties of OGAFC mixes.

3.5.2.1 Mean texture depth evaluation through sand patch test

The sand patch test method conforming to ASTM E965 (2019) was used to determine the mean texture depth (MTD) of the OGAFC mixes with and without BOF steel slag aggregates with both binders. The sand patch test method is a commonly used test that determines the macrotexture of a surface using a volumetric measurement (Araujo *et al.*, 2015). Standard sand of known volume (approximately 25000 mm^3) was spread over cleaned and dried OGAFC slab specimens using a spreading tool, such that it occupied in a circular outline (as shown in Figure 3.26). The mass of standard sand used to flush the surface voids of the slab specimen was recorded, and its corresponding volume (V_{MTD} in mm^3) was computed using its unit weight. The MTD (in mm) of the OGAFC mixes was calculated using Equation (3.10), where D_{MTD} denotes the average diameter of the sand patch formed on each specimen in mm. Higher MTD values correspond to a rougher pavement surface with a higher macrotexture. Three replicate tests were performed for each OGAFC mix type.

$$MTD = \frac{4V_{MTD}}{\pi D_{MTD}^2} \qquad (3.10)$$

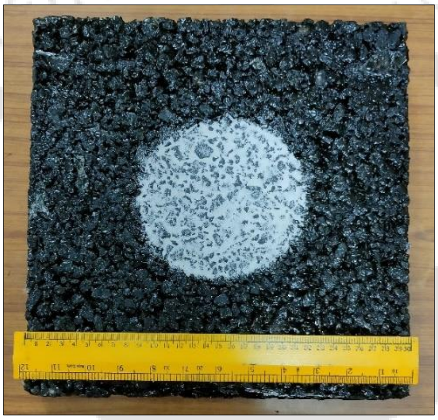


Figure 3.26: Mean texture depth evaluation by sand patch method.

3.5.2.2 British pendulum test

A British pendulum tester (BPT) was used to determine the skid resistance characteristics of OGAFC mixes. The BPT is a friction test device with wide acceptance and has been deployed in several research studies (Asi, 2007; Dan *et al.*, 2017; Pattanaik *et al.*, 2017). BPT comprises a pendulum swinging about a shaft fastened to a vertical pillar. A known mass is mounted at the extremity of the tubular arm of the BPT along with a rubber slider such that the pendulum arm slides over the specimen surface approximately at a velocity of 10 kmph and with a contact pressure of 0.21 MPa, when released from its horizontal holding position (Giles *et al.*, 1965; Southern and Walker, 1974; Alhasan *et al.*, 2018). The BPT is operated in accordance with ASTM E303 (2018) and the skid resistance value obtained from the BPT is reported as the British pendulum number (BPN).

BPN values of the ten OGAFC mix combinations were determined using the BPT under three different surface conditions – dry, wet, and ponding. The dry surface condition represents the skid resistance of an OGAFC surface during dry ambient environmental conditions. Nine replicate specimens of each combination were tightly held together with the help of a test assembly, as shown in Figure 3.27(a). The test was conducted after the OGAFC slab specimen was cleaned of any dust or foreign particles (Figure 3.27(b)). The wet set of BPN evaluation was carried out following ASTM E303 (2018) specification by spraying a requisite quantity of water to thoroughly cover the test surface with a thin film of water (Figure 3.27(c)). The application of water during this test ensured that the specimen surface was just wet before the pendulum's swing. The surface was just wetted with no ponding/flowing water in order to avoid fluid drag on the rubber slider with a film of water between the specimen and rubber slider that may affect the skid friction (Chu *et al.*, 2022).

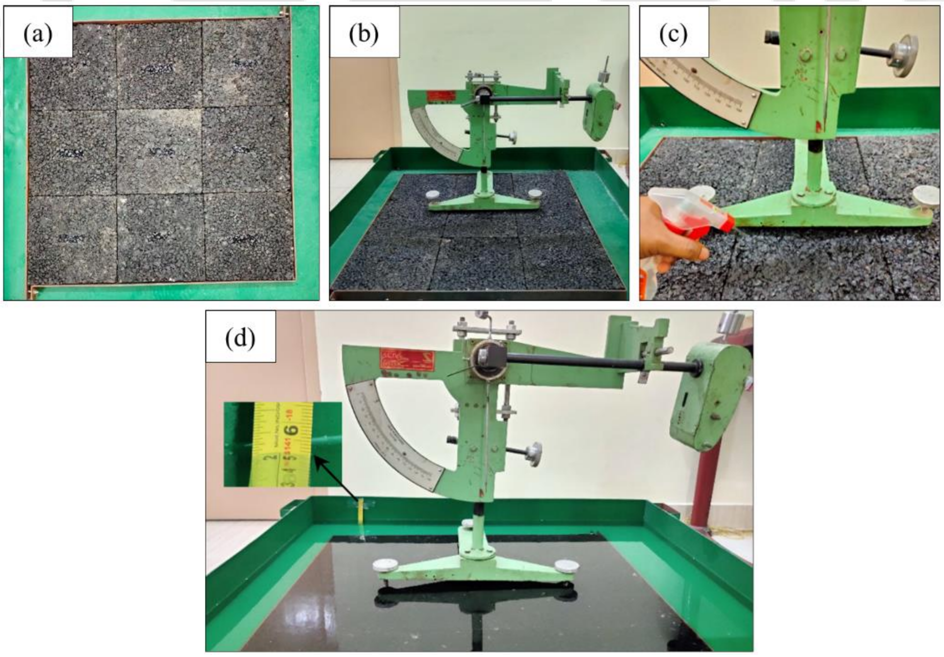


Figure 3.27: Test setup for assessing the frictional characteristics of OGAFC mixtures. (a) Test specimens, (b) Evaluation of dry BPN, (d) Evaluation of wet BPN, (d) Evaluation of ponding BPN.

The third testing condition was the ponding condition representing the extreme situation of an OGAFC surface when the surface loses its drainage capability due to clogging/excess rain, resulting in a thin film of water over its surface. In order to replicate such extreme conditions, the BPN of the OGAFC test specimens were evaluated under the presence of 1 mm water film (ponding condition). The 1 mm water film thickness was achieved by filling a tray holding the samples up to a water depth of 51 mm (Figure 3.27(d)), confirmed by a vertical ruler affixed along the walls of the tray. For all three surface conditions, five test points were randomly selected over the test surface area, and five BPN readings were taken at each test point. The average of the last four readings at each of the test points was reported as the BPN of the test specimen.

3.5.2.3 Evaluation of adhesion and hysteresis components of skid resistance

Adhesion and hysteresis are the two primary mechanisms contributing to the resistance to skidding of vehicle tyres. Adhesion is the loss of energy associated with sliding of the vehicle tyre over the travelled road surface, while hysteresis is the loss resulting from bulk deformation of the tyre while it slides over the pavement asperities. The procedure reported by Bazlamit and Reza (2005) was used in this study to separately evaluate adhesion and hysteresis components of the friction. For the computation of adhesion and hysteresis, two sets of wet BPN measurements were performed over the OGAFC slab specimens; firstly, with water (surface wet condition discussed earlier) and secondly, using liquid hand soap as a lubricant. It is expected that liquid hand soap will eliminate the contribution of the adhesion component, and hence the measured BPN will reflect only the hysteresis component of the friction (Bazlamit and Reza, 2005). The first and second sets of measurements are denoted as BPN_1 and BPN_2, respectively. The BPN_1 value represents the wet frictional resistance of the mix while BPN_2 value represents the hysteresis loss component of friction. The difference between the two sets of measurement ($BPN_1 – BPN_2$) represents the adhesion component of friction.

3.5.2.4 Dynamic friction test

The dynamic friction tester (DFT) is a lightweight, portable friction measuring device used to evaluate the frictional characteristics of paved surfaces both in the laboratory and in field. The DFT device was used following the ASTM E1911 (2019) specifications. The device consists of an electric motor that assists a horizontal spinning disk loaded with three spring-mounted rubber sliders located at a diameter of 284 mm (Figure 3.28). The test setup also consists of a steel water tank connected to the DFT device through a nozzle and a plastic hose. The horizontal spinning disk is first accelerated during testing to attain a pre-defined circumferential velocity (80 kmph used in this study). Before attaining the target velocity, water from the steel tank is gravity-fed to the DFT unit and sprayed from the bottom of the device onto the test surface. As the rubber sliders attain the pre-defined velocity, the electric motor disengages, and the disk along with the measuring pads is lowered down onto the wet test surface with a uniform vertical load of 3.6 kg (each rubber slider carries 1.2 kg weight). A transducer attached to the disk continuously measures the tyre-pavement friction as the velocity of the rubber sliders gradually decreases to zero due to the loss of kinetic energy resulting from the friction generated between the decelerating rubber sliders and the test surface.

From the recorded data, a continuous spectrum of friction coefficient is obtained from 80 kmph to 10 kmph. (Arámbula-Mercado *et al.*, 2018; Wu and Abadie, 2018; Chen *et al.*, 2019; Tan *et al.*, 2019). The dynamic friction coefficients corresponding to sliding velocities ranging from 80 kmph to 10 kmph were recorded every 5 kmph interval for all OGAFC mix combinations. The friction coefficient measured from DFT in the presence of water from the DFT water supply system can be taken to represent the frictional properties of the OGAFC surface during wet weather conditions. For the measurement of coefficient of friction, the same nine replicates of OGAFC slab specimens prepared for BPT were used, and the test was conducted randomly over five selected locations. The average coefficient of friction corresponding to each slip speed was reported as the dynamic friction coefficient. For all DFT tests, the time required for the rubber slider to come to a halt after attaining its desired initial circumferential velocity was also recorded manually.

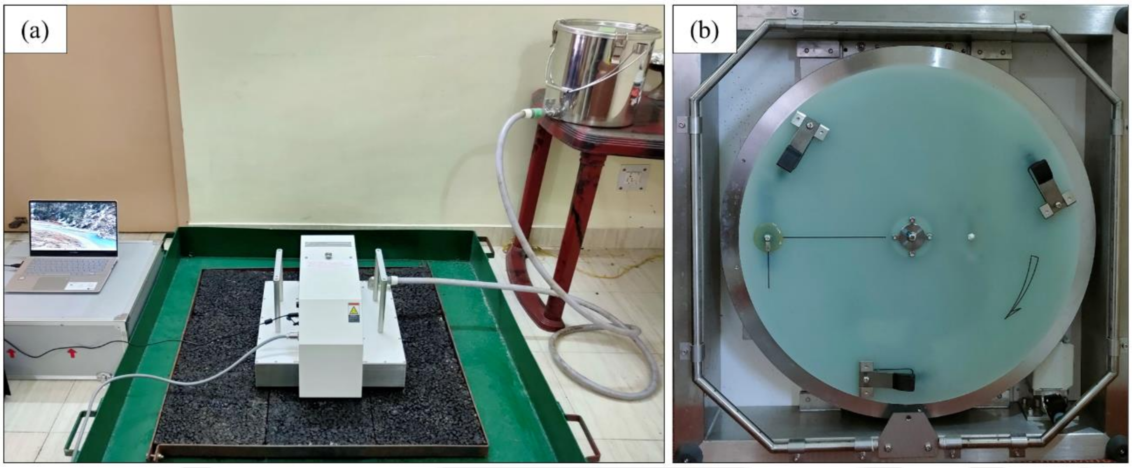


Figure 3.28: Dynamic friction tester used in the study: (a). Test setup, and (b). Horizontal spinning disk loaded with three spring-mounted rubber sliders.

3.5.2.5 Effect of polishing on frictional characteristics

In order to evaluate the effect of polishing of aggregates during service life on frictional characteristics of OGAFC mixes, a simple method was followed. Five kg batches of coarse-size (19.0–2.36 mm) natural coarse stone aggregates and BOF steel slag aggregates with the same gradation were made and then subjected to two levels (1000 and 2000 revolutions at 30 rpm) of abrasion in the Los Angeles abrasion drum. The abrasion undergone by the aggregates was considered to help to understand/compare the abrasion/degradation of the BOF steel slag and natural aggregates during the service life of OGAFC mixes. To avoid smashing of the aggregates by impact loading of the steel balls (generally used for the Los Abrasion test), the test was conducted in the absence of the steel balls (Kuang *et al.*, 2017). All aggregates were then individually washed clean, dried, and sieved corresponding to the following sizes: 19.0–12.5 mm, 12.5–9.5 mm, 9.5–4.75 mm, and 4.75–2.36 mm. This step further ensured proper gradation control for subsequent fabrication of OGAFC mixes with these polished and abraded aggregate particles. OGAFC slab specimens were prepared using abraded aggregates for all ten OGAFC combinations used in this study. In this way, it was ensured that the aggregate gradation of the polished OGAFC specimens remained identical to the unpolished OGAFC specimens. Three replicates of each slab specimen were fabricated for PMB and CRMB binders and evaluated for wet BPN and MTD values as per the methodology discussed in the earlier sections.

After subjecting the aggregates to 1000 and 2000 Los Angeles revolutions, the changes in the macroscopic surface morphology were quantitatively characterised by measurement of 'particle index' as per ASTM D3398 (2006) specifications. The particle index value quantifies aggregate shape and texture characteristics. The aggregates were placed in a cylindrical mould of known mass and volume *(v)* at two compaction levels. In the first level, the cylinder was filled into three layers, and each layer was subjected to 10 drops of a tamping rod. The combined mass of aggregates and the container was measured to obtain the mass of the compacted aggregates and was denoted as m_{10}. In the second level, 50 drops of the tamping rod were used on each layer. Correspondingly the mass of compacted aggregates was measured and denoted as m_{50}. The voids in the compacted aggregates for both compaction levels (V_{10} and V_{50} corresponding to 10 and 50 drops, respectively) were then calculated using Equations (3.11) and (3.12):

$$V_{10} = (1 - m_{10}/sv) \times 100 \tag{3.11}$$

$$V_{50} = (1 - m_{50}/sv) \times 100 \tag{3.12}$$

where, *s* is the bulk specific gravity of the aggregate. The aggregate particle index (I_a) for each aggregate type was then computed using Equation (3.13):

$$I_a = 1.25\, V_{10} - 0.25\, V_{50} - 32 \tag{3.13}$$

3.6 Durability assessment of OGAFC mixes with and without BOF steel slag

Due to their high air voids content/permeability and a higher exposure to moisture, OGAFC mixes are susceptible to binder draindown, binder ageing/hardening, ravelling and moisture damage/stripping. The use of predominantly coarse sized uniform aggregate gradation and lack of fines makes OGAFC mixes susceptible to binder draindown and ageing during production, construction and service. Hardening/ageing of asphalt binder as well as a low binder content or inadequate asphalt film may cause ravelling, which is the dislodgement/loss of aggregate particles during the service life of OGAFC mixes. In this study, the durability of OGAFC mixes was evaluated in terms of moisture damage characterisation and evaluation of long-term binder draindown characteristics.

3.6.1 Moisture damage characterisation of OGAFC mixes

Moisture damage is one of the primary factors affecting the durability of asphalt mixtures post construction and laydown. Kiggundu and Roberts (1988) have precisely defined moisture damage as "the progressive functional deterioration of a pavement mixture by loss of the adhesive bond between the asphalt cement and the aggregate surface and/or loss of the cohesive resistance within the asphalt cement principally from the action of water". The occurrence and severity of moisture induced damage is dependent on factors that can be divided in two categories — (i) internal factors, such as characteristics of aggregates and asphalt binder, and characteristics of asphalt mixture (air void content and distribution, permeability, thickness of binder film over aggregates, *etc.*), and (ii) external factors, such as environmental conditions and traffic (Esmaeili *et al.*, 2019).

OGAFC mixes have now been in use for decades. However, problems relating to their durability still persist. Since OGAFCs are designed to be water-draining mixtures, a larger surface area of their mix structure is exposed to water that may result in moisture induced damage affecting its durability. Most laboratory-based tests currently in use to identify moisture susceptibility of asphalt mixtures use some sort of moisture conditioning protocol to mobilise ingress of moisture into the mixture and measure its strength before and after the conditioning. The water used for this purpose is generally neutral (pH about 7.0). Distilled water or tap water with pH of about 7.0 is used to conduct the tests, but this may not always represent the rainwater which may have a slightly lower pH of about 5.5 (i.e., slightly acidic).

Further, owing to increase in the number of automobiles and the use of fossil fuels for power generation, there have been frequent occurrences of acid rain reported globally. Clean rain has a pH of about 5.5; however, when rain chemically combines with nitrogen and sulphur oxides (released from power stations and automobiles), the rain becomes more acidic with a pH in the range of 4.2–4.4 (Environmental Protection Agency, 2019). A decrease in pH of one point (say from 6.0 to 5.0) implies that the acidity is ten times greater. Adhesion of asphalt to the aggregates is also influenced by the pH of contact water (Scott, 1978; Yoon, 1987; Kiggundu and Roberts, 1988). Low pH (acidic) conditions favour the dissolution of surface layers of carbonates present on the aggregate surface, leading to an aggregate–asphalt interface with lower adhesive strength (Jamieson *et al.*, 1995; Caro *et al.*, 2008). Studies have been conducted to understand the moisture susceptibility characteristics of OGAFC mixtures incorporating steel slag aggregates (Shen *et al.*, 2009; Pattanaik *et al.*, 2019) under a neutral pH environment. In this study, the evaluation of the moisture damage of OGAFC mixtures was done under different pH environments at different substitution percentages of BOF steel slag and natural aggregates.

The main aim of this phase of the study was to evaluate the performance of OGAFC mixtures against moisture damage with different replacement percentages of coarse aggregates with BOF steel slag under different pH environments. The pH of conditioning water was changed to create neutral and acidic environments. Moisture damage characterisation was then performed through modified boiling water test, modified Lottman test, and wet abrasion loss test. Permeability of OGAFC mixtures was also evaluated before and after moisture conditioning, at different BOF slag contents.

For evaluation of the moisture susceptibility of the OGAFC mixtures, 100 mm diametric cylindrical specimens were prepared at 6.0% binder content and 0.3% cellulose fibres (by mixture weight). A uniform compaction effort of 50 Marshall blows on both faces were adopted for the preparation of OGAFC specimens. Figure 3.29 summarises the experimental protocol adopted to evaluate the moisture susceptibility of OGAFC mixes with BOF steel slag and modified binders.

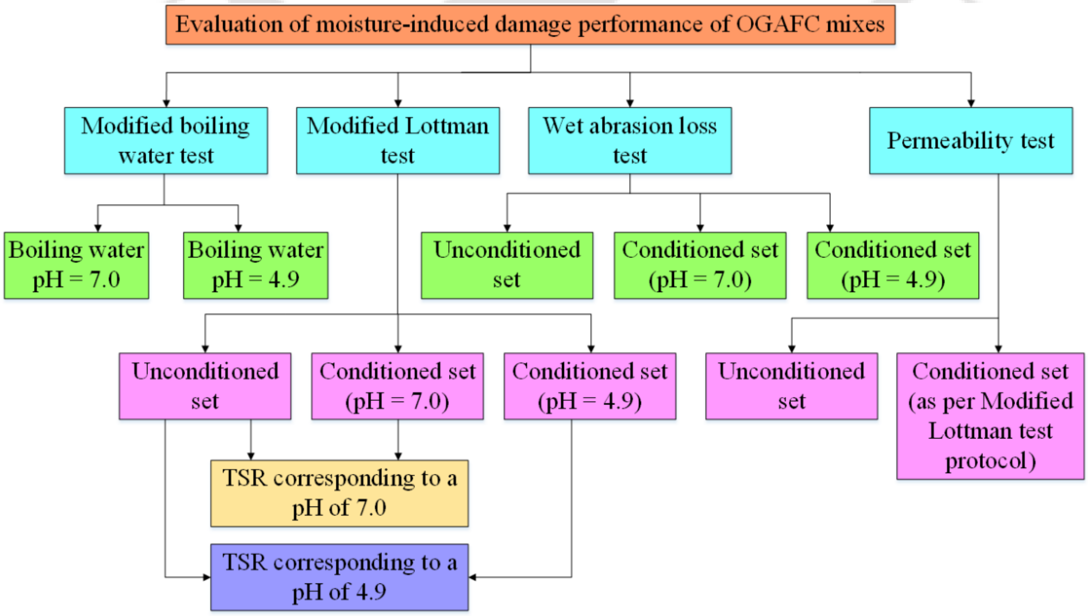


Figure 3.29: Flowchart for assessment of moisture susceptibility of OGAFC mixes.

3.6.1.1 Simulation of different pH environments

The moisture susceptibility of the OGAFC mixtures were evaluated under two different environmental conditions — neutral and acidic environment. Both the environmental conditions were reproduced/simulated by altering the pH of the water used in conditioning of OGAFC specimens. To attain a neutral moisture environment, distilled water having a pH of 7.0 was used. For an acidic environment, a solvent of 4.9 pH was prepared, following the TCLP test method discussed in Section 3.2.2.4, in sufficient quantity to perform the moisture conditioning of OGAFC specimens. In the TCLP test method, an acidic environment of 4.9 pH was attained by adding 5.7 mL glacial acetic acid (CH_3COOH) to 500 mL distilled water to which another 64.3mL 1N NaOH was added to attain a pH of 4.33±0.05. This acidic solution was diluted with required volume of 1N NaOH to attain the target pH of 4.9.

3.6.1.2 Modified boiling water test

ASTM D3625 (2012) recommends a boiling water test that involves visual estimation of stripping in an asphalt mix. In order to quantify the stripping, the test was slightly modified by extending the duration of boiling and quantifying the stripped off binder in terms of its weight (Chen *et al.*, 2014; Pattanaik *et al.*, 2019). In this test, about 250 g of pre-heated aggregate was coated with 5.0% binder (by weight of aggregate) and allowed to cool to about 80–100°C. The mix was transferred to a container and allowed to boil in the presence of water for 30 min after which it was carefully transferred to a paper once it attained the room temperature for further drying. The stripping index was evaluated as per Equation (3.14):

$$Stripping\ Index\ (\%) = \frac{W_{cab} - (W_{caa} + W_{fp})}{W_{cab} - W_{a}} \tag{3.14}$$

where, W_a is the weight of dry aggregates, W_{cab} is the weight of binder coated aggregate before the test, and W_{caa} is the weight of binder coated aggregate after the test. Often, the use of boiling water may lead to the disintegration of aggregate particles from their surface. The dry weight of such disintegrated aggregate particle is denoted as W_{fp}. Thus, $W_{cab} - (W_{caa} + W_{fp})$ yields the mass of binder stripped and aggregates lost from the mixture. Stripping index denotes the adhesive strength between the binder and the different aggregates used in the study. As this test was carried under water of two different pH environments, it also provides a distinction in the effect of pH of water on binder stripping. The test was repeated three times for each mix type and environmental condition (neutral and acidic), and the average value from the three tests was reported as the stripping index value.

3.6.1.3 Modified Lottman test

The modified Lottman test is a widely adopted test method to assess the moisture susceptibility of asphalt mixtures. The test evaluates the split strength of an asphalt mix before and after moisture conditioning and compares the change (decrease) in its strength. In case of conventional asphalt mixtures (dense graded asphalt mixtures), the specifications stated in AASHTO T283 (2003) are generally followed; however, in case of OGAFC mixes, certain recommendations as specified in ASTM D7064 (2013) are to be considered. Under the modified Lottman test, cylindrical OGAFC samples were diametrically subjected to compressive loading through two loading strips generating a relatively constant tensile stress along the diametral plane. A compressive load at a uniform displacement of 50 mm/min was applied until the sample split along the plane of loading. For each mix type, six replicates were prepared, three specimens each for conditioning and unconditioning. For the conditioning of the OGAFC mixes, specimens were subjected to a vacuum saturation of 87.8 kPa for ten minutes (irrespective of the degree of saturation), followed by a freezing cycle of 16 hours at –18°C. For OGAFC mixes, during the freezing cycle, it was ensured that the sample remained submerged in water. The freezing cycle was followed by a 24 hours thawing cycle at 60°C. In comparison to a usual one freeze-thaw cycle for dense-graded asphalt mixtures, five consecutive freeze-thaw cycles were performed on OGAFC specimens, following which the specimens were tested for indirect tensile strength (ITS) at 25°C. Figure 3.30 illustrates the different steps involved in the moisture conditioning along with the ITS test apparatus used.

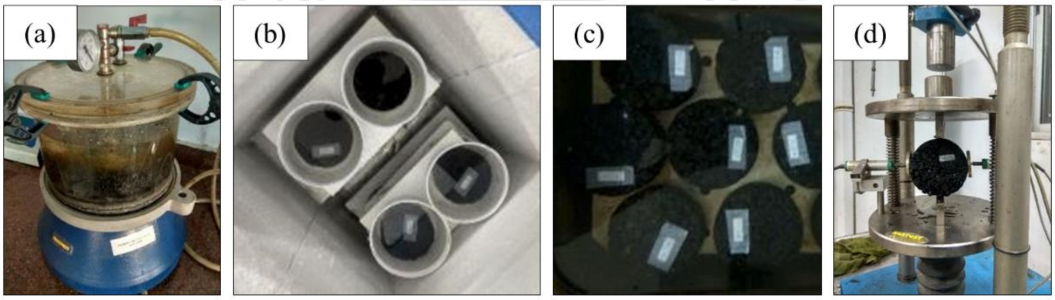


Figure 3.30: Moisture conditiong and ITS test setup: (a). Sample saturation of 87.8 kPa for 10 minutes, (b). Freezing cylce at -18°C for 16 hours, (c). Thawing cycle at 60°C for 24 hours, and (d). ITS test setup.

Both conditioned and unconditioned samples were first placed in a temperature controlled water bath at 25°C for 2 hours and then the ITS value was computed using Equation (3.15):

$$ITS = \frac{2000P_{max}}{\pi Dt} \tag{3.15}$$

where, *ITS* is the indirect tensile strength of the sample in kPa, P_{max} is the failure load in N, D and t are diameter and thickness of the sample in mm, respectively. The extent of moisture damage was examined by calculating the tensile strength ratio (TSR) which is the measure of decrease in the ITS of the mix when subjected to moisture conditioning and is calculated using Equation (3.16):

$$TSR = \frac{ITS_{conditioned}}{ITS_{unconditioned}} \times 100 \tag{3.16}$$

where, TSR is the tensile strength ratio in percent, $ITS_{unconditioned}$ and $ITS_{conditioned}$ are the indirect tensile strengths calculated using Equation (3.15) for unconditioned and conditioned set of samples, respectively. To see the effect of different pH environments on ITS and TSR values, the moisture conditioning of the OGAFC specimens was performed by using conditioning water having different pH. For neutral pH environment, distilled water was used for the conditioning while for acidic pH environment, acidic solvent corresponding to a pH of 4.9 was used.

3.6.1.4 Wet abrasion loss test

Ravelling is the commonly reported distress in OGAFC mixes. The chances for ravelling during the service life of OGAFC mixes increases with the hardening/stiffening of the asphalt film due to oxidative ageing. Under the moisture damage characterisation, the effect of conditioning environments on ravelling resistance was also evaluated. Moisture intrusion/exposure in OGAFC mixes may lead to the stripping of asphalt film from the aggregate surface which will reduce the adhesion between the asphalt binder and aggregate. The lack of adhesive strength will enhance the chances of ravelling in OGAFC mixes. Thus, evaluation of the effect of moisture conditioning environment on ravelling resistance can also be an important aspect in regard to durability of OGAFC mixes.

Cantabro abrasion loss test (as discussed in Section 3.4.7) was used to evaluate the effect of moisture conditioning on the ravelling performance of OGAFC mixes. Three replicates of each of the ten OGAFC mixes were prepared and subjected to moisture conditioning (five freeze-thaw cycles) under both neutral and acidic pH environments [the conditioning procedure was same as discussed for Modified Lottman test in the previous section (Section 3.6.1.3)]. The samples then subjected to Cantabro abrasion loss test in a Los Angeles drum machine for 300 revolutions at a speed of 30 rpm without any steel charge. The percentage loss in weight was computed and reported as the wet abrasion loss (WAL) value. The WAL value was compared with the unaged abrasion loss (UAL) values of the OGAFC mixes prepared with 6.0% binder content to compare the effect of moisture conditioning environments on the ravelling potential.

3.6.1.5 Permeability characteristics

The effect of moisture damage (under different moisture conditioning environments) on the drainability was evaluated through the permeability measurement of the different OGAFC mixes. Permeability of the OGAFC mixes was measured both before and after moisture conditioning under the two different pH environments (neutral and acidic). Moisture conditioning was done as per the conditioning protocol of Modified Lottman test as discussed in Section 3.6.1.3. A falling head permeameter, as described in Section 3.5.1.1, was used for the evaluation of the permeability values of the OGAFC specimens following the FDOT FM 5-565 (2015) test standard and computed using the Equation (3.9), as discussed in Section 3.5.1.1. Permeability of the OGAFC specimens were compared for — unconditioned set, moisture conditioned under neutral environmental condition, and moisture conditioned under acidic environmental condition. The permeability values under the three different conditions were compared to understand the effect of moisture damage on permeability of the mixes.

3.6.2 Long-term draindown evaluation of OGAFC mixes

A higher asphalt binder film thickness with an open aggregate skeleton/structure with low fines raises the concern of binder draindown in OGAFC mixes. Draindown refers to the vertical movement of the asphalt binder film present on aggregate particles, at elevated temperatures during OGAFC production and construction (Putman and Lyons, 2015). High temperatures during production, storage, hauling, and compaction of OGAFC mixes may cause the downward migration of the asphalt binder in the mix. This draindown, referred to as production-stage draindown in this study, is mainly addressed in two ways—the use of fibres that absorb and hold the excess asphalt binder and the use of additives/modifiers (e.g., polymers, crumb rubbers, *etc.*) to increase the viscosity/stiffness of asphalt binder (Huber, 2000). In this study, both fibres (organic cellulose fibre) and modified binders (PMB and CRMB) were used to minimise the production-stage draindown.

Long-term binder draindown is another form of draindown observed in OGAFC mixes and is reported usually after five to six years of the service life (Ferguson, 2005). During the summer season, heat softens the asphalt binder, and it gradually migrates downward to the comparatively cooler interior/lower section of the OGAFC layer, where it cools and clogs the pores, resulting in a decrease in drainability. This results in the formation of an asphalt mix with a variable binder content across the depth of the OGAFC layer. Long-term binder draindown thus may divide an OGAFC section into three segments, as schematically presented in Figure 3.31.

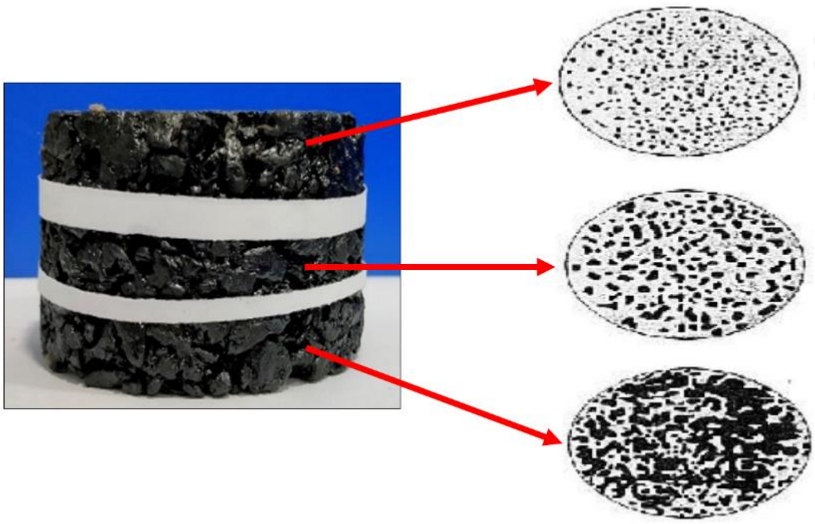


Figure 3.31: Schematic representation of variation in binder content due to long-term binder draindown.

The topmost section may have a binder content lower than the OBC resulting in a thinner asphalt film making the mix susceptible to ravelling, moisture damage, and permanent deformation. The middle section of the layer may exhibit a binder content nearly equivalent to the OBC while the bottommost section of the mix may have a binder content higher than the OBC which will clog the pores of the mix thereby affecting the functionality in terms of lower drainability.

The effect of long-term binder draindown on the durability of OGAFC mixes at different replacement percentages of natural aggregates with BOF steel slag was thus evaluated. OGAFC mixes were prepared at five BOF steel slag replacement percentages with the two modified binders (PMB and CRMB) at 6.0% binder content with 50 Marshall blows on both sides of the specimens. The prepared mixes were first subjected to different long-term binder draindown conditions/protocols (different conditioning temperature and time period) and examined for permeability and porosity. The mixes were evaluated for permeability and porosity after the conditioning of the specimens and once it reached the room temperature. The drainage/permeability test results helped in the finalisation of the conditioning protocol to be used to simulate long-term binder draindown of the OGAFC mixes.

The effect of long-term binder draindown on the OGAFC mixes with and without BOF steel slag aggregates were then evaluated in terms of moisture susceptibility, ravelling resistance, and permanent deformation resistance through the modified Lottman test, wet abrasion loss test, and static creep test, respectively. OGAFC specimens before and after being subjected to long-term binder draindown were used to assess the extent of changes in OGAFC mix durability. Figure 3.32 presents the experimental program used to assess the effect of long-term binder draindown.

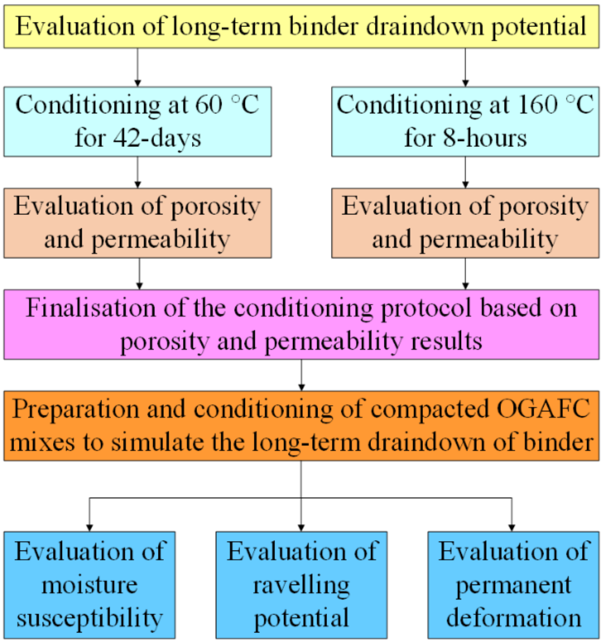


Figure 3.32: Flowchart for determination of long-term binder draindown of OGAFC mixes.

3.6.2.1 Simulation of long-term binder draindown in OGAFC mixes

For reproduction/simulation of the long-term binder draindown, 100-mm diameter cylindrical OGAFC specimens were first subjected to trial conditioning procedures (variable conditioning temperature and time). Permeability and porosity tests were performed in accordance to FDOT FM 5-565 (2015) and ASTM D7063 (2018) specifications, respectively to confirm the long-term binder draindown of the mixes. It was first attempted to replicate the long-term binder draindown by conditioning compacted OGAFC specimens at a controlled temperature of 60°C for 42-days (Figure 3.33). The permeability/drainability of the OGAFC specimens were evaluated at intervals of 7-days continuously for 42-days. The permeability of the specimens showed a small increment with time, which was found contrary to the general perception that long-term binder draindown reduces permeability. These results are discussed in detail in Chapter 6. Conditioning at 60°C was thus not found adequate to introduce long-term binder draindown in the OGAFC mixes.

Figure 3.33: Simulation of long-term binder draindown by conditioning at 60°C.

It was then attempted to condition the compacted specimens in a force-draft oven at 160°C (the compaction temperature) and measure the permeability of mixes at every 2-hour intervals. To prevent the distortion of the samples at 160°C, the samples were placed inside the Marshall mould itself along with the base plates throughout the conditioning period as presented in Figure 3.34. When tested, conditioning at 160°C for 8-hours resulted in significant decrease in the permeability of the mixes, and thus confirmed the presence of long-term binder draindown. Detailed discussion of these aspects is provided in *“Chapter 6: Assessment of Durability of OGAFC Mixes with BOF Steel Slag Aggregates”*.

Figure 3.34: Simulation of long-term binder draindown by conditioning at 160°C.

3.6.2.2 Effect of long-term binder draindown on moisture susceptibility

The modified Lottman test (discussed in Section 3.6.1.3) was used to evaluate the effect of long-term binder draindown on moisture susceptibility characteristics of the

OGAFC mixes. The ITS values of the mixes were evaluated under three conditions—unconditioned, moisture conditioned, and combined moisture and long-term conditioned. The unconditioned and moisture conditioned specimens were prepared as per the discussion in Section 3.6.1.3; while the combined moisture and long-term conditioned specimens were prepared by conditioning OGAFC specimens at 160°C for 8-hours followed by five consecutive freeze-thaw cycles.

3.6.2.3 Effect of long-term binder draindown on ravelling potential

The Cantabro abrasion loss test (discussed in Section 3.4.7) was also used to evaluate the effect of long-term draindown on the ravelling potential of OGAFC mixes. Ravelling resistance was evaluated under three conditions—unaged, long-term conditioned, and combined moisture and long-term conditioned. Moisture conditioning was added to further evaluate the effect of both moisture damage and long-term draindown conditioning on ravelling resistance. Moisture conditioning was carried out as described for the Modified Lottman test (discussed in Section 3.6.1.3).

3.6.2.4 Effect of long-term binder draindown on permanent deformation

The effect of long-term binder draindown conditioning on OGAFC mixes with and without BOF steel slag aggregates was also studied in terms of its effect on permanent deformation, through the static creep test in accordance to BS 598-111 (1995) by using a universal testing machine (UTM). The permanent deformation was measured under two test conditions—unconditioned and long-term conditioned. For both test conditions, three replicates were prepared and subjected to the static creep test. The test specimens and the test assembly were pre-conditioned at 40°C for 4-hours in a temperature-controlled chamber. Then, a load of 100±2 kPa was applied for a duration of 3600 seconds. Linear variable displacement transducers (LVDTs) were used to record the deformation. Once the loading period was complete, the stress was removed and the specimen was allowed recover for another 3600 seconds. The axial strain was calculated using Equation (3.17):

$$\varepsilon(t) = \frac{\Delta h(t)}{h_0} \times 10^6 \quad (3.17)$$

where, $\varepsilon(t)$ is the axial strain at any time '*t*' in microstrain, $\Delta h(t)$ is the change in specimen height at any time '*t*' in mm, and h_0 is the initial specimen height in mm. From the test, five different strain components can be generated – initial strain (strain developed within 15 s loading), final strain (strain accumulated at the end of loading period; *i.e.* at 3600 s), total strain (sum of initial and final strain), permanent strain (the final strain recorded at the end of unloading cycle or after 7200 s), and recoverable strain (strain recovered during the unloading cycle or the difference between total strain and permanent strain).

3.7 Performance evaluation of OGAFC mixes with BOF steel slag

As OGAFC courses are not usually considered structural layers, most of the previous studies have focussed mainly on the functionality and durability aspects of these mixes, with a limited interest on their mechanical characteristics. To further evaluate the benefits of incorporating BOF steel slag in OGAFC mixes, the purpose of this phase of the study was to evaluate the mechanical performance parameters/properties of OGAFC mixes with BOF steel slag aggregates. The performance properties of the OGAFC mixes were evaluated in terms of rutting resistance, cracking potential, fatigue life, and modulus properties through the dynamic creep test, Hamburg wheel tracking device (HWTD) test, indirect tensile strength (ITS) test, cracking tolerance index (CT_{Index}) test, indirect tensile fatigue (ITF) test, semi-circular bend (SCB) test, indirect tensile stiffness modulus (ITSM) test, and resilient modulus (RM) test.

100 mm specimens were used for the dynamic creep test, ITF test, ITSM test, and RM test; while 150 mm specimens were used for the HWTD test, ITS test, CT_{Index} test, and

SCB test. For 100 mm diametric cylindrical specimen, OGAFC samples were fabricated using 50 Marshall blows on both sides at the design air voids content. The 150 mm diametric specimens were fabricated using Superpave gyratory compactor (SGC) at the corresponding target air voids content. Similar compaction methodology of uniform compaction effort has also been reported in previous studies on OGAFC mixtures (Skaf *et al.*, 2019; Chai *et al.*, 2020; Pattanaik *et al.*, 2021). Three replicates of each OGAFC mix combination were prepared at binder content of 6.0% (by weight of the mixture). The research program adopted is presented in Figure 3.35 and detailed test procedure and the parameters considered are discussed in the subsequent sections.

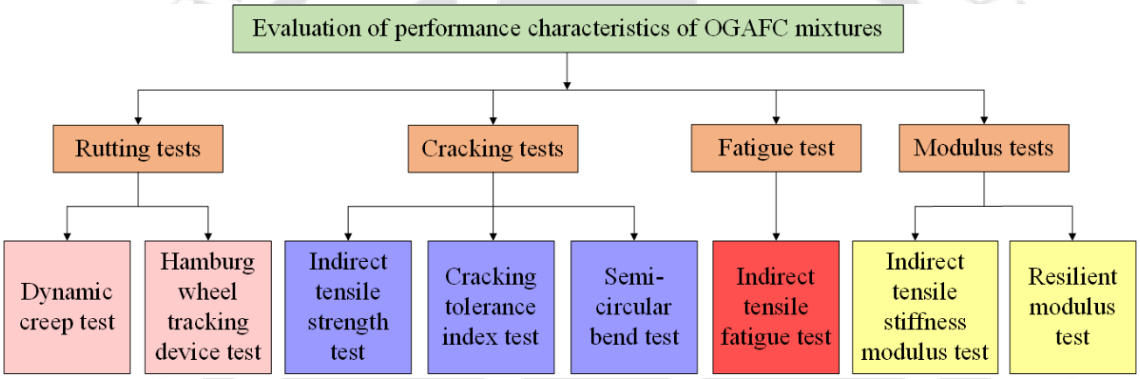


Figure 3.35: Flowchart for evaluation of performance properties of OGAFC mixes.

3.7.1 Dynamic creep test

The creep potential of the mixtures subjected to a repetitive load was examined through the dynamic creep test as per BS DD 226 (1996) using a universal testing machine (UTM) at a test temperature of 40°C. The test setup used for the test is presented in Figure 3.36(a). The test specimen along with the test jig were kept inside a temperature-controlled chamber at the test temperature for 4-hour prior to the test. A load equivalent to a stress level of 10 kPa was used to pre-load the test specimen for initial 600 ± 6 seconds to ensure proper contact between the loading platen the test specimen. At the end of the pre-loading period, the load was then increased to apply a stress equivalent to 100 kPa in a square waveform pattern at 0.5 Hz frequency (1 second load and 1 second rest). The axial deformation of the test specimen during the loading and the rest period was continuously monitored by LVDTs and the axial strain at the end of every rest period was computed using Equation (3.17), discussed earlier under the static creep test (Section 3.6.2.4). The specimens were subjected to a total of 10,000 cycles in this test.

3.7.2 Hamburg wheel tracking device test

Hamburg wheel tracking device (HWTD) test subjects a mix specimen to a combined action of moisture and repetitive wheel loading. The test was performed following the AASHTO T324 (2017) method. In this test, a reciprocating steel wheel carrying a wheel load of 705 N rolls over two 150 mm diametric cylindrical specimens of height 60 mm sawed off along a secant line and joined together to provide a wheel path of 230 mm. The specimens were fabricated using the SGC. During the entire test, specimens were submerged under water at 40°C to examine the action of moisture on the rutting potential of the mixes. LVDTs mounted along the wheel recorded the deformation observed along the wheel path for a total of 20,000 passes (52 passes per minute). The test assembly of the HWTD test is presented through Figure 3.36(b)–3.35(d).

3.7.3 Indirect tensile strength test

The indirect tensile strength (ITS) test was performed in accordance with ASTM D6931 (2017) using 150 mm diametric cylindrical OGAFC specimens prepared on an SGC. The test was carried out at 25°C with 2-hour conditioning of the specimens. The specimens were diametrically compressed at 50 mm/min loading rate through two loading strips as illustrated in Figure 3.36(e) resulting in a tensile stress along the perpendicular diametrical plane. The maximum load at which the specimen failed was noted and the ITS of the specimen was computed using Equation (3.15) discussed earlier under Section 3.6.1.3.

3.7.4 Cracking tolerance index test

The resistance of the OGAFC mixtures to cracking was determined through the cracking tolerance index (CT_{Index}) obtained from the load-displacement curve of the ITS test in accordance with ASTM D8225 (2019). The ITS test was continued till a load of 0.1 kN was reached (post the peak load). The work of failure (W_f) is computed as the area under the load versus load-line displacement curve (LLD) using Equation (3.18) following the quadrangle rule. The failure energy (G_f) is then obtained by dividing the work of failure by the cross-sectional area of the specimen as illustrated in Equation (3.19). Finally, using the failure energy and the parameters of the LLD curve ($|m_{75}|$, Equation (3.20)), the CT_{Index} of the specimens was calculated using Equation (3.21).

$$W_f = \sum_{i=1}^{n-1}((l_{i+1} - l_i) \times P_i + \frac{1}{2} \times (l_{i+1} - l_i) \times (P_{i+1} - P_i)) \tag{3.18}$$

$$G_f = \frac{W_f}{D \times t} \times 10^6 \tag{3.19}$$

$$|m_{75}| = \frac{P_{85} - P_{65}}{l_{85} - l_{65}} \times 10^6 \tag{3.20}$$

$$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \tag{3.21}$$

where, W_f is the work of failure (in Joules) l_i and l_{i+1} are respectively the LLD (in mm) corresponding to the i^{th} and the $(i+1)^{th}$ step, P_i and P_{i+1} are respectively the applied loads (in kN) corresponding to the i^{th} and the $(i+1)^{th}$ load step applications, G_f is the failure energy (in Joules/m^2), D and t are the respective diameter and thickness of the specimen in mm, $|m_{75}|$is the absolute value of the post peak slope computed using a linear relationship along the data between $P_{85}(l_{85})$ and $P_{65}(l_{65})$, P_{85}, P_{75}, and P_{65} are the 85%, 75%, and 65% of the peak load (in kN) measured at the post peak stage, l_{85}, l_{75}, and l_{65} are the displacement (in mm) corresponding to the 85%, 75%, and 65% peak load measured at the post peak stage. CT_{Index} is a unitless quantity.

3.7.5 Semi-circular bend test

The semi-circular bend (SCB) test was conducted per ASTM D8044 (2016) at 25°C and it characterises the fracture resistance of asphalt mixtures in terms of the critical strain energy release rate or critical J-integral (J_c) shown in Equation (3.22). The SCB test was performed at three variable notch depths (25 mm, 32 mm, and 38 mm). A constant deformation load was applied at a rate of 0.5 mm/min till the fracture of the specimen and a series of load-deformation data were recorded to generate a load versus deformation curve. Figure 3.36(f) illustrates the SCB test configuration used.

$$J_c = \frac{-1}{b} \times \frac{dU}{da} \tag{3.22}$$

where, J_c is the critical strain energy release rate (kJ/m^2), b is the thickness of the specimen (m), a is the notch depth (m), U is the strain energy at failure (kJ), and dU/da is change of strain energy with notch depth (kJ/m).

3.7.6 Indirect tensile fatigue test

The indirect tensile fatigue (ITF) test evaluates the fatigue cracking potential of asphalt mixtures subjected to repeated tensile loads and was conducted per BS EN 12697-Part 24 (2012). 100 mm diametric cylindrical specimens were subjected to repetitive stress of 200 kPa along the diametrical plane to attain a strain in the range of 100–400 με. LVDTs were mounted perpendicular to the loading plane and horizontally to record the deformation/strain. The load was applied in a haversine form at 2 Hz frequency (0.1 second load duration and 0.4 second rest duration). The test was conducted at 20°C and was continued till the test specimens failed. Fatigue life was defined as the number of cycles prior to complete fracture of the test specimen. Figure 3.36(g) and Figure 3.36(h), respectively illustrate the test assembly and a fractured test specimen.

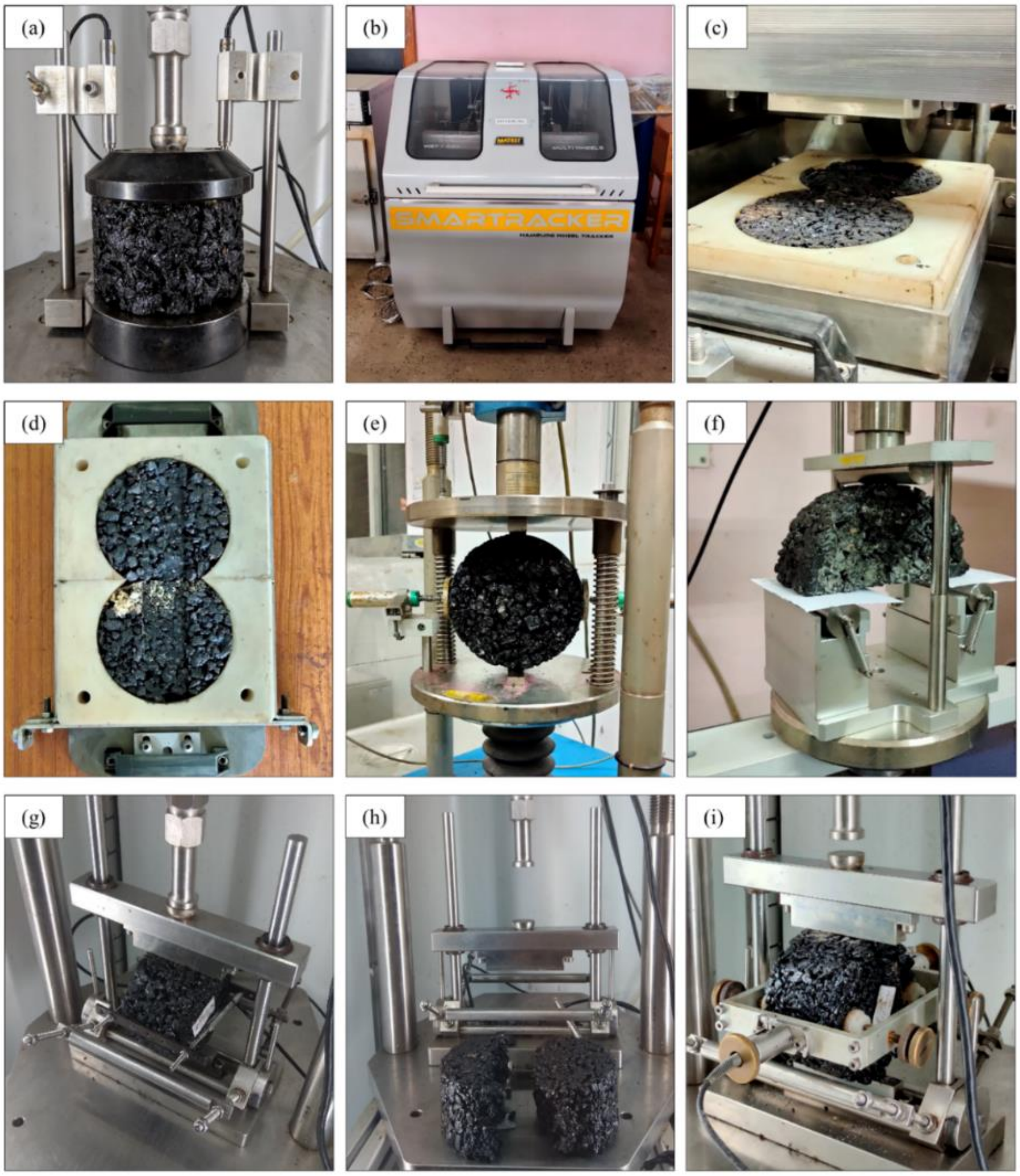


Figure 3.36: Test setup – a). Dynamic creep test setup, b). HWTD, c). HWTD test setup, d). HWTD test specimen after rutting, e). ITS and CT_{Index} test setup, f). SCB test setup, g). ITF test setup, h). ITF test specimen at fracture, and i). ITSM and RM test setup.

3.7.7 Indirect tensile stiffness modulus test

The indirect tensile stiffness modulus (ITSM) test evaluates the stiffness properties of asphalt mixtures. The ITSM test was performed in accordance with BS EN 12697-Part

26 (2012) and at 20°C. The test was conducted at 20°C, same as the one used in ITFT test, to evaluate the stiffness modulus of the OGAFC mixes. Prior to the test, specimens and the test setup were pre-conditioned at the test temperature for 4-hours. The test assembly for the test is shown in Figure 3.36(i). During the test, the load actuator applied a compressive repetitive load along the vertical diametric plane of the test specimen in a haversine waveform with a rise time of 124 micro-second (ms). The load was adjusted such that the target peak transient deformation was 0.005% of the specimen diameter. Ten repetitive load pulses were applied for conditioning the specimen followed by five load pulses to calculate the stiffness modulus. This was repeated after rotating the specimen by 90°. The transient deformation was recorded by the LVDTs throughout the test and was used to compute the stiffness modulus using Equation (3.23):

$$S_m = \frac{F \times (\mu + 0.27)}{Z_{SM} \times h} \tag{3.23}$$

where, S_m is stiffness modulus of the test specimen in MPa, F is applied peak load in N, μ is Poisson's ratio of the mix, Z_{SM} is amplitude of horizontal deformation during the load cycle in mm, and h is original height of the specimen in mm.

3.7.8 Resilient modulus test

The resilient modulus (RM) test was performed per AASHTO TP 31 (1996) specifications on an UTM device at a test temperature of 40°C. The RM test was conducted at 40°C to understand the resilient modulus behaviour of the OGAFC mixes corresponding to the rutting test temperature. The mixes were first subjected to the ITS test at 25°C as per the test procedure stated in Section 3.6.1.3 to obtain the ITS value. 5% of the obtained ITS value was used as the load for RM testing. During the test, 10% of this load was considered as the sitting load while the remaining 90% was applied as the cyclic stress at a fixed amplitude for 0.1 second loading period followed by 0.9 second rest period. The specimen was subjected to 105 cycles in which 100 were for conditioning and five for the calculation of RM. During the final five loading cycles, the horizontal deformation was recorded by the LVDTs. At the end of the 105^{th} loading cycle, the test specimen was rotated by 90° and the procedure was repeated. The test assembly for RM test is presented in Figure 3.36(i). The RM was evaluated at 40°C and computed using Equation (3.24). Prior to the test, both the test specimen and the test setup were conditioned at the test temperature for 4-hours.

$$M_R = \frac{F \times (\mu + 0.27)}{Z_{RM} \times h} \tag{3.24}$$

where, M_R is the resilient modulus of the mix in MPa, F is the applied peak load in N, μ is the Poisson's ratio of the mix, Z_{RM} is the recoverable horizontal deformation in mm, and h is the original height of the specimen in mm.

3.8 Summary

This chapter presented a discussion on the characterisation of the selected materials – natural stone aggregates, BOF steel slag aggregates, modified binders (PMB and CRMB), and cellulose fibre. The experimental programme adopted to achieve the objectives of the study was presented and the test procedures and test parameters adopted for the design of the OGAFC mixes and evaluation of functionality, durability, and performance properties were discussed in this chapter.

Chapter 4: Design of OGAFC Mixes with BOF Steel Slag Aggregates

4.1 General

Open graded asphalt friction courses (OGAFCs) are asphalt courses comprising of aggregate skeleton with proper stone-to-stone contact and bonded by a thick film of stiffer asphalt binders to achieve the desired drainability and stability. The aggregate skeleton predominantly comprises of coarse aggregates to achieve a network of interconnected air voids. High interconnected air voids lead to an effective/quick drainage of the rainwater which enables reduced hydroplaning, enhanced wet surface friction, diminished splash and spray of the rainwater, improved visibility during wet weather conditions, and reduced glare at night. Provision of a large network of interconnected air voids demands design considerations which are quite different to that adopted for conventional dense graded asphalt mixtures. The design considerations help to ensure a proper stone-to-stone contact along with a minimum permeability for the OGAFC mixes.

As OGAFC mixes demand higher binder film thickness for a good resistance to ageing and moisture damage, under elevated temperatures during mixing, hauling and laying operations, the high binder content of OGAFCs often leads to undesirable binder draindown due to the lack of fines to hold it together. In addition to stiffer grade binders (typically modified binders), additives/fibres are also used in OGAFC mixes for better cohesion. The high air voids content of OGAFC mixes also make them prone to accelerated ageing and ravelling compared to the conventional dense graded asphalt courses. The ravelling resistance of OGAFC mixes in ensured through the measurement of unaged and aged Cantabro abrasion loss during the mix design stage.

Design of an OGAFC course involves an optimisation of functionality and durability. Therefore, in designing OGAFC mixes, the primary aim is to obtain an aggregate skeleton with adequate stone-on-stone contact for a durable mix with an air voids content that guarantees the expected functionality (drainability) along with a good resistance to ravelling. It is to be noted that Indian specifications on OGAFC were not yet available during the execution of the mix design phase of this study. Therefore, the design of OGAFC mixes was carried following the ASTM D7064 (2013) guidelines. The requirements as listed in Table 4.1 were used to determine the optimum binder content (OBC) of the OGAFC mix for a particular combination of steel slag content and binder type.

Table 4.1: Requirements for selection of OBC for OGAFC mixes.

Design parameters	*Requirements*
Air voids content	Minimum 18%
Stone-on-stone contact	VCA-ratio < 1.0
Binder draindown	Maximum 0.3%
Unaged abrasion loss	Maximum 20%
Aged abrasion loss	Maximum 30%

This chapter presents the results of the design parameters of OGAFC mixes fabricated with 0, 25, 50, 75, and 100% substitution of coarse natural aggregates with industrial waste basic oxygen furnace (BOF) steel slag. The mix with 0% steel slag replacement (i.e., with 100% natural aggregates) was prepared as the control mix for comparison. Two different modified binder types: polymer modified bitumen (PMB) and crumb rubber modified bitumen (CRMB), were employed to fabricate and evaluate OGAFC mixes at different slag and binder contents. Properties evaluated included bulk specific gravity, air voids content, stone-on-stone contact, binder draindown, and Cantabro abrasion loss (under both unaged and aged conditions). The detailed methodology adopted to assess the above mentioned characteristics was presented in *"Chapter 3 – Materials and Experimental Programme"* of this thesis. The test results were statistically analysed using the analysis of variance (ANOVA) at 5% level of significance (α=0.05).

4.2 Mix design parameters

4.2.1 Bulk specific gravity

The bulk specific gravity values of the OGAFC-PMB and OGAFC-CRMB mixes fabricated at different BOF steel slag contents are presented in Figure 4.1. It is observed that for both binder types, the bulk specific gravity increased with an increase in the binder content. Higher binder dosage enhanced the workability and thus aided in achieving better compaction and a higher bulk specific gravity. Bulk specific gravity also increased with the increase in replacement percentage of coarse aggregate by BOF steel slag (shown as 'steel slag content' in Figure 4.1). This is attributed to the high specific gravity of coarse BOF steel slag (3.268) compared to natural stone aggregate (2.958). Due to higher specific gravity of BOF steel slag, the volume of aggregate particles decreases with an increase in the steel slag content, and thus provides a lower surface area for the binder to coat. As the total surface area of the aggregate decreases, the demand of the asphalt to coat also decreases. This resulted in the availability of a higher quantity of residual binder (the term 'residual' binder is used to refer to the quantity of binder that is available in excess (per unit volume) for an OGAFC-BOF mix when compared to that in a control mix with natural aggregates, when fabricated at a constant weight of total aggregates and a constant binder content by weight of the mix). This high residual binder also eased the compaction process and resulted in higher bulk specific gravities of compacted OGAFC specimens with BOF steel slag aggregates.

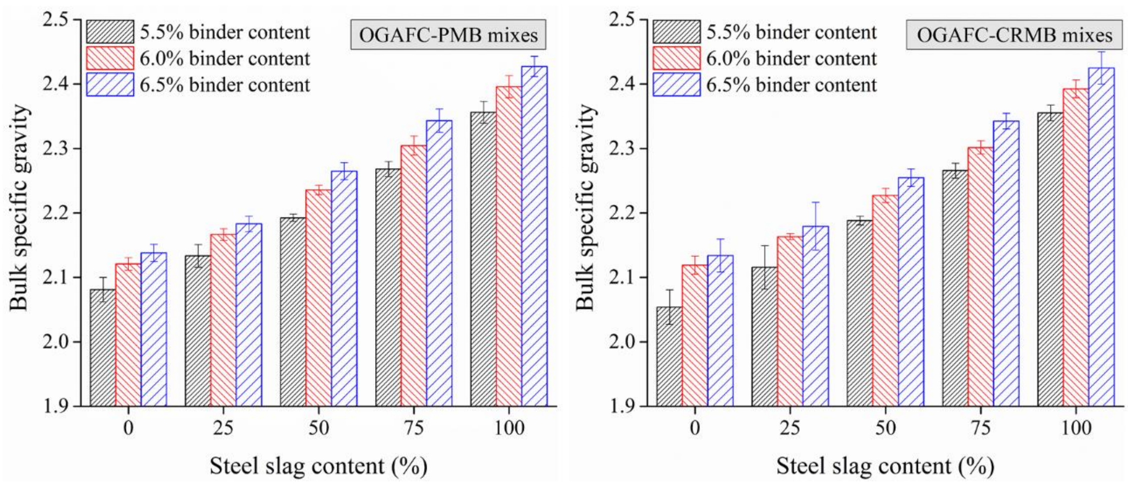


Figure 4.1: Variation of bulk specific gravity with steel slag content and binder type.

4.2.2 Air voids content

OGAFC mixes are designed with a predominantly uniform/single-sized aggregate gradation to maximise the voids space within the mix skeleton that allows a quick drainage of rainwater. The variation of air voids content with change in binder contents for various percentage replacements of BOF steel slag for OGAFC-PMB and OGAFC-CRMB mixes is presented in Figure 4.2. Air voids for OGAFC mixes with both PMB and CRMB binders decreased with an increase in binder content and steel slag content. An increase in binder content resulted in the availability of higher effective binder to improve the workability during compaction resulting in a lower air voids content. Meanwhile, a higher specific gravity of BOF steel slag aggregates resulted in a lower aggregate surface area for a given (constant) weight of aggregates and resulted in the availability of a higher effective binder that further enhanced the workability of the mix resulting in better compaction and lower air voids content. The air voids content results agree with the bulk specific gravity results illustrated in Figure 4.1. ASTM D7064 (2013) specifies a minimum air voids content of 18% to ensure an adequate drainage capacity of OGAFC mixes (as listed earlier in Table 4.1). Except for OGAFC-PMB and OGAFC-CRMB mixes prepared with 75% and 100% BOF steel slag at the trial binder content of 6.5%, all other combinations of OGAFC mixes met the minimum air voids criteria of 18%.

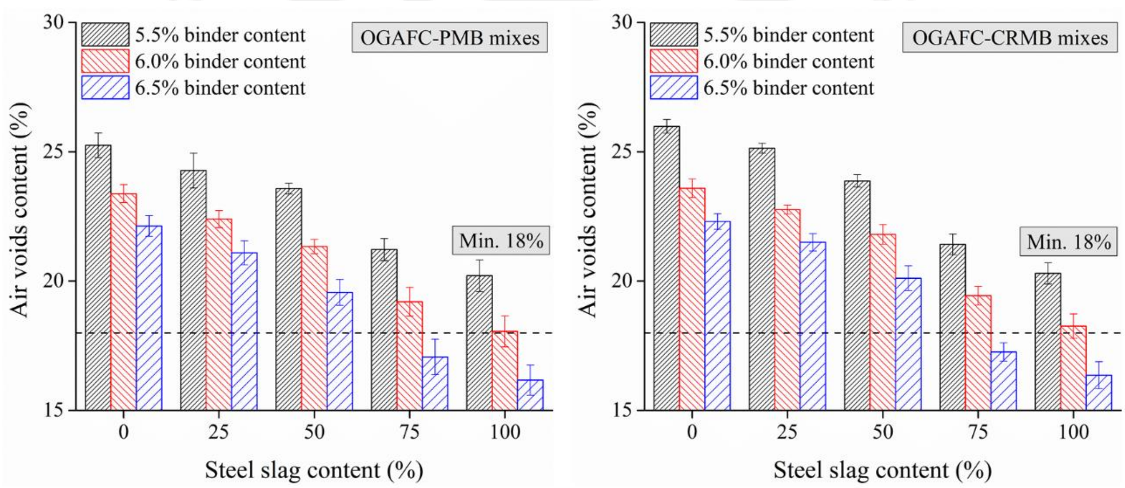


Figure 4.2: Variation of air voids content with steel slag content and binder type.

Since air voids is an important parameter for functional requirements of OGAFC mixes and also an indirect measurement of bulk specific gravity of mixes, ANOVA was performed on the test results of air voids content at 5% (α=0.05) significance level using binder content (BC), slag content (SC), and binder type (BT) as factors. The results of ANOVA analysis are presented in Table 4.2. All three factors (BC, SC, and BT) had statistical significance over air voids content. All two-way interactions (BC:SC, BC:BT and SC:BT) were found to be non-significant.

Table 4.2: Results of ANOVA conducted on mix design parameters at 5% significance level.

Factors	*Air voids content*	*Binder draindown*	*Unaged abrasion loss*	*Aged abrasion loss*
	p-value, S/NS	*p-value, S/NS*	*p-value, S/NS*	*p-value, S/NS*
Binder content (BC)	<0.001, S	<0.001, S	<0.001, S	<0.001, S
Slag content (SC)	<0.001, S	<0.001, S	<0.001, S	0.002, S
Binder type (BT)	<0.001, S	<0.001, S	0.004, S	0.009, S
BC:SC	0.13, NS	0.35, NS	0.49, NS	0.87, NS
BC:BT	0.69, NS	0.44, NS	0.55, NS	0.20, NS
SC:BT	0.66, NS	0.56, NS	0.99, NS	0.99, NS

Note: 'S': Significant effect; 'NS': Non-significant effect

4.2.3 Stone-on-stone contact

The presence of stone-on-stone contact in the coarse aggregate skeleton of an OGAFC mix is of prime importance to ensure the transfer of vehicular load through the contact points of the coarse aggregate to the underlying layer and to ensure adequate stability and resistance to permanent deformation. The stone-on-stone contact condition was evaluated through the VCA-ratio, the ratio between the percent voids in coarse aggregate of the compacted mixture (VCA_{mix}) to the percent voids in coarse aggregate of the coarse aggregate fraction alone (VCA_{DRC}) in dry-rodded condition. The stone-on-stone criterion is achieved when the VCA-ratio (VCA_{mix}/VCA_{DRC}) is less than unity (ASTM D7064, 2013). The variation of VCA_{DRC} with varying percentages of steel slag is shown in Figure 4.3. An increase in the BOF steel slag replacement percentage increased VCA_{DRC}, likely due to the higher angularity of steel slag (angularity number = 11) compared to natural stone aggregate (angularity number = 9).

Figure 4.4 shows the variation of VCA_{mix} for OGAFC-PMB and OGAFC-CRMB mixes. For a particular binder content, VCA_{mix} decreased with the increase in steel slag content. The VCA_{mix} is the sum of the volumes of fine aggregate, filler, binder and air voids content in a compacted OGAFC specimen. At a given binder content, the volumes of fine aggregate, filler and binder remain constant. The variation observed in VCA_{mix} is due to the variation in air voids content and the overall volume of the mix. It was observed that VCA_{mix} at a particular binder content followed a trend similar to that of air voids content. Similarly, for a particular percentage of steel slag, with volume of fine aggregate and filler remaining constant, the variation in VCA_{mix} with binder content was observed to decrease with an increase in the binder content due to decrease in air voids content (as also seen in Figure 4.2).

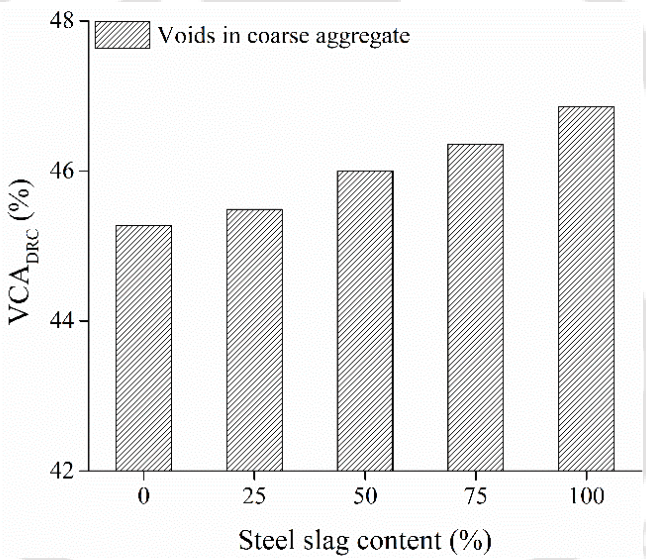


Figure 4.3: Variation of voids in coarse aggregate under dry rodded condition (VCA_{DRC}) with steel slag content.

Figure 4.5 shows the variation of VCA-ratio (VCA_{mix}/VCA_{DRC}) for OGAFC-PMB and OGAFC-CRMB mixes. An increase in binder content and percentage replacement of BOF steel slag reduced the VCA-ratio, indicating enhancement in the stone-on-stone contact. It is generally acknowledged that OGAFC mixes with lower VCA-ratio show better overall performance (Suresha *et al.*, 2009a). OGAFC mixes with BOF steel slag are thus expected to show good resistance to permanent deformation under traffic loads. ASTM

D7064 (2013) specifies a VCA-ratio less than 1.0 to attain the stone-on-stone contact criterion. The VCA-ratio was found to be lower than 1.0 for all combinations of OGAFC mixes except for those at 5.5% binder content (for both OGAFC-PMB and OGAFC-CRMB mixes) and 0% and 25% slag contents. At low binder content of 5%, the air voids were quite high due to a lack of workability resulting in higher VCA_{mix} values when compared to VCA_{DRC}. A VCA-ratio higher than 1.0 in OGAFC mixes has also been reported in other studies (Motz and Geiseler, 2001; Pattanaik *et al.*, 2018b).

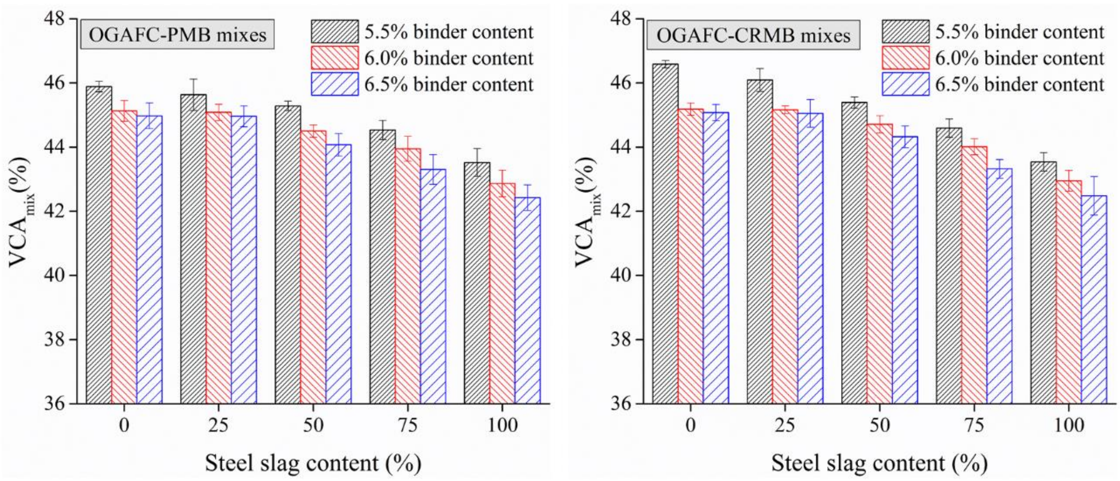


Figure 4.4: Variation of voids in coarse aggregate of the compacted specimens (VCA_{mix}) with steel slag content and binder type.

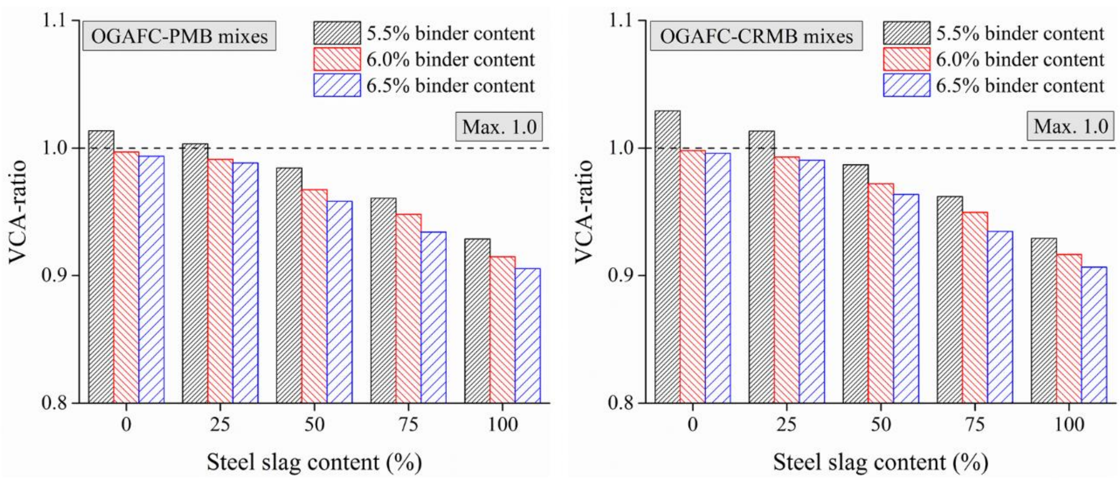


Figure 4.5: Variation of VCA-ratio (VCA_{mix}/VCA_{DRC}) with steel slag content and binder type.

4.2.4 Binder draindown

Since OGAFC mixtures are fabricated and prepared using a little volume of fine aggregate and a subsequently high amount of coarse aggregate fraction, it thereby increases the potential of binder draindown during mixing, hauling, and laying operations. The binder draindown test values for OGAFC-PMB and OGAFC-CRMB mixes are presented in Figure 4.6. Results indicated an increase in draindown with an increase in binder content and increase in BOF steel slag replacement percentage. For an OGAFC mix with a particular steel slag content, an increase in binder content increased the binder draindown. Also, an increase in the replacement with BOF steel slag resulted in increase in binder draindown because of the availability of the higher binder for coating at a given binder content, due to the reduced surface area of BOF steel slag aggregates.

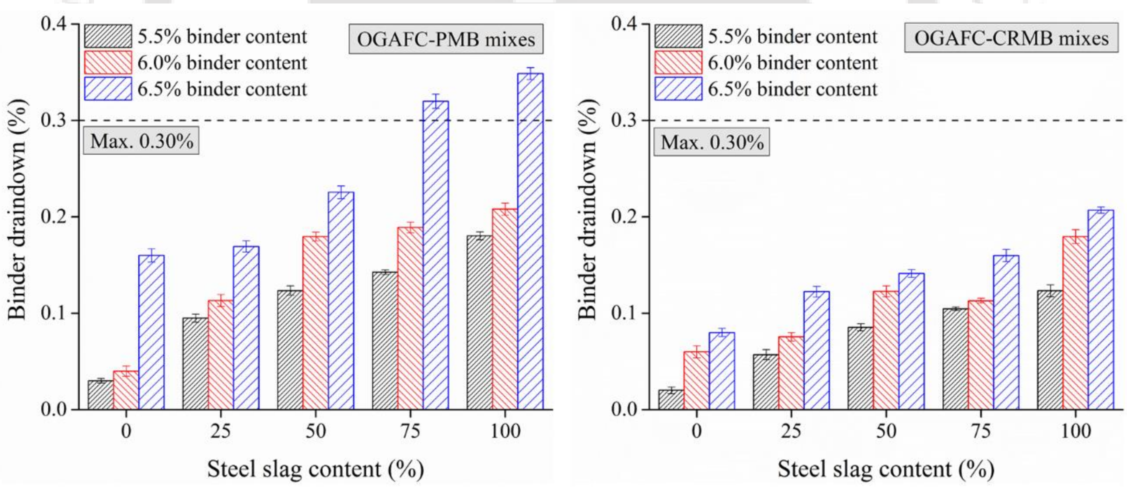


Figure 4.6: Variation of binder draindown with steel slag content and binder type.

Table 4.2 shows the results of ANOVA performed on binder draindown test results. The three main factors BC, SC and BT had statistically significant effect on the draindown results. OGAFC mixes with CRMB binder had lower draindown than those fabricated with PMB binder, which may be attributed to the slightly higher viscosity of CRMB binder compared to the PMB binder, as shown in the Table 3.1 of Chapter 3. Binder type also plays an important role in the draindown behaviour of an OGAFC mix type. All two-way interactions (BC:SC, BC:BT and SC:BT) were non-significant.

4.2.5 Cantabro abrasion loss

The compacted OGAFC specimens were examined for resistance to ravelling and disintegration in terms of Cantabro abrasion mass loss. The Cantabro abrasion test was conducted on both unaged and aged (aged for 7-days at 60°C) compacted OGAFC specimens. Upper limits of 20% and 30% are specified by ASTM D7064 (2013) for abrasion loss of unaged and aged specimens, respectively. The results of unaged and aged abrasion loss are presented in Figures 4.7 and 4.8, respectively. It was observed that percent loss in abrasion decreased with an increase in steel slag content, indicating an enhanced ravelling resistance of OGAFC mixes with BOF steel slag for both PMB and CRMB binders when compared to the natural stone aggregate. It can be explained by the rough and pitted surface features (Figure 3.3) and higher angularity of BOF steel slag than the natural stone aggregates, which provided better adhesive strength and interlocking/stability respectively to OGAFC mixes (Shen *et al.*, 2018). Further, for all OGAFC mixtures, increase in binder content decreased the abrasion loss as higher binder content enhances the aggregate-binder bonding and also the cohesive strength of the mix.

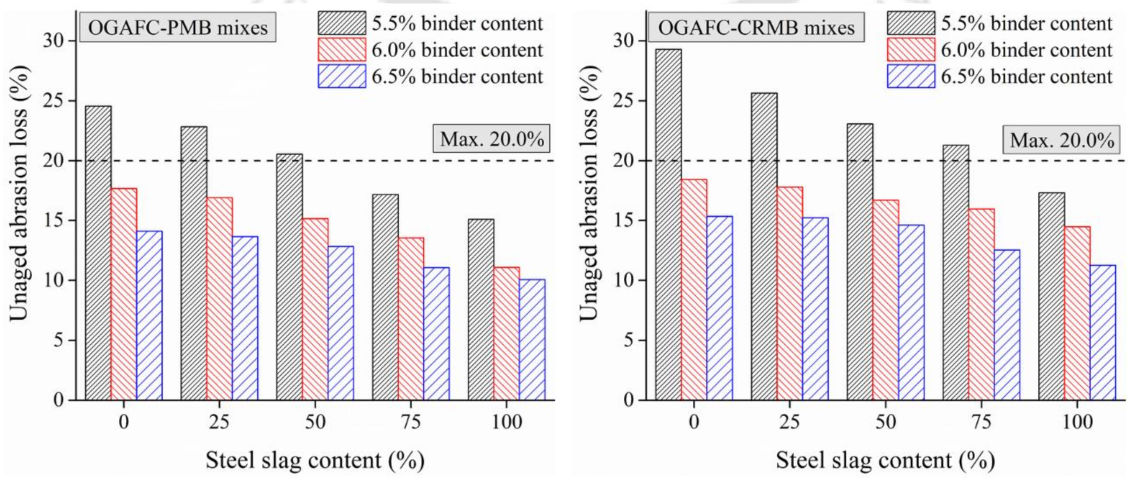


Figure 4.7: Variation of unaged abrasion loss with steel slag content and binder type.

Table 4.2 shows the results of ANOVA performed on unaged and aged abrasion loss results. The results were similar for both unaged and aged conditions. The three main factors BC, SC and BT were found to have statistically significant effect on abrasion loss. OGAFC mixes with CRMB binder had comparatively higher abrasion loss values than those fabricated with PMB binder. All three two-way interactions (BC:SC, BC:BT and SC:BT) were non-significant.

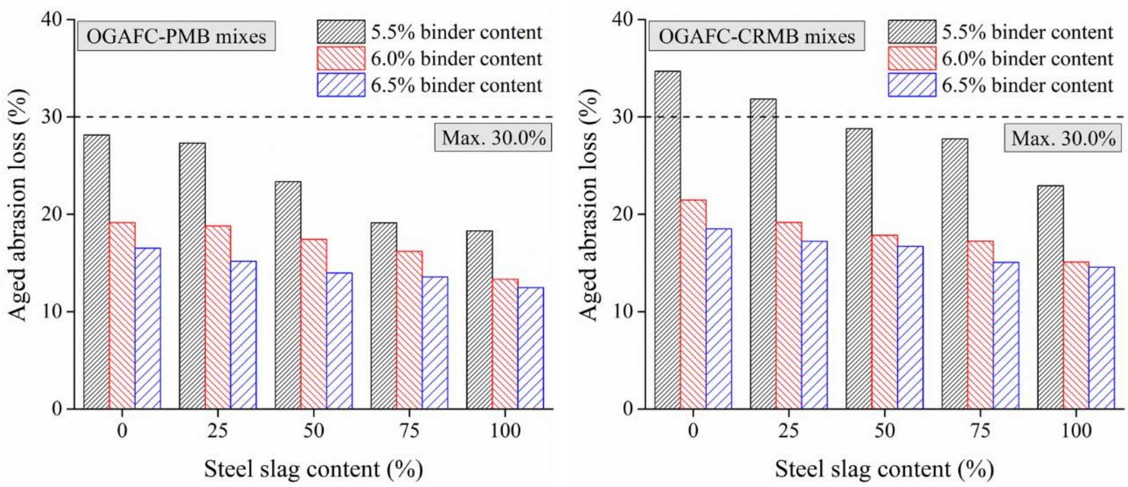


Figure 4.8: Variation of aged abrasion loss with steel slag content and binder type.

4.3 Optimum binder content

The mix design results obtained for the different OGAFC mix combinations at variable BOF steel slag contents for both CRMB and PMB binder types at the three trial binder contents were compared with the ASTM D7064 (2013) requirements (presented in Table 4.1), for arriving at the OBC for each mix type. Tables 4.3 and 4.4 present the conformance to the requirements by OGAFC-PMB and OGAFC-CRMB mixes, respectively at various binder contents and BOF steel slag replacement percentages. The lowest binder content at which all requirements were met was selected as the OBC (shown highlighted in Tables 4.3 and 4.4).

It is observed that the binder content at which all mix design parameters met the specified limits decreased with an increase in BOF steel slag substitution. For OGAFC-PMB mixes, the minimum binder content meeting the mix design requirements for steel slag content of 0% (control mix), 25%, and 50% was 6.0%, while it was 5.5% for mixes with 75% and 100% steel slag. For OGAFC-CRMB mixes, the minimum binder content meeting the mix design requirements for steel slag content of 0% (control mix), 25%, 50%, and 75% was 6.0%, while it was 5.5% for the mix with 100% BOF steel slag substitution. The results indicated lower binder requirement for producing OGAFC mixes at higher BOF steel slag replacement percentages.

Table 4.3: Mix design results for OGAFC-PMB mixes.

Steel slag content	*%BC*	*VCA-ratio (less than 1.0)*	*Air voids (min. 18%)*	*Draindown (max. 0.3%)*	*UAL (max. 20%)*	*AAL (max. 30%)*
0%	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%	✓	×	×	✓	✓

Note: '✓': Meets the criterion; '×': Doesn't meet the criterion

At a binder content of 5.5%, VCA-ratio, unaged abrasion loss, and aged abrasion loss of OGAFC mixes with lower steel slag content exceeded the maximum permissible limits while at 6.5% binder content, OGAFC mixes with higher percentage of BOF steel slag substitution were unable to meet the requirement for air voids content and binder draindown. However, at 6.0% binder content, all combinations of OGAFC mixes with both binder types were found to meet the specified requirements for all design parameters as per ASTM D7064. As OGAFC mix is practically a drainage layer, it generally demands a higher binder content for the desired moisture damage and ravelling resistance. ASTM D7064 (2013) also recommends a minimum binder content of 6.0% and therefore in this study, 6.0% binder content was considered as the OBC for all ten combinations of mixes.

Table 4.4: Mix design results for OGAFC-CRMB mixes.

Steel slag content	*%BC*	*VCA-ratio (less than 1.0)*	*Air voids (min. 18%)*	*Draindown (max. 0.3%)*	*UAL (max. 20%)*	*AAL (max. 30%)*
0%	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%	✓	×	✓	✓	✓

Note: '✓': Meets the criterion; '×': Doesn't meet the criterion

4.4 Summary

This chapter presented the mix design results of OGAFC mixes at different trial binder contents for different replacement percentages of BOF steel slag with natural aggregates, using both CRMB and PMB binders. The coarser fraction (>2.36 mm in size) of the natural stone aggregate was replaced with 0% (control mix with no replacement), 25%, 50%, 75% and 100% of equivalent size of BOF steel slag. The OGAFC mixes were evaluated for bulk specific gravity, air voids content, stone-on-stone contact criterion, binder draindown, and ravelling resistance. Based on the results and analyses, it was observed that the high specific gravity and low surface area of BOF steel slag aggregates resulted in better compaction and subsequently lower air voids content. Replacement of coarse natural stone aggregate with BOF steel slag also resulted in a better stone-on-stone contact due to the angular and rough surface texture of BOF steel slag aggregates. Binder draindown was observed to increase with an increase in the steel slag percentage replacement due to the availability of higher residual binder. Ravelling resistance, under both unaged and aged conditions, was found to improve with an increase in the percentage replacement of steel slag content. At 6.0% binder content (by mix weight), the mix design parameters for all ten combination of mixes were found to meet the specified requirements and therefore 6.0% binder content was considered as the OBC of the mixes. Hence forward, all the functionality, durability and performance evaluations of the OGAFC mixes were conducted at a binder content of 6.0%.

Chapter 5: Functionality of OGAFC mixes with BOF steel slag aggregates

5.1 General

Functionality of an OGAFC mixture is defined as its ability to allow the flow of rainwater runoff through the network of interconnected voids to improve frictional properties and minimise hydroplaning particularly during wet weather conditions. The functionality of the OGAFC mixes is mainly evaluated in terms of drainage/permeability and frictional characteristics. This chapter presents the results of evaluation of functionality, in terms of permeability and frictional characteristics, of OGAFC mixes at varying BOF steel slag contents of 0, 25, 50, 75, and 100% with the two types of modified binders (PMB and CRMB). Drainage/permeability characteristics were determined for different clogging environments, and the frictional characteristics were determined for varying surface conditions. The drainability as well as the likelihood of clogging in the OGAFC mixes was evaluated under three clogging environments: particle-related clogging, stripping-related clogging, and deformation-related clogging; while the frictional properties of the OGAFC mixes were examined for three surface conditions — dry, wet, and ponding. Further the adhesion and hysteresis components of surface friction were also evaluated separately. The frictional performance of the OGAFC mixes during later years of service life was examined with artificially polished/wore off aggregates. The following sections discuss in details the different test results obtained during the evaluation of the drainability and frictional properties of BOF steel slag incorporated OGAFC mixes.

5.2 Permeability and clogging characteristics of OGAFC mixes

5.2.1 Initial permeability and porosity

Permeability of an OGAFC mix plays an important role in its durability and long term benefits/performance. Although total air voids content of an OGAFC mix is an indicator of permeability, but it may not provide a complete picture as permeability depends on interconnected voids than the total void content, and thus determination of porosity is beneficial to evaluate drainability. The porosity and permeability of the different OGAFC mixtures were evaluated in this study using a CoreLok device and a flexible-wall falling head permeameter, respectively. Porosity was measured through the vacuum sealing method (Figure 3.19) specified in ASTM D7063 (2013). The permeability of OGAFC specimen was measured using a falling head permeameter (Figure 3.20) in accordance with FDOT FM 5-565 (2015) standard. The trends of initial porosity and initial permeability (K_i) of the OGAFC mixtures with varying BOF steel slag content and binder type are illustrated in Figure 5.1.

All the combinations of OGAFC mixtures exhibited permeability quite higher than the minimum recommended value of 100 m/day (ASTM D7064, 2013). OGAFC-CRMB mixtures exhibited slightly higher permeability values (8-10% higher) than OGAFC-PMB mixtures due to their relatively high porosity. This is also in agreement with the high air void content values for OGAFC mixes with CRMB binder as presented in Figure 4.2 of Chapter 4. For every 25% increment in the steel slag content, permeability of OGAFC-PMB and OGAFC-CRMB mixtures decreased by 45 m/day and 50 m/day, respectively. Permeability decreased with an increase in steel slag content due to the reduced porosity (indicating possible reduction in the network of water permeable voids) with an increase in the steel slag content. During compaction, an increase in residual binder content due to higher specific gravity of BOF steel slag results in higher density and lower porosity of OGAFC mixes with BOF steel slag. Similar observations on porosity/permeability with varying steel slag content have also been reported by other researchers (Pattanaik *et al.*, 2018a).

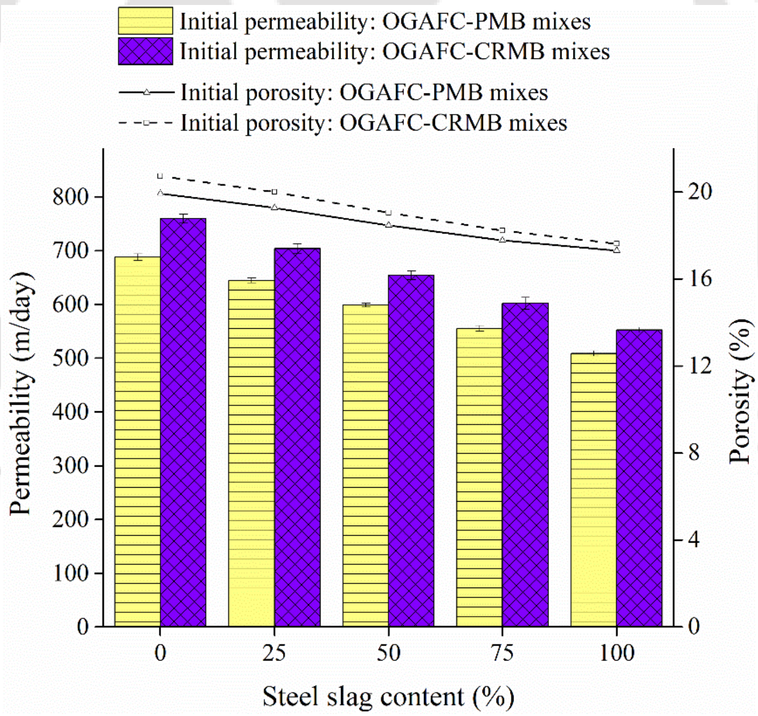


Figure 5.1: Initial permeability and porosity of OGAFC mixtures.

Two-way ANOVA was performed on porosity and permeability values, and the results are presented in Table 5.1. Out of the two factors — slag content (SC) and binder type (BT), only SC was found to be significant for porosity values, while both SC and BT were found to be significant for permeability values. This shows that even if porosity testing can be done for a comparison, permeability measurements are more important to ensure the desired drainability of OGAFC mixes. Further, the interaction between the two factors (SC:BT) was not found significant for both porosity and permeability.

Table 5.1: ANOVA test results of initial porosity and permeability values at 5% significance level.

Factors	*Degree of freedom*	*F-value*	*P-value*	*Significance*
Porosity values				
Slag content (SC)	4	31.073	<0.001	Yes
Binder type (BT)	1	9.619	0.011	No
SC:BT	4	0.288	0.879	No
Permeability values				
Slag content (SC)	4	486.822	<0.001	Yes
Binder type (BT)	1	312.829	<0.001	Yes
SC:BT	4	2.619	0.066	No

5.2.2 Initial clogging of OGAFC mixes

The functionality of an OGAFC mix in terms of drainability is achieved when the void structure allows free flow of the rainwater. When these voids are clogged, the interconnectivity is disrupted and OGAFC mixtures may begin to behave like conventional dense-graded surfaces, and the associated advantages of OGAFC cease to exist. Clogging can be attributed to — particle-related clogging (due to intrusion of foreign material like sand/debris), stripping-related clogging (due to deposition of stripped off bitumen-fines mortar in the mix structure), and deformation-related clogging (reduced drainability as a mixture undergoes permanent deformation).

To evaluate the effect of particle-related clogging on drainability of OGAFC mixes, permeability of the unclogged (initial permeability), surface-clogged, and de-clogged

OGAFC specimens with varying percentages of BOF steel slag aggregates was measured using the flexible wall permeameter and the obtained results are shown in Figure 5.2. Graded sand conforming to ASTM C778 (2017) was used to clog OGAFC specimens as per the procedure described in Section 3.5.1.2 of Chapter 3. The permeability values significantly decreased after surface-clogging for all mixes as a result of the surface voids being crammed with sand. For both OGAFC-PMB and OGAFC-CRMB mixes and at all five steel slag contents, an average 25% decrease in the permeability was observed due to surface clogging. Even though the surface-clogged permeability was substantially lower than the initial permeability of the OGAFC mixtures, it was still well above the minimum specified requirement of 100 m/day.

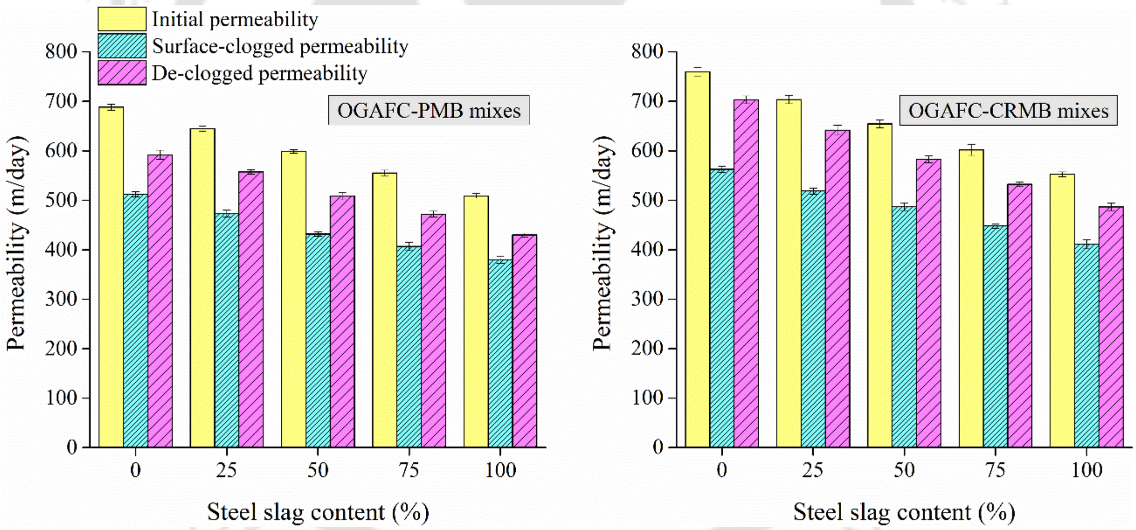


Figure 5.2: Permeability values of OGAFC mixtures comprising of initial permeability, surface-clogged permeability, and de-clogged permeability.

Using the initial permeability and surface-clogged permeability, the initial clogging rate ($CR_{initial}$) of all mixes was computed using Equation (5.1) and is shown in Figure 5.3.

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

where, K_{sc} and K_i are the permeability of the OGAFC specimens after and before surface clogging with graded sand and m_{sand} is the mass of graded sand used for surface clogging of the OGAFC mixtures. The initial clogging rate is an indicator of the clogging potential of the OGAFC mix and a mix with a higher clogging rate may be expected to show a higher reduction in its permeability upon surface clogging than the one with a lower clogging rate. The initial clogging rates of the OGAFC mixtures were found to decrease with an increase in steel slag content and OGAFC-PMB mixtures showed a lower initial clogging rate than OGAFC-CRMB mixtures. Possible explanations for these observations are provided later in this section.

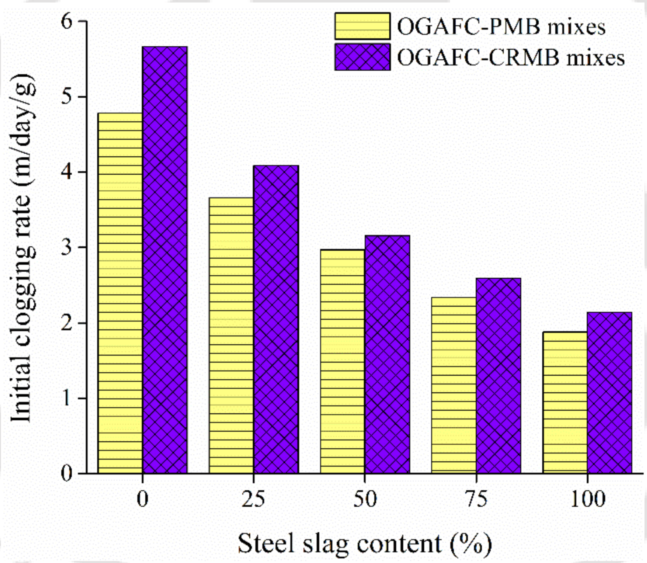


Figure 5.3: Initial clogging rate of OGAFC mixtures with PMB and CRMB binders.

The permeability of de-clogged OGAFC specimens is also illustrated in Figure 5.2. On an average, the de-clogging process was able to restore approximately 85% and 90% of the initial permeability of OGAFC-PMB and OGAFC-CRMB mixes, respectively. The restoration in the de-clogged permeability with respect to the initial permeability is not 100% probably due to the fact that certain mass of clogged materials must have migrated to the internal pores and channels of the mix skeleton, thereby escaping the de-clogging forces.

5.2.3 *Step-wise clogging of OGAFC mixes*

Considering the obtained de-clogged permeability (K_{dc}) as baseline for step-wise clogging procedure, the permeability of the OGAFC mixes was further measured after placement of successive batches (each batch of 14 g) of the clogging material (sand). Figure 5.4 shows the permeability deterioration during the step-wise clogging of all OGAFC mixes. The permeability significantly decreased with an increment in the clogging material for both OGAFC-PMB and OGAFC-CRMB mixtures. The step-wise clogging was continued until a terminal permeability was obtained (variation in permeability became less than 3% of the previous value). The terminal permeability values of all OGAFC mix combinations with and without steel slag aggregates were more than the minimum specified permeability value requirement of 100 m/day.

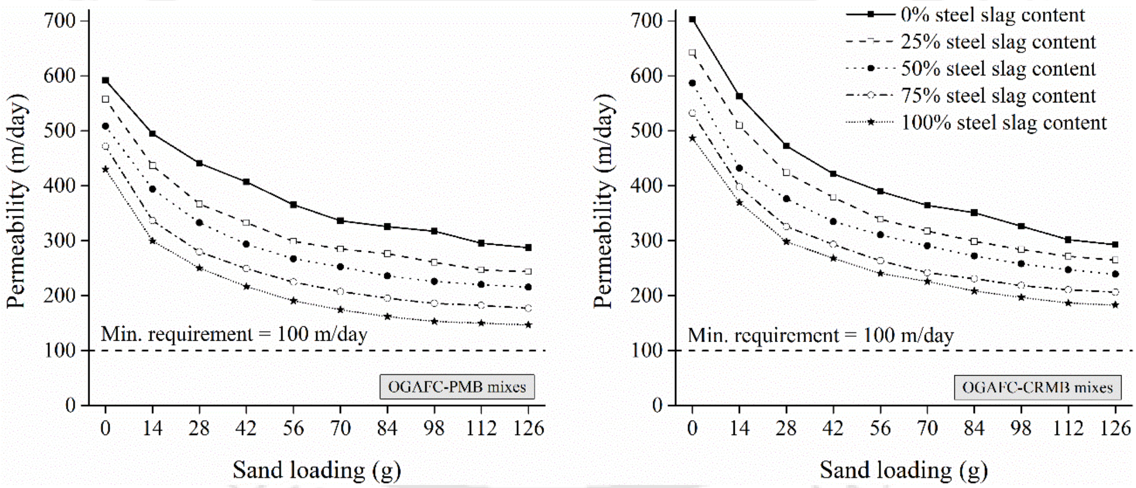


Figure 5.4: Permeability reduction plot with step-wise clogging of OGAFC mixtures with varying steel slag content and modified binders.

The step-wise clogging curves indicate that there is a rapid decrease in permeability when the clogging material is introduced up to about 56 g (up to first four batches of the clogging material) beyond which the permeability reduces at a relatively slower and linear rate. The slope of the linear portion of the clogging curve was computed as the secondary clogging rate and is shown in Figure 5.5. The secondary clogging rate is an important parameter for the design and application of OGAFC mixtures as it is the typical clogging rate more likely expected in the field when the OGAFC mixes get clogged and are subjected to de-clogging activities. Martin *et al.* (2014) therefore referred the secondary clogging rate as the operational clogging rate. Similar to the initial clogging rate, the secondary clogging rate was also observed to decrease with an increase in BOF steel slag content with a lower clogging rate for OGAFC-PMB mixtures than OGAFC-CRMB mixtures.

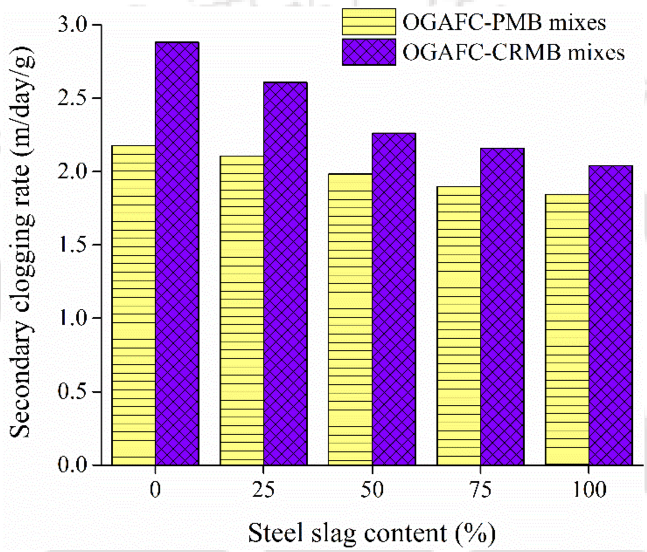


Figure 5.5: Secondary clogging rate of OGAFC mixtures with PMB and CRMB binders.

Generally, the secondary clogging rate was observed as approximately 20-40% of the initial clogging rate. Other researchers have also reported a higher initial clogging rate than the secondary (Martin *et al.*, 2014; Pattanaik *et al.*, 2018a). This behaviour can be explained as follows. The decrease in permeability is rapid when the specimen is first clogged and the permeability reduces from K_i to K_{sc}. De-clogging the specimen only removes clogging material this is easily accessible by vacuum pressure and reverse flushing, but there may be particles trapped in deep voids that are not flushed out, and hence K_{dc} (de-clogged permeability) is lower than K_i. The trapped clogging material may thus be responsible for the initial rapid drop in OGAFC permeability (Suresha *et al.*, 2010; Martin *et al.*, 2014). Thereafter, when the specimen is subjected to step-wise clogging, the trapped particles are already present in the specimen and additional clogging material only has a lower effect on the rate of decrease in permeability, as indicated by the secondary clogging rate.

The preceding results clearly indicate the beneficial effect of BOF steel slag aggregates in reducing the clogging susceptibility of OGAFC mixes while meeting the minimum permeability requirements. Steel slag aggregates have a higher angularity than natural stone aggregates, implying that slag aggregates have sharper edges and more variable boundary and surface features (Cui *et al.*, 2018; Cui *et al.*, 2020). Some clogging material is likely to get confined within such boundary features present on BOF steel slag aggregates, and consequently delay the rate of disruption/blockage of interconnected void channels. This, in turn, leads to a lower rate at which a BOF steel slag incorporated OGAFC mix would deteriorate its permeability. Figure 5.6 shows the boundary features on the surface of BOF steel slag aggregates while lack of such features can be observed on the surface of natural aggregate.

The boundary features are also visible on the surface of asphalt binder coated aggregates picked out from OGAFC mixes. In case of natural stone aggregates, due to the absence (or lack) of such features on the surface, the void channels responsible for causing the flow of water gets blocked relatively quickly with increments in the amount of clogging material. This results into lower values of both initial and secondary clogging rates for steel slag incorporated OGAFC mixes. Both clogging rates reduce further with an increase in steel slag content. Considering the effect of binder type, it is reasonable to assume that the discrete crumb rubber particles present in CRMB may have the tendency to partially occupy the boundary features on the steel slag leaving less space for the confinement of the clogging material. Eventually, OGAFC-CRMB mixes have a slightly higher clogging rate than OGAFC-PMB mixes.

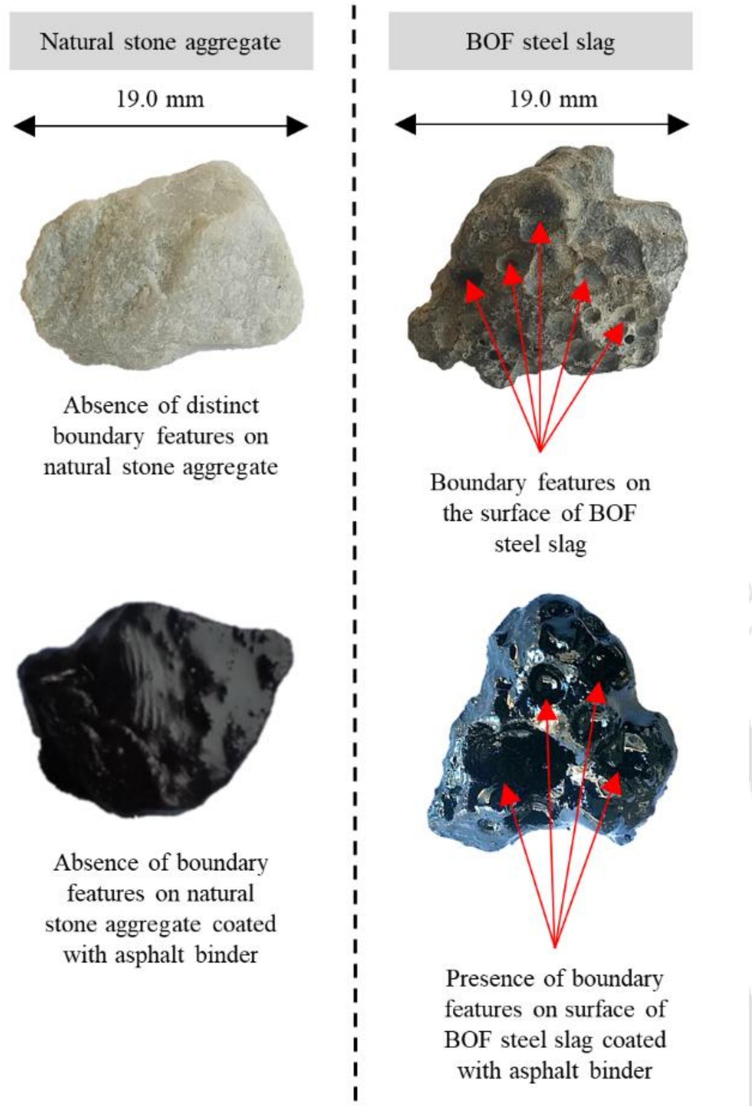


Figure 5.6: Macroscopic view of natural stone aggregate and BOF steel slag with boundary feature.

5.2.4 *Effect of binder stripping on porosity and permeability*

The effect of binder stripping on the porosity and permeability values of OGAFC mixes was examined by measuring the drainage properties of compacted OGAFC specimens before and after being subjected to the modified boiling water test (100°C for 30-minutes) as described in Section 3.5.1.3 of Chapter 3. Figures 5.7 and 5.8 respectively present the porosity and permeability values of OGAFC mixes before and after moisture conditioning to reproduce the stripping of asphalt binder from the aggregate surface.

Compared to their initial values, both porosity and permeability of the moisture conditioned OGAFC mixes decreased after modified boiling water test conditioning. This decrease can be attributed to the deposition of stripped off material (mixture of fines and asphalt binder) in the interconnected voids as a result of the action of the boiling water.

For better understanding of the influence of BOF steel slag in resisting the moisture induced damages and retaining its initial properties, the trend in percentage change in both porosity and permeability with steel slag content was also investigated. The percentage change in porosity and permeability was computed as the percentage decrease in porosity and permeability with respect to their initial values. From Figures 5.7 and 5.8, the percentage change in porosity and permeability of the OGAFC mixtures were observed to decrease with an increase in BOF steel slag content. This indicates that stripping of bitumen from the aggregate surface course decreases with an increase in steel slag content.

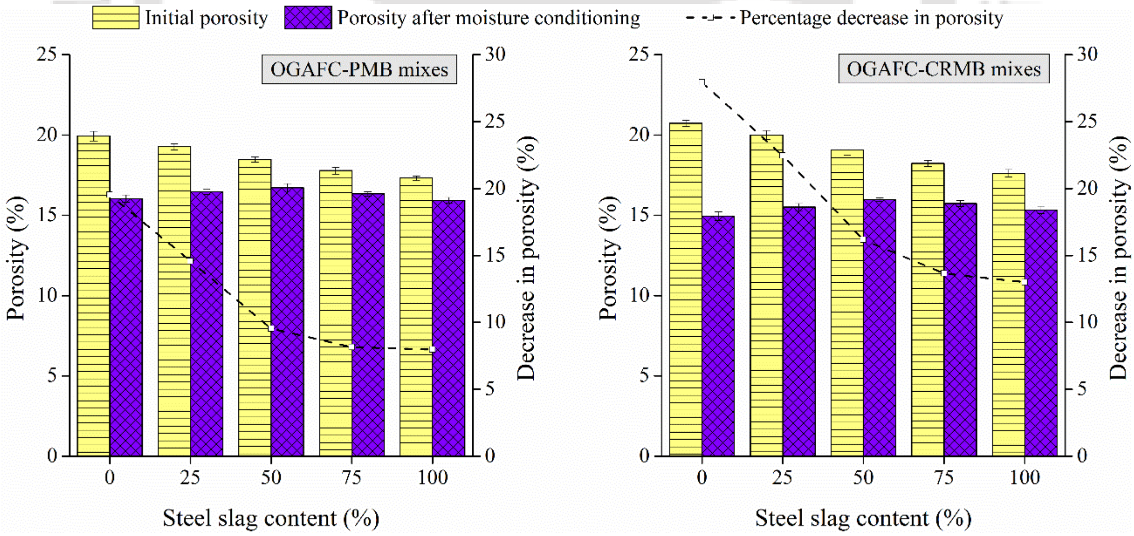


Figure 5.7: Porosity of OGAFC mixtures before and after moisture conditioning.

A large proportion of natural aggregates available and used in different regions are siliceous, which usually have a higher affinity towards water than bitumen. This affinity of aggregates towards water decreases with an increase in the aggregates basicity (CaO/SiO_2 ratio). As reported in Table 3.3, BOF steel slag demonstrated a higher basicity (3.75) than natural stone aggregates (0.16). The higher basicity of BOF steel slag attributes to higher adhesion and lower stripping of asphalt binder from its surface and thereby caused lower stripping-related clogging and subsequently lower change in porosity and permeability. The results indicate that incorporation of BOF steel slag reduces the decrease in drainability properties of OGAFC mixtures due to the moisture conditioning. The porosity and permeability values of the moisture conditioned OGAFC-PMB mixtures were found to be marginally higher than OGAFC-CRMB mixtures. Further, the change in drainage properties was observed to be more for OGAFC-CRMB mixtures than OGAFC-PMB mixtures indicating that PMB bitumen performs better in resisting the stripping of asphalt film due to moisture induced damages than CRMB bitumen. Furthermore, all moisture-conditioned mixes meet the minimum 100 m/day permeability requirement.

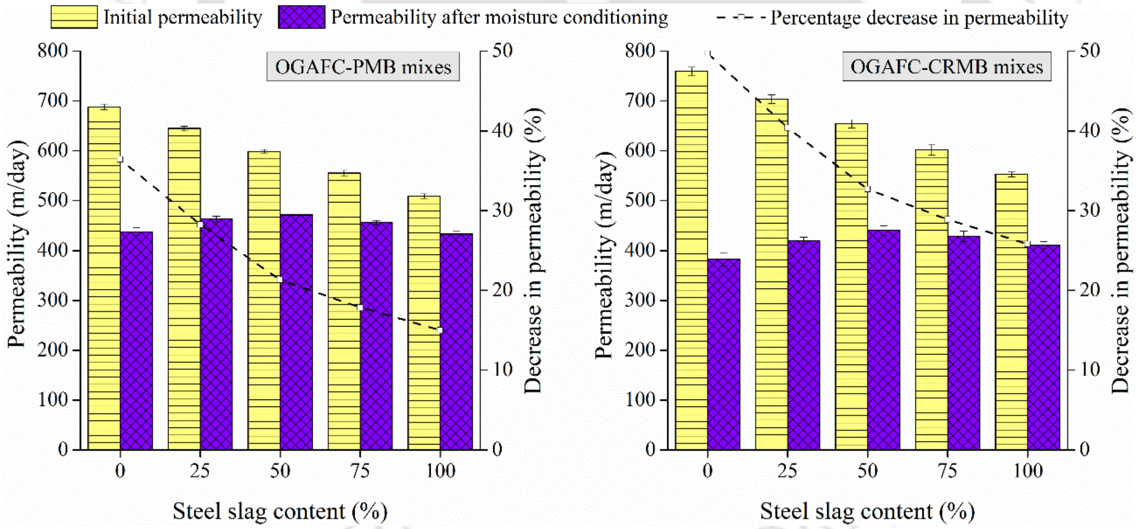


Figure 5.8: Permeability of OGAFC mixtures before and after moisture conditioning.

5.2.5 Effect of permanent deformation on porosity and permeability

The effect of permanent deformation (or rutting) on porosity and permeability values of OGAFC mixes was examined by measuring the drainage properties of compacted OGAFC specimens before and after being subjected to the dynamic creep test (100 kPa stress for 10,000 cycles at 40°C) performed using a 14 kN capacity servo-pneumatic universal testing machine. Figures 5.9 and 5.10 respectively illustrate the porosity and permeability of the BOF steel slag incorporated OGAFC mixtures after being subjected to dynamic creep test to simulate deformation-related clogging. The repeated creep loading is expected to alter the mix skeleton by condensing the water accessible air voids and thereby hindering the drainability. As expected, both porosity and permeability of the specimens after undergoing dynamic creep test were significantly lower than their initial values.

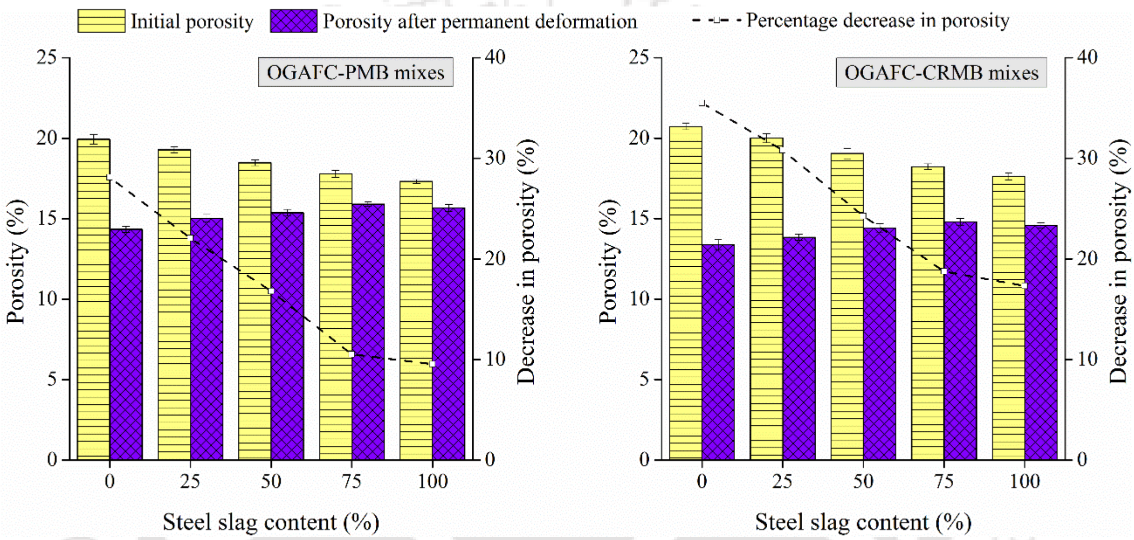


Figure 5.9: Porosity of OGAFC mixtures before and after dynamic creep test.

Percentage change in porosity and permeability values with steel slag content were also computed for further understanding the influence of BOF steel slag contents on limiting the loss in permeability due to permanent deformation. It was observed that percentage change in porosity and permeability decreased with an increase in BOF steel slag content. This suggests that changes in the aggregate skeleton leading to blockage of water accessible voids was less for mixtures with steel slag aggregates, when subjected to the dynamic loading, indicating that steel slag can better resist changes in drainability caused due to deformation-related clogging. The conditioned drainage properties of OGAFC-PMB mixtures were found comparatively higher than OGAFC-CRMB mixtures. Also, the change in porosity and permeability values of conditioned OGAFC-PMB mixes were lower than OGAFC-CRMB mixes suggesting that mixes with PMB binder were more efficient in resisting permanent deformation due to repeated loading when compared to the ones with CRMB binder. All OGAFC mix combinations met the minimum (100 m/day) permeability requirement as per ASTM D7064 (2013) requirements even after being subjected to the dynamic creep test. The percent reductions in porosity and permeability caused by deformation-related clogging were higher than those caused by stripping.

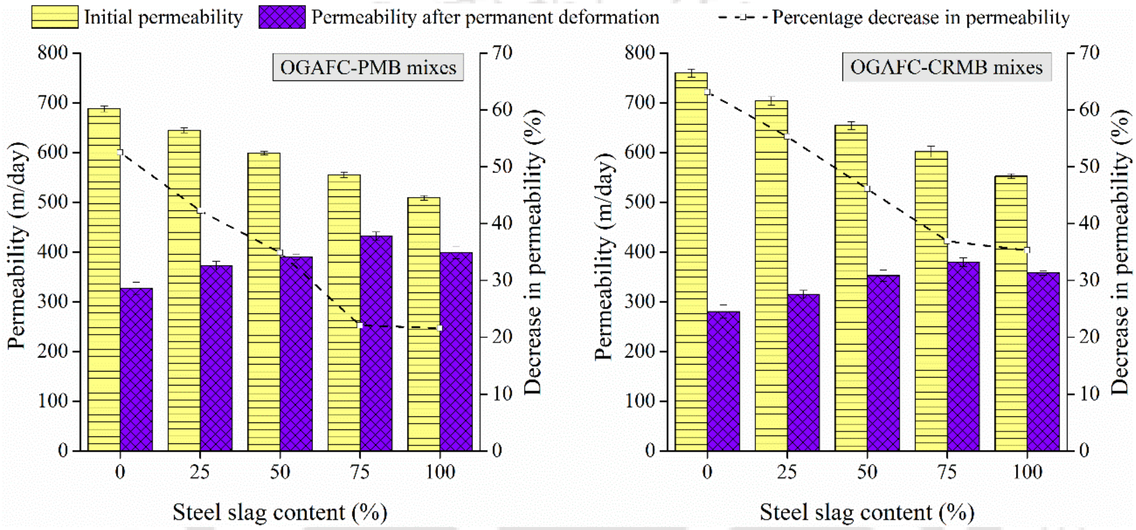


Figure 5.10: Permeability of OGAFC mixtures before and after dynamic creep test.

5.3 Frictional characteristics of OGAFC mixes

5.3.1 Mean texture depth

Skid resistance or frictional resistance of an OGAFC mix is of paramount importance to achieve the desired benefits and a safe manoeuvrability of traffic, especially under wet weather conditions. The mean texture depth (MTD) of an OGAFC mixture is an intrinsic characteristic influencing its frictional properties that measures the macrotexture of a test surface using a volumetric technique (Araujo *et al.*, 2015). The MTD was evaluated using the volumetric sand patch method as per ASTM E965 (2015) specifications as described in Section 3.5.2.1 of Chapter 3. The MTD results of OGAFC mixes with different slag percentages and the two modified binder types are shown in Figure 5.11. It is seen that an increase in slag percentage leads to an increase in MTD value. For example, in OGAFC-PMB mixes, MTD increased from 1.73 mm (for control mix) to 3.21 mm for OGAFC mixes with 100% substitution of BOF slag. While for OGAFC-CRMB mixes, MTD ranged from 1.83 mm (for control mix) to 3.27 mm for BOF-100 mixes. In general, each 25% increment in steel slag content resulted in an approximate increase of 0.3 mm in the MTD. Further, the MTD values of OGAFC-CRMB mixes were slightly higher than OGAFC-PMB mixes by an average of 0.1 mm. A higher MTD indicates that at higher vehicular speed, the hysteresis component of friction of the road surface will be higher and shall boost the skid resistance of the surface by increasing the friction speed gradient and expediting the water drainage (Bloem, 1971; Hall *et al.*, 2009).

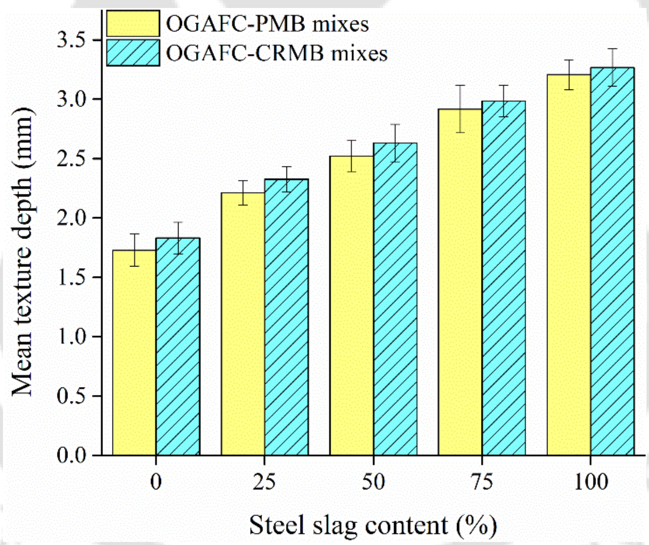


Figure 5.11: Mean texture depth values of the OGAFC mixes obtained from sand patch test method.

ANOVA test results performed on the MTD values at $\alpha = 0.05$ are listed in Table 5.2. Both test factors – slag content (SC) and binder type (BT) were found to have a significant effect on MTD values. The F-values obtained from the ANOVA test indicated that SC was more sensitive compared to BT. The two-way interactions between the two factors were found non-significant.

Table 5.2: ANOVA test results on mean texture depth values obtained from the sand patch test.

Factors	*Degree of freedom*	*F-value*	*P-value*	*Significance*
Slag content (SC)	4	135.472	<0.001	Yes
Binder type (BT)	1	4.665	0.037	Yes
SC:BT	4	0.020	0.999	No

5.3.2 British pendulum test (BPT)

The BPT is a widely accepted friction test device (Asi, 2007; Dan *et al.*, 2017; Pattanaik *et al.*, 2017), in which a rubber slider attached to the pendulum arm slides over the specimen surface when released from its horizontal holding position. The skid resistance value obtained from the BPT is reported as the British pendulum number (BPN). BPN values of the ten OGAFC combinations were determined using the BPT under three different surface conditions – dry, wet, and ponding. These three test conditions for BPN tests were described in detail in Section 3.5.2.2 of Chapter 3. Figure 5.12 presents the variation of BPN for the five percentage replacements of BOF steel slag under the three surface conditions (dry, wet, and ponding) for OGAFC-PMB and OGAFC-CRMB mixes. A significant improvement in BPN values was observed under the three surface conditions with an increase in BOF steel slag content for both the asphalt binders.

The BPN is also an indirect measure of the aggregate micro-texture with a higher BPN denoting a higher micro-texture (Highways Department, 1989; Shirini and Imaninasab, 2016). Gradual increase in the BPN values with increment in the steel slag content indicates that the micro-texture of the OGAFC mixes increases with an increase in percentage substitution of BOF steel slag. The BPN values under the dry surface condition to increased from 70 to 117 and 74 to 122 with increment in the steel slag content (0% to 100%) for the OGAFC-PMB and OGAFC-CRMB mixes, respectively. A similar increase in the BPN values was also seen under wet and ponding surface conditions. Corresponding to each 25% increment in steel slag content, BPN values increased by about 12 BPN units for both binders and under the three surface conditions. The enhancement in the skid resistance properties of OGAFC mixes with the application of steel slag particles was attributed to the steel slag particles' geometric characteristics in terms of higher angularity and rougher surface morphology (texture).

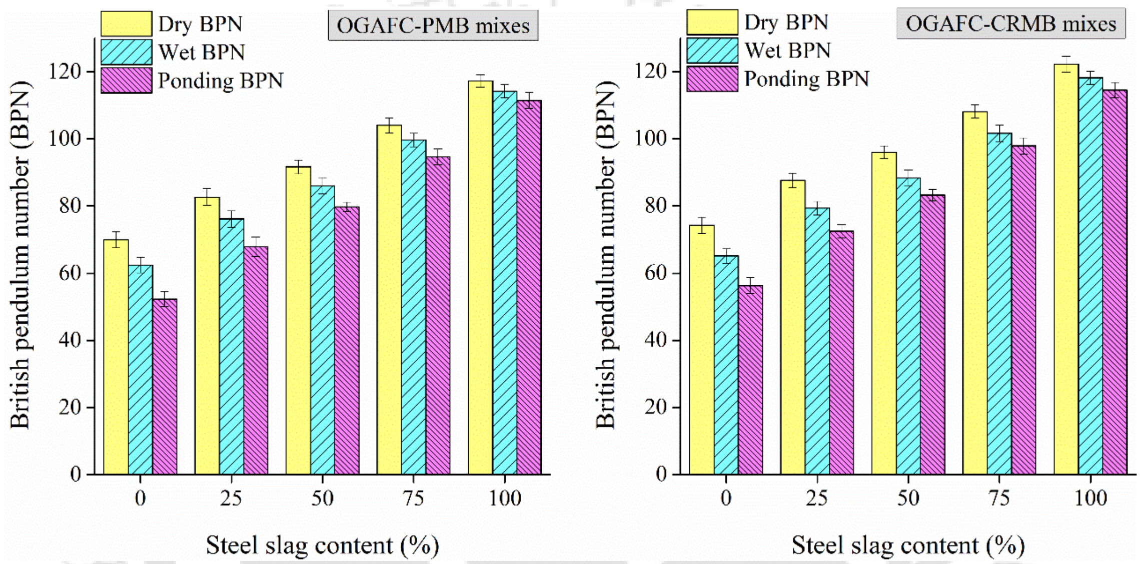


Figure 5.12: British pendulum numbers of the OGAFC mixes obtained from British pendulum test.

In terms of the different surface conditions, the BPN values of all OGAFC mixes decreased from dry to wet to ponding surface conditions. In the wet surface condition, the presence of water results in a decrease in the adhesion between the rubber slider and test surface resulting in a corresponding decrease in BPN. Whereas, in the case of ponding surface condition, the presence of a continuous film of water (thickness of about 1 mm) between the rubber slider and the test surface results in a negative drag, which subsequently further reduced the BPN value. The difference between the dry and ponding BPN values (dry BPN – ponding BPN) was about 18 BPN units for the control mixes (average for PMB and CRMB binders), which reduced to 6.8 BPN units for OGAFC mixes prepared with

100% BOF steel slag content. This is probably due to the higher micro-texture and macro-texture of the steel slag incorporated OGAFC mixes which breaks the thin film of water at the surface and helps achieve higher frictional characteristics than the control mixes without slag. Further, OGAFC-CRMB mixes reported relatively higher BPN values (about 3.5 BPN units higher) compared to OGAFC-PMB mixes, which is likely due to the presence of crumb rubber particles in the binder surface resulting in a higher adhesive bond with the rubber slider and these trends also agree with the MTD test results.

The adhesion and hysteresis components of the BPN recorded under wet surface condition were also evaluated separately and are reported in Figure 5.13. Adhesion force is more responsive to asperities at the micro-level (micro-texture), while hysteresis force is more responsive to asperities at the macro-level (macro-texture) (Kouchaki *et al.*, 2018). Both adhesion and hysteresis BPNs were found to increase with an increase in BOF steel slag content, indicating that the use of steel slag increases both micro-texture and macro-texture of OGAFC mixes.

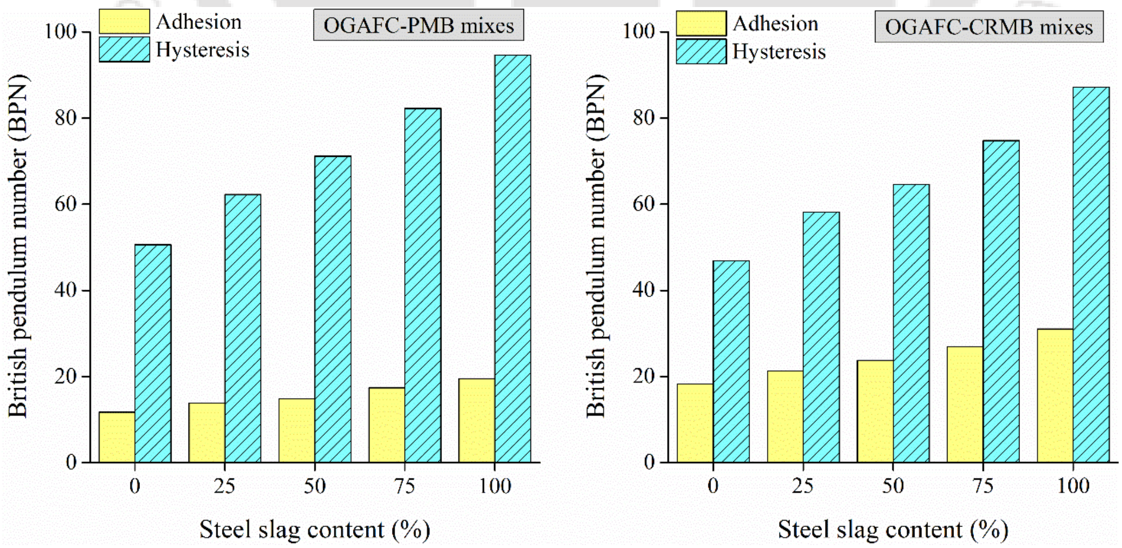


Figure 5.13: Adhesion and hysteresis components of BPN under wet surface condition.

Adhesion BPN was computed to be about 17% and 26% of the wet BPN for OGAFC-PMB and OGAFC-CRMB mixes, respectively. The hysteresis component of skid friction was significantly higher than the adhesion component, and such percentage shares have also been reported by other researchers (Bazlamit and Reza, 2005). A slightly higher adhesive force for OGAFC-CRMB mixes indicates that the interface shear strength developed at the mix surface with the rubber slider is higher when the CRMB binder is used than the PMB. The adhesion component governs the skid resistance under dry surface condition, while the hysteresis component is more prominent during the wet surface condition (Henry, 2000; Hall *et al.*, 2009). The adhesive and hysteresis force trends are in consensus with the BPN measurements under dry and wet surface conditions.

Table 5.3 shows the results of ANOVA performed on BPN results at 5% significance level. The two factors – slag content (SC) and binder type (BT) were found to have a significant impact on the BPN values obtained under different surface conditions. Non-significant two-way interactions observed for the interaction between SC and BT suggest that BPN values follow similar trends for different binder types and varying slag contents.

Table 5.3: ANOVA test results of BPN values at 5% significance level.

Factors	*Dry BPN*	*Wet BPN*	*Ponding BPN*	*Hysteresis*
	p-value, S/NS	*p-value, S/NS*	*p-value, S/NS*	*p-value, S/NS*
Slag content (SC)	<0.001, S	<0.001, S	<0.001, S	<0.001, S
Binder type (BT)	<0.001, S	<0.001, S	<0.001, S	<0.001, S
SC:BT	0.874, NS	0.416, NS	0.531, NS	0.713, NS

Note: 'S' – significant effect; 'NS' – non-significant effect

5.3.3 Dynamic friction test

The dynamic friction test (DFT) was conducted over the OGAFC mixes to find the variation of friction coefficient with slip speed. The DFT device was used according to ASTM E1911 (2019) specifications. The device consists of a horizontal spinning disk loaded with spring-mounted rubber sliders, which were first accelerated during testing to attain a pre-defined circumferential velocity and then the disk along with the measuring pads was lowered down onto the wet test surface to measure the dynamic frictional coefficient. Figure 5.14 presents the variation of dynamic friction coefficient with respect to varying slip speeds (initial speed used is 80 kmph) for the OGAFC mixes.

The test results are reported from a slip speed of 80 kmph to 10 kmph. Friction coefficients corresponding to a slip speed of 80, 60, 40, and 20 kmph are typically reported for wet pavements, but the frictional coefficient corresponding to a slip speed of 20 kmph is generally preferred as the ideal representation of the surface microtexture and is most commonly adopted for comparison studies (Subedi *et al.*, 2016). With a variation in the slip speed from 20 kmph to about 70 kmph, the dynamic friction coefficient of all the mixes was found to decrease by about 0.15 for all OGAFC mix combinations indicating that under both moderate and high-speed driving environments, OGAFC mixes showed a decrease in the frictional coefficient for any steel slag content and binder type. This is also evident from almost equal slopes of the DFT coefficient versus speed curves, as seen from Figure 5.14.

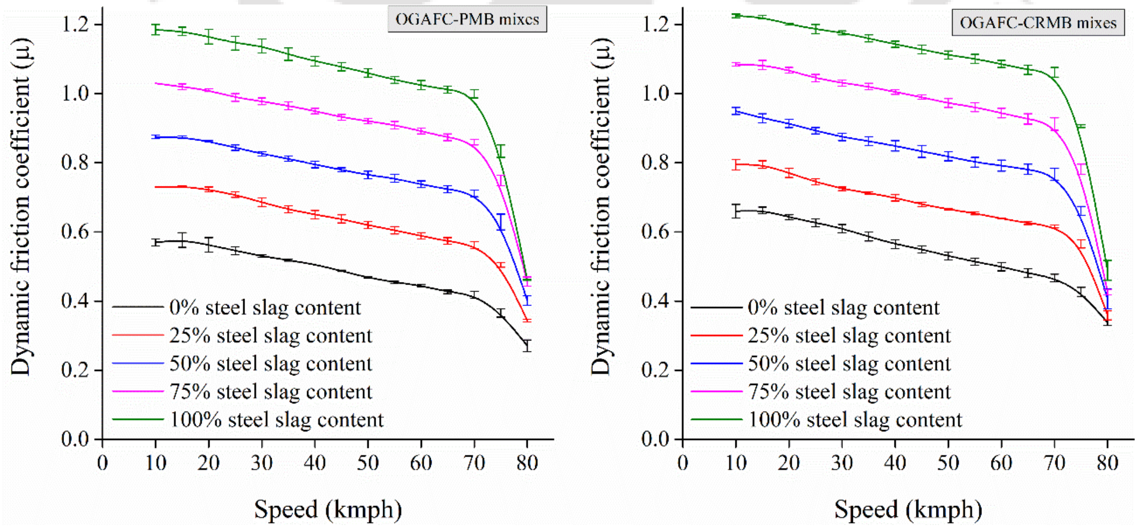


Figure 5.14: Dynamic friction coefficient values of OGAFC mixes.

The dynamic friction coefficients of steel slag incorporated OGAFC mixes increased with an increase in BOF steel slag content. The higher texture of the steel slag incorporated mixes helps break the continuous thin film of water present over the mix surface, diminishing the effect of hydroplaning and resulting in higher skid resistance. At moderate to high-speed driving environments (*i.e.*, speeds from 20 to 70 kmph), the dynamic friction coefficients were observed to increase by about 0.15 for every 25% increment in BOF steel slag replacement. The results agree with the British pendulum results. The most probable reason for the enhanced frictional characteristics is the rougher surface texture of the BOF steel slag aggregates, as seen in the FESEM micrographs (Figure 3.3). Further, friction coefficients corresponding to a slip speed of 20 kmph for OGAFC-CRMB mixes were also found to be higher than OGAFC-PMB mixes due to the higher adhesive attraction of the crumb rubber particles and probably also due to the enhancement of the microtexture of the aggregate surface when coated with crumb rubber. The results of DFT were found to show a quite similar trend to those obtained during BPN measurements.

Results of ANOVA performed on the DFT values (friction coefficients corresponding to a slip speed of 20 kmph) are listed in Table 5.4. The main effects of the two factors (SC and BT) significantly affect dynamic friction coefficients. A higher F-value for SC indicates that steel slag percentage has the highest influence on DFT characteristics of OGAFC mixes compared to BT. The two-way interaction between SC and BT was found to be not-significant.

Table 5.4: ANOVA test results of DFT test values at 5% significance level.

Factors	*Degree of freedom*	*F-value*	*P-value*	*Significance*
Slag content (SC)	4	608.117	<0.001	Yes
Binder type (BT)	1	94.206	<0.001	Yes
SC:BT	4	0.544	0.705	No

In the DFT measurement, the time was recorded for the rubber slider to come to a halt (referred here as deceleration time) after commencing the measurement from an initial velocity of 80 kmph. The deceleration time could provide an indirect measure of the braking time required by a vehicle moving at a speed of 80 kmph to come to a stop and has also been used by other researchers (Tan *et al.*, 2019) to get an indirect measure of the frictional characteristic of a road surface. Figure 5.15 shows the results of deceleration time for the OGAFC mixes. A lower deceleration time is desirable as it indicates a better skid resisting surface. The deceleration time was found to decrease with an increase in the BOF steel slag content. Thus, an OGAFC mix incorporating BOF steel slag aggregates will offer a comparatively safer manoeuvrability/stoppage of vehicles, which is an important aspect for vehicle safety especially under wet weather conditions.

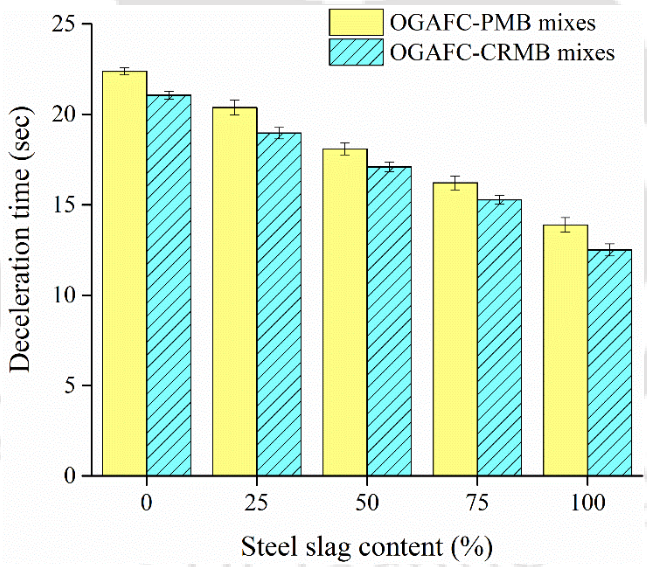


Figure 5.15: Comparison of deceleration time of OGAFC mixes.

5.3.4 *Effect of polished aggregates on BPN and MTD values of OGAFC mixes*

To examine the effect of polishing of stone aggregates on the frictional properties of OGAFC mixes at laboratory scale, both natural stone aggregate and BOF steel slag were subjected to polishing action in a Los Angeles abrasion machine for 0, 1000, and 2000 cycles without accommodating any steel charge. OGAFC specimens were prepared using polished aggregates and then evaluated for their frictional characteristics, using the British pendulum tester and the sand patch test method. Figure 5.16 shows photographs of natural aggregates and BOF steel slag aggregates after being subjected to 0, 1000 and 2000 cycles of abrasion. The surface features of the aggregates underwent substantial macroscopic changes after being subjected to 1000 and 2000 Los Angeles (LA) revolutions. Since the aggregates were subjected to continuous attrition against each other and with the Los Angeles abrasion drum's inner wall, the abraded aggregates showed a higher sphericity, roundness, and lower angularity than the virgin non-abraded aggregates.

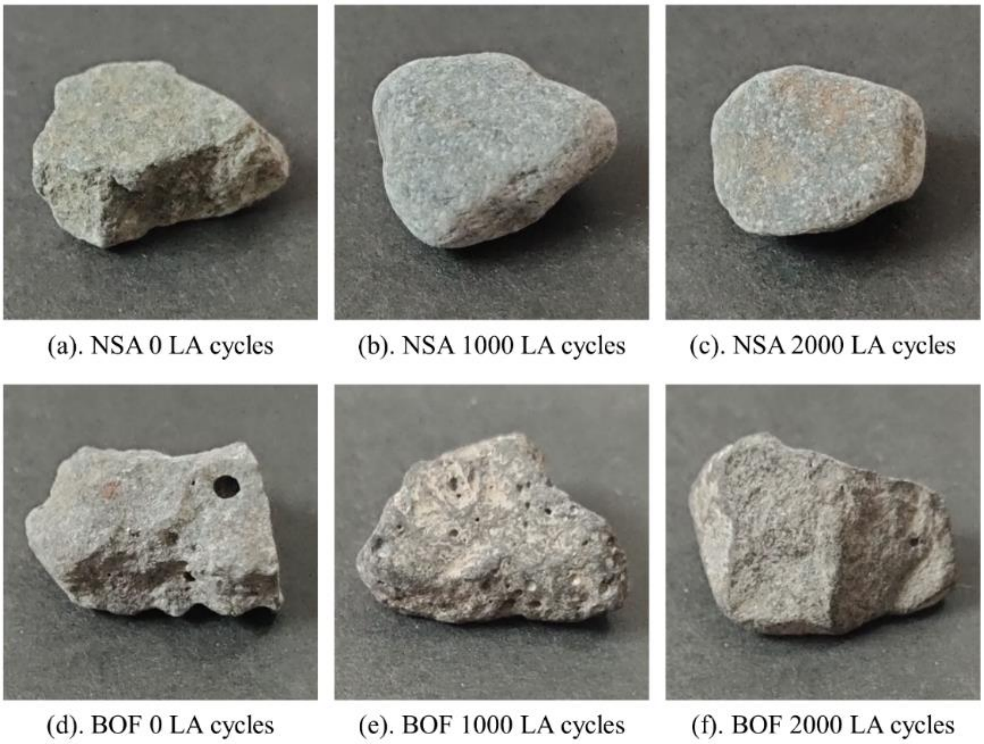


Figure 5.16: Macroscopic surface morphology of aggregates subjected to 0, 1000 and 2000 cycles of LA abrasion. (a). NSA 0 LA cycles, (b). NSA 1000 LA cycles, (c). NSA 2000 LA cycles, (d). BOF 0 LA cycles, (e). BOF 1000 LA cycles, and (f). BOF 2000 LA cycles.

The natural and BOF steel slag aggregates before and after the abrasion cycles were also checked and compared for particle index values *(I_a)* determined in accordance with

ASTM D3398 (2006). The corresponding results are presented in Table 5.5. A higher I_a value indicates a more angular aggregate. The indices of BOF steel slag were found higher than the natural stone aggregates. I_a values decreased with an increase in the abrasion cycle; however, the percentage decrease with the abrasion cycle was not the same for both the aggregates. After 1000 cycles of abrasion, I_a of natural stone decreased by about 19% while that of BOF steel slag by about 2–3% only. Similarly, after 2000 cycles of abrasion, the I_a of the natural stone aggregate reduced by about 25%, whereas for BOF steel slag, the reduction was about 6–8%. From the visible and quantitative investigation of the abraded aggregates in terms of I_a, it can be stated that BOF steel slag can retain the original texture to a greater extent compared to natural stone aggregate, and this can be credited to higher abrasion resistance and inherent higher hardness due to the presence of a higher concentration of minerals such as iron oxides (as reported in Table 3.3) compared to natural stone aggregates.

Table 5.5: Particle index values of aggregates subjected to 0, 1000 and 2000 cycles of LA abrasion.

Number of cycles	*Natural stone aggregate*	*BOF steel slag*
0	12.6	15.9
1000	10.2	15.6
2000	9.6	14.9

OGAFC slab specimens corresponding to the five steel slag contents with both binders were fabricated with the polished aggregates and evaluated for frictional and surface texture characteristics. Figures 5.17 and 5.18 respectively illustrate the variation of BPN (under wet surface condition) and MTD with aggregates subjected to 0, 1000, and 2000 abrasion cycles. Both BPN and MTD values of OGAFC mixtures showed the following trend: BPN and MTD at 0 cycles of abrasion > 1000 cycles of abrasion > 2000 cycles of abrasion.

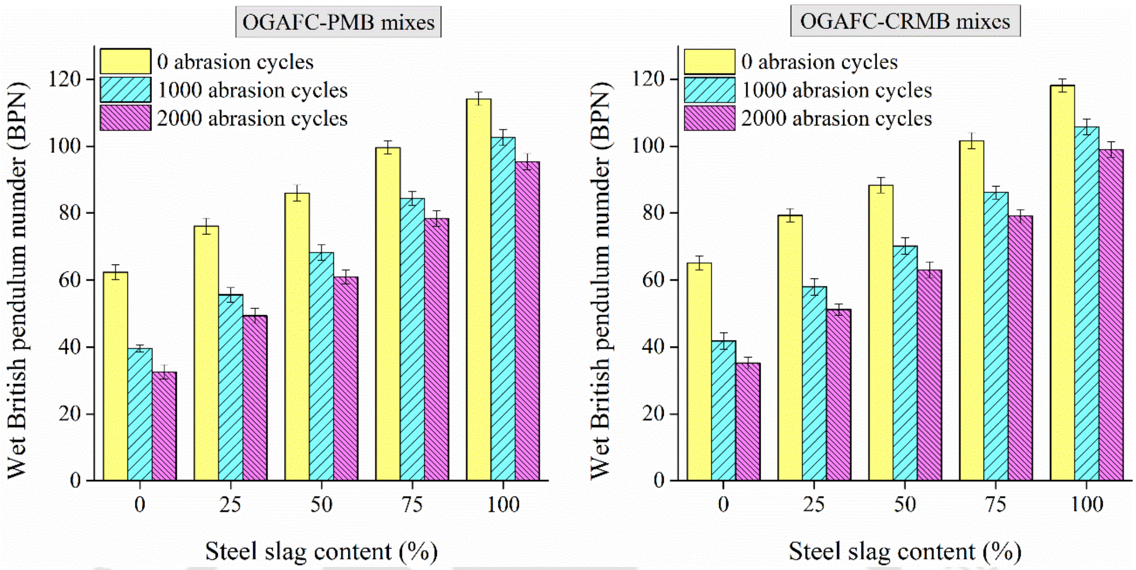


Figure 5.17: Wet BPN values of OGAFC mixtures with polished aggregates.

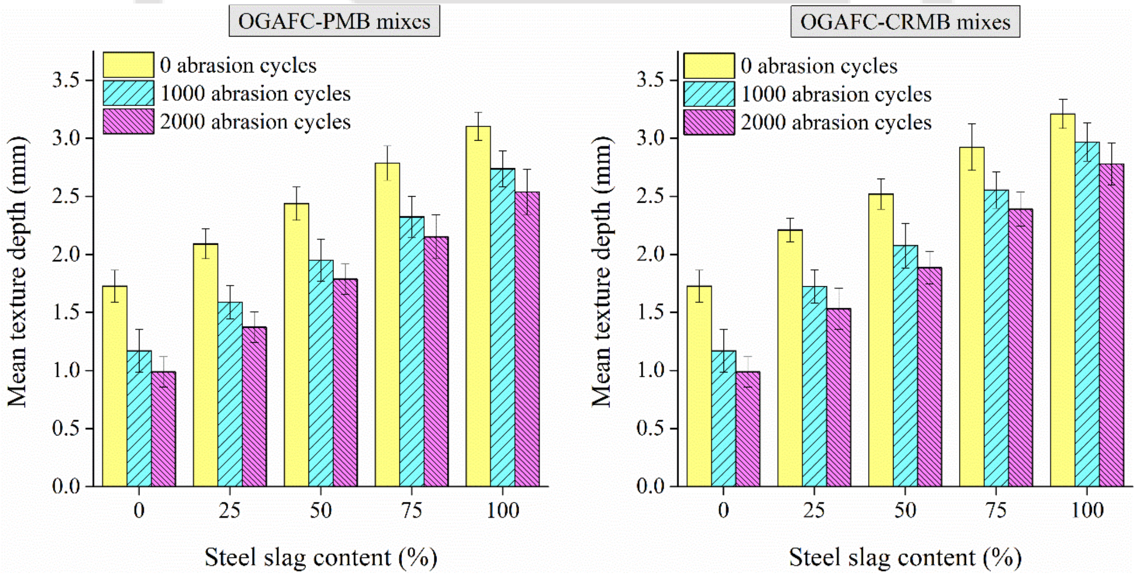


Figure 5.18: MTD values of OGAFC mixtures with polished aggregates.

A decrease in the angularity and the surface roughness/texture decreased the MTD and BPN values of the OGAFC mixes, respectively. For the control OGAFC mixes (with 0% steel slag content), the variation in BPN and MTD with abrasion cycles was found to be the maximum. BPN values decreased by about 23 units and 29 units after 1000 and 2000 cycles of abrasion. For OGAFC mixes with 100% steel slag, this decrease was only about 14 and 21 BPN units corresponding to 1000 and 2000 abrasion cycles, respectively. A similar trend was also observed in the MTD values for the different OGAFC mixtures.

Table 5.6 presents the ANOVA results of the polished OGAFC mixes for wet BPN and MTD values. Three factors were considered: slag content (SC); binder type (BT); and polishing cycle (PC). For both BPN and MTD values, the three factors were found significant. Two-way interaction for SC:PC was found to be significant for wet BPN results. This significance in the interaction is expected as the difference in the BPN values after both 1000 and 2000 polishing cycles was not the same with the variation in the steel slag content. The difference was observed to be highest for OGAFC mixtures with 0% BOF steel slag content, and the difference decreased with the increase in the BOF slag content. This is due to the intrinsic characteristic of the steel slag aggregates to retain more of the virgin shape and texture than the natural aggregates. However, no two-way interaction was found significant in the case of MTD.

Table 5.6: ANOVA test results of BPN and MTD values of polished OGAFC mixes at 5% significance level.

Factors	*Wet BPN*	*MTD*
	p-value, S/NS	*p-value, S/NS*
Slag content (SC)	<0.001, S	<0.001, S
Binder type (BT)	<0.001, S	0.014, S
Polishing cycle (PC)	<0.001, S	<0.001, S
SC:BT	0.123, NS	0.996, NS
SC:PC	<0.001, S	0.791, NS
BT:PC	0.863, NS	0.967, NS

Note: 'S' – significant effect; 'NS' – non-significant effect

5.4 Summary

This chapter presented the results of functionality of the BOF steel slag incorporated OGAFC mixes in terms of drainability (permeability), clogging potential, and frictional properties. The drainability and clogging behaviour of OGAFC mixes was studied by substituting BOF steel slag as 0% (control mix), 25%, 50%, 75%, and 100% of the coarse natural aggregates with the two types of modified binders. The initial porosity and permeability of the mixes were found to decrease with an increase in BOF steel slag content, and OGAFC-CRMB mixes reported a slightly higher permeability and porosity compared to OGAFC-PMB mixes. Three different clogging mechanisms were considered: particle-related clogging (due to intrusion of foreign material such as sand); stripping-related clogging (due to the deposition of stripped off bitumen-fines mortar), and deformation-related clogging (reduced drainability due to permanent deformation). Comparisons were made to investigate the effect of BOF steel slag on the clogging potential of OGAFC mixes. Particle-related clogging results indicated that the presence of boundary features in the surface of the BOF steel slag reduced the clogging potential of OGAFC mixes. The stripping and deformation-related clogging results showed that BOF steel slag incorporated OGAFC mixes exhibited lower clogging potential and better performance in resisting clogging due to stripping and permanent deformation, respectively.

Friction properties of OGAFC mixtures play an essential role in ensuring traffic safety, especially under wet weather conditions. The friction characteristics of BOF steel slag aggregate incorporated OGAFC mixes were evaluated through the sand patch test, British pendulum test, and dynamic friction test. Nine replicates of OGAFC mixes (square slab specimens) were fabricated at each five percentage replacements (0, 25, 50, 75, and 100%) of the coarse natural aggregate fraction by BOF steel slag aggregates. The effect of modified binder type (polymer and crumb rubber modified) on the frictional characteristics of OGAFC mixes was also examined. Multiple friction performance aspects were studied: (1) effect of surface condition (dry, wet, and ponding) on the measured friction coefficient; (2) separate evaluation of adhesion and hysteresis friction components; (3) variation of friction coefficient with varying slip speeds, and (4) friction performance later in the OGAFC service life using artificially polished aggregates. Results revealed that the use of steel slags in OGAFC mixes considerably enhanced the frictional characteristics and skid resistance of the mixes. Frictional resistance of the mixes was found to increase with an increase in steel slag content. OGAFC mixes comprising polished steel slag aggregates also showed promising results with the increment in BOF steel slag content.

Chapter 6: Assessment of Durability of OGAFC Mixes with BOF Steel Slag Aggregates

6.1 General

In this study, the resistance of OGAFC mixes to the effects of moisture and binder draindown is included under the term 'durability'. Researchers and practitioners have reported binder draindown and moisture damage as common concerns with OGAFC mixes. OGAFC mixes have high binder content and low fines and are therefore prone to binder draindown during production, storage, haulage, and compaction and also during the service life. High temperatures during production, storage, hauling, and compaction of OGAFC mixes may cause the downward migration of the asphalt binder in the mix. This draindown is referred as production stage draindown in this study and is checked during mix design as per ASTM D6390 (2011) specifications. Long-term binder draindown is another form of draindown observed in OGAFC mixes and is usually reported after five to six years of the service life (Ferguson, 2005). Long-term binder draindown may lead to an OGAFC mix with a variable binder content across the depth of the course. Long-term binder draindown and ageing of binder during the service life of OGAFC mixes also make them susceptible to challenges related to reduced permeability/clogging and increased chances of ravelling.

For assessing the long-term binder draindown potential of the OGAFC mixes, compacted specimens were fabricated at five steel slag replacement percentages (0, 25, 50, 75, and 100%) with the two modified binders (PMB and CRMB) and were subjected to two different long-term binder draindown protocols. To evaluate the effect of long-term binder draindown on the durability of OGAFC mixes, compacted OGAFC specimens were subjected to the selected long-term binder draindown protocol and then evaluated for moisture susceptibility, ravelling resistance, and permanent deformation resistance. The test results of the long-term binder draindown conditioned specimens were compared with the unconditioned specimens (control mixes) to evaluate the durability of these mixes.

OGAFC mixes are exposed to water for longer durations and therefore their resistance towards moisture damage needs to be ensured for an adequate performance during their service life. Moisture damage can cause loss in the strength and increased chances for ravelling. In this phase of the study, the OGAFC mixes were evaluated in terms of performance against moisture induced damage and binder draindown. For the moisture susceptibility evaluation, OGAFC mixes prepared with five varying BOF steel slag contents and PMB and CRMB binders were subjected to moisture conditioning under two different pH environments — neutral (pH 7.0) and acidic (pH 4.9). Most of the moisture resistance tests make use of distilled/neutral water for conditioning which has a pH of about 7.0. Two different moisture conditioning environments were selected in this study to understand the effect of acid rain/acidic water on the moisture damage resistance of the OGAFC mixes. OGAFC mixes were evaluated for stripping potential, split strength, ravelling potential, and permeability properties through the modified boiling water test, modified Lottman test, wet abrasion loss test, and permeability test, respectively. The tests were conducted under neutral and acidic conditioning environments and the results were compared to understand the effect of the conditioning environment on the moisture susceptibility of the mixes.

This chapter discusses in details the test results of the moisture susceptibility and long-term binder draindown evaluations of the OGAFC mixes.

6.2 Assessment of moisture susceptibility of OGAFC mixes with BOF steel slag

6.2.1 Modified boiling water test results

The modified boiling water test was conducted on loose mixtures prepared at different BOF steel slag contents with PMB and CRMB binders. The loose mixes were kept under boiling water with two different pH (7.0 and 4.9) for 30 minutes as per the ASTM D3625 (2012) specifications with some modifications as described in Section 3.6.1.2 of Chapter 3. The stripping index was then evaluated as per Equation 3.14. As the degree of ionisation increases with an increase in water temperature, the amount of hydrogen ions (H+) active in water are therefore expected to increase with temperature, and the actual pH may be somewhat lower than that reported. The test was repeated three times for each mix type and the environmental condition (neutral and acidic), and an average of the three test values was reported as the stripping index value. Results of the stripping index derived from the modified boiling water test on OGAFC-PMB and OGAFC-CRMB mixtures are shown in Table 6.1. The stripping index is an indicator of the extent of binder stripped off from the surface of aggregates because of immersion of the mix in boiling water, and thus helps to quantify the loss of adhesion between aggregates and the binder.

Table 6.1: Results of modified boiling water test of OGAFC mixes.

Steel slag content (%)	*Stripping Index (%)*			
	OGAFC-PMB mixes		*OGAFC-CRMB mixes*	
	pH: 7.0	*pH: 4.9*	*pH: 7.0*	*pH: 4.9*
0	9.6	20.0	13.7	24.2
25	7.0	14.7	9.7	17.0
50	5.8	9.1	7.4	11.3
75	3.1	5.7	5.8	9.7
100	2.5	4.2	1.0	8.2

Table 6.1 shows that the stripping index increased for OGAFC-PMB and OGAFC-CRMB mixtures as the pH of the conditioning water reduced from 7.0 to 4.9. A more acidic environment leads to a greater moisture damage in the OGAFC mixtures. However, the stripping index reduced with an increase in the BOF steel slag content. For example, considering OGAFC-PMB mixtures, stripping indices of 100%-BOF-OGAFC mixture were about four to five times lower than those for the control mixture with natural aggregates. An inclusion of BOF slag as coarse aggregate in the OGAFC mixture allows the mixture to perform appreciably well against stripping. The rough particle surface of BOF steel slag aggregates with higher basicity enables the development of stronger adhesion between binder and aggregate (Kambole *et al.*, 2017). From the XRF analysis, the basicity ratios (CaO/SiO_2) for natural stone aggregate and BOF steel slag were obtained and compared. The steel slag (basicity = 3.75) showed a higher basicity than the natural stone aggregate (basicity = 0.16). A higher basicity makes aggregates hydrophobic and helps to enhance aggregate–binder adhesion and the moisture damage resistance of the resulting OGAFC mixtures. Similar findings were observed by other researchers on steel slag incorporated asphalt mixtures (Ameri *et al.*, 2013; Oluwasola *et al.*, 2015).

6.2.2 Modified Lottman test results

To conduct the Modified Lottman test the AASHTO T283 (2003) specifications were followed considering the additional recommendations of ASTM D7064 (2013) for the same. While conditioning the OGAFC mixes, specimens were subjected to a vacuum saturation of 87.8 kPa for 10 minutes, followed by a freezing cycle of 16 hours at –18°C. During the freezing cycle, it was ensured that the sample remained submerged in water. The freezing cycle was followed by a 24 hours thawing cycle at 60°C. A total of five consecutive freeze and thaw cycles were performed as per ASTM D7064 (2013) guidelines instead of usual one freeze-thaw cycle for dense graded wearing course mixtures, following which the sample was evaluated for indirect tensile strength (ITS) at 25°C.

The results of indirect tensile strength (ITS) and tensile strength ratio (TSR) of OGAFC mixtures with PMB and CRMB binders measured under unconditioned and conditioned (pH environments of 7.0 and 4.9) environments are presented in Figure 6.1. The conditioned ITS was evaluated after subjecting the OGAFC mixtures to five freeze–thaw cycles under the two different pH environments (neutral and acidic). It was observed that both unconditioned and conditioned ITS values increased with an increase in the BOF steel slag content, clarifying that there was an increase in mix strength and cohesion on the incorporation of BOF slag as coarse aggregate. There was also a clear evidence that higher BOF steel slag contents help to attenuate the decrease in ITS after conditioning. For example, considering OGAFC-PMB mixtures, the conditioned ITS for control mix reduced by 23% and 35% at pH values of 7.0 and 4.9, respectively, compared with the reductions of 7% and 10% for the mix with 100% BOF slag as coarse aggregate. A rough and porous surface texture along with higher basicity (CaO/SiO_2) ratio of BOF steel slag helps to enhance the moisture damage resistance of the OGAFC mixture with BOF steel slag aggregates (Xie *et al.*, 2012). Visual examination of the fractured surfaces of all mixtures (Figure 6.2) did not reveal any notable evidence of stripping.

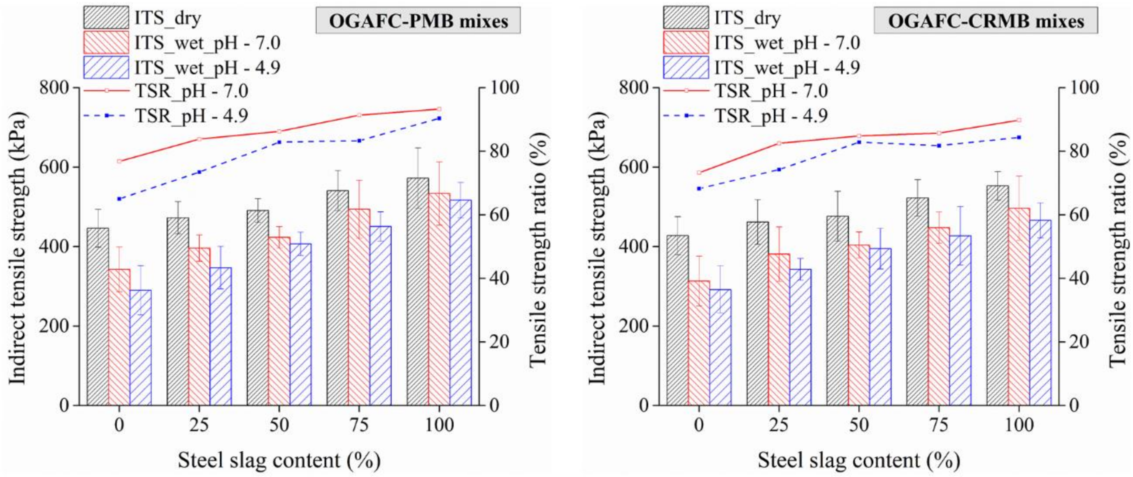


Figure 6.1: Indirect tensile strength (ITS) test results of OGAFC mixes.

Figure 6.1 also presents the results of TSR for OGAFC-PMB and OGAFC-CRMB mixtures corresponding to the two pH environments, evaluated after five freeze–thaw cycles. A minimum TSR of 80% has been specified as the acceptance criterion for OGAFC mixtures by ASTM D7064 (2013). The TSR values of control mix with natural aggregates was marginally less than the stated requirement of 80%, with both PMB and CRMB binders. OGAFC mixtures containing BOF slag satisfied the acceptance criterion under neutral (pH=7.0) environment at all slag replacement percentages whereas the mixtures with 50%, 75%, and 100% BOF steel slag substitution percentages met the criterion under acidic (pH=4.9) environment. The results indicated that TSR increased with an increase in BOF steel slag content in the mixture, indicating enhanced resistance of the OGAFC mixtures at higher slag contents. The results indicated that BOF slag incorporated OGAFC mixtures provided higher resistance against the effects of moisture under neutral as well as acidic environments.

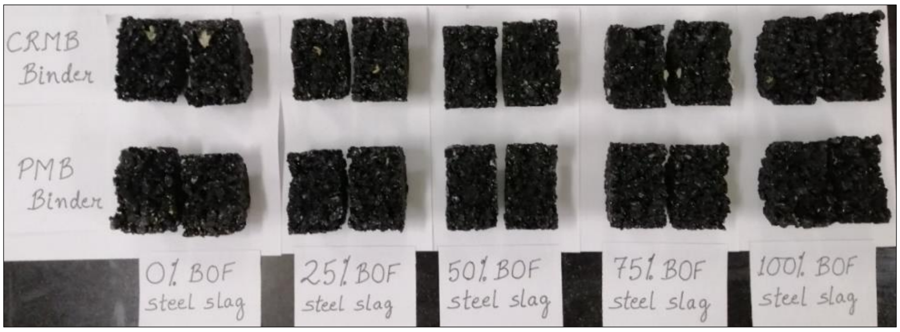


Figure 6.2: Fractured surfaces of specimens from indirect tensile strength tests (conditioned under acidic environment).

6.2.3 Wet abrasion loss test results

Moisture conditioning may lead to the stripping of asphalt film from the aggregate surface and thus may reduce the adhesion between the asphalt binder and aggregates and the cohesion of the mix, and therefore may can cause ravelling. OGAFC specimens subjected to moisture conditioning (five freeze-thaw cycles) under both neutral and acidic pH environments were subjected to Cantabro abrasion loss test in a Los Angeles machine for 300 revolutions at a speed of 30 rpm without any steel charge to determine the wet abrasion loss (WAL).

Figure 6.3 presents the variation WAL results of OGAFC-PMB and OGAFC-CRMB mixtures under unconditioned and conditioned (pH=7.0 and pH=4.9) states. Increase in WAL after conditioning under both neutral and acidic environments can be observed from Figure 6.3. After conditioning in an acidic environment, the abrasion loss was higher compared to the conditioning under a neutral environment. This was likely because acidic conditions favour dissolution of surface layers of carbonates presents on the aggregate surface, which results in an aggregate–asphalt interface with low adhesive strength (Jamieson *et al.*, 1995; Caro *et al.*, 2008). From Figure 6.3, it is also observed that WAL (conditioned and unconditioned) percentage values decreased with an increase in the

BOF steel slag content. OGAFC mixtures with 100% BOF steel slag content demonstrate the lowest abrasion loss under both pH environments of conditioning.

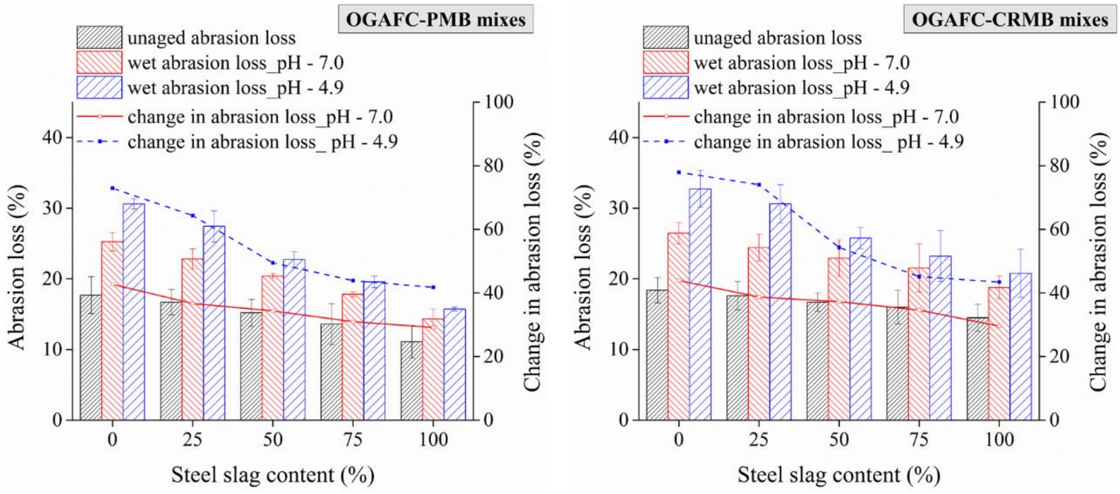


Figure 6.3: Wet abrasion loss (WAL) test results of OGAFC mixes.

Figure 6.3 also shows the line plots of the percent increase in WAL values compared to the standard abrasion loss under unaged state, for each OGAFC mix. The relative increase in abrasion loss on conditioning under neutral and acidic environments reduced with an increase in the BOF slag content. For OGAFC-PMB mixture, the abrasion loss for control mixture (0% BOF steel slag) in unconditioned state was 17.7%, which increased to 30.6% after moisture conditioning in an acidic environment. On the other hand, abrasion loss for 100% BOF-OGAFC mixture was 11.1% in unconditioned state and 15.7% after conditioning in an acidic environment. The results indicate a significant effect of different rainwater environments on moisture sensitivity characteristics of OGAFC mixes along with beneficial effect of BOF slag as coarse aggregate toward retaining the asphalt binder coating and cohesive strength of mix under adverse moisture and acidic environments.

6.2.4 Effect of moisture conditioning on permeability characteristics

Permeability is an important functional characteristic of an OGAFC mixture. Longer exposure to moisture may cause damage to the cohesive strength of OGAFC mixes and may affect their permeability/drainage characteristics. Permeability values of OGAFC specimens were determined before and after subjecting the mixtures to five freeze–thaw cycles, as per AASHTO T283 (2003) and ASTM D7064 (2013) specifications, under both pH environments. It was hypothesised that on being subjected to the effects of moisture, there may be some stripping off of the asphalt mastic from the aggregates, which may clog the air voids to some extent leading to a reduction in the permeability. At the same time, it is also possible that the formation of ice in the freezing process may cause some expansion/damage in the aggregate structure/aggregate-asphalt matrix and therefore may lead to increase in permeability. ASTM D7064 (2013) specifies a minimum permeability of 100 m/day to ensure adequate drainability of OGAFC mixtures.

Results of permeability on the conditioned OGAFC-PMB and OGAFC-CRMB specimens are shown in Figure 6.4. It is observed that there was indeed a slight increase in permeability of OGAFC mixtures after conditioning for five freeze–thaw cycles under neutral environment, which may be attributed to the loss of cohesion and pushing of aggregates apart in the mix during the freezing action when the specimen is continuously kept submerged in water. Studies in the past have also reported increase in the porosity of OGAFC mixtures after being subjected to freeze-thaw cycles due to freezing (and consequent expansion) of the conditioning water (Chen *et al.*, 2018b). This increase in permeability however reduced with replacement of natural stone aggregate with BOF steel slag, indicating higher asphalt binder adhesion and cohesion of the mix with steel slag aggregates.

Permeability of specimens subjected to five freeze–thaw cycles under an acidic environment (pH=4.9) was found lower than that for neutral environment (pH=7.0). This was likely because of clogging up of the pores of the OGAFC mixtures by the larger quantities of stripped off material in the case of the acidic environment. Higher stripping and adhesion loss thus occurred in OGAFC mixtures when being conditioned in an acidic/harsher environment. The OGAFC mixes under standard pH conditions (pH=7.0) showed a reduction in the percentage change in the permeability values because of moisture conditioning (five freeze–thaw cycles) with an increase in the slag content. In the case of acidic environment (pH=4.9), no definite trend was observed. Furthermore, all OGAFC mixtures showed permeability well above the minimum requirement of 100 m/day, even after moisture conditioning under different environments.

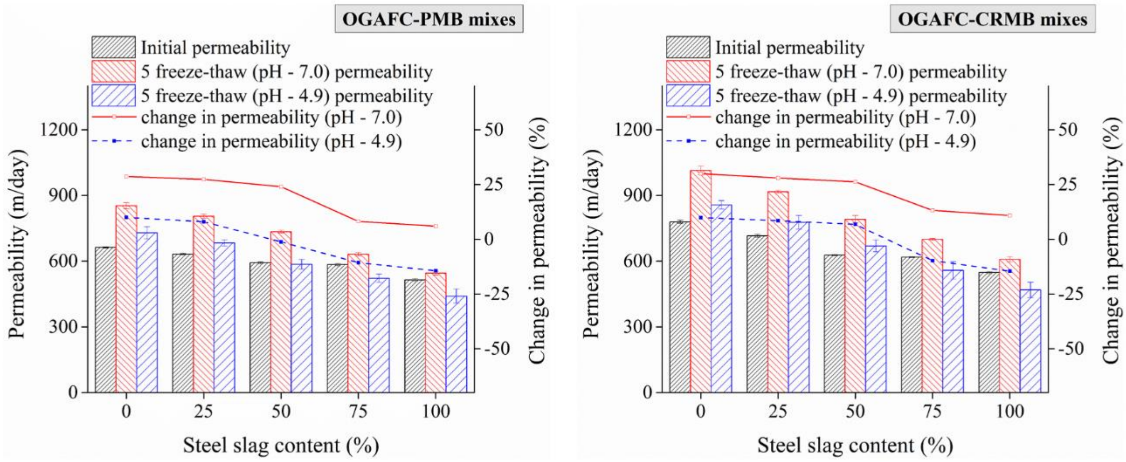


Figure 6.4: Permeability characteristics of OGAFC mixes before and after moisture conditioning.

6.3 Statistical analysis of the moisture susceptibility test results

Results of the moisture susceptibility analysis of the BOF steel slag incorporated OGAFC mixes with PMB and CRMB binders were statistically analysed through analysis of variance (ANOVA) at 5% level of significance. The main and interaction effects of three factors: [slag content (SC), binder type (BT), and environment type (EN)]; were evaluated for the following response variables: ITS, WAL, and permeability. Table 6.2 presents the results of ANOVA performed on the response variables.

Table 6.2: Analysis of variance (ANOVA) rest results for moisture susceptibility analysis at 5% significance level.

Factors	*ITS*	*WAL*	*Permeability*
	p-value, S/NS	*p-value, S/NS*	*p-value, S/NS*
Slag content (SC)	<0.001, S	<0.001, S	<0.001, S
Binder type (BT)	0.108, NS	<0.001, S	<0.001, S
Environment type (EN)	<0.001, S	<0.001, S	<0.001, S
SC:BT	0.980, NS	0.672, NS	0.762, NS
SC:EN	0.822, NS	0.612, NS	0.006, S
BT:EN	0.879, NS	0.091, NS	0.465, NS

Note: 'ITS' stands for 'indirect tensile strength', 'WAL' stands for 'wet abrasion loss', 'S' stands for 'significant effect' and 'NS' stands for 'non-significant effect

The main effects of the three factors (SC, BT, and EN) were found to be significant in each case with an exception of the effect of BT on ITS. The type of environment (unconditioned, neutral, or acidic) had a statistically significant effect on all three mix performance parameters evaluated after moisture conditioning. The two-way interactions (SC:BT, SC:EN, and BT:EN) were found non-significant, indicating that the effect of one factor on the response variables is independent of the level of the other factor. However, the two-way interaction EN:SC for permeability was significant, implying that permeability characteristics were influenced by both the conditioning environment and slag content.

6.4 Assessment of long-term binder draindown characteristics

High temperatures during storage, hauling, and compaction of OGAFC mixes cause the downward migration of the asphalt binder in the mix. This draindown, referred to as production-stage draindown in this study, and is usually counteracted in two ways—through the use of fibres and through the use stiffer/modified binders (Huber, 2000). In this study, both fibres (organic cellulose fibre) and modified binders (PMB and CRMB) were used to minimise the production-stage draindown. Long-term binder draindown is another form of draindown usually observed in OGAFC mixes after five to six years of the service life (Ferguson, 2005), under which the binder migrates downward to the comparatively interior/lower section of the OGAFC layer, where it cools and clogs the pores, resulting in a lower drainability/permeability and ravelling resistance of the mix.

The long-term draindown, discussed in detail in Section 3.6.2, was initially simulated by measuring the permeability of compacted OGAFC mixes subjected to 42-days conditioning at a temperature of 60°C at 7 day interval. Figure 6.5 shows the permeability results that indicate an increase in permeability up to 14-days of conditioning after which the permeability attained a nearly constant value. This observation is contrary to what one would expect in a long-term draindown phenomenon. However, similar finding was also reported in a previous study that evaluated OGAFC long-term draindown (Wurst and Putman, 2013), and the minor increment in the permeability can be attributed to oxidation of volatiles present in the modified binders when subjected to conditioning. The volatilisation likely reduces the binder film thickness thereby slightly increasing the void space.

The increase in the permeability values after 14-days conditioning was not uniform for both binder types used in the study. The average percentage rise in permeability was about 20% and 13% for OGAFC mixes fabricated with PMB and CRMB binders, respectively. The lower rise in permeability values of mixes fabricated with CRMB binders can be attributed to the fact that the CRMB binder used for this study comprised of a higher content of crumb rubber (12-15%) compared to a lower content of elastomeric modifier (3-4%) present in the PMB binder, implying that the percentage of neat bitumen comprising the volatile materials was higher for PMB binders. The loss in volatile constituents results in a decrease in the asphalt film thickness thereby slightly increasing the permeability. The increase in the porosity values with conditioning at 60°C was ascertained through the porosity test results (plotted on secondary *y*-axis of Figure 6.6) which indicates an average percentage increment of about 8.3% and 5.5% in the initial porosity of OGAFC mixes corresponding to PMB and CRMB binders respectively when subjected to conditioning at 60°C for a duration of 42 days. An increase in steel slag content also resulted in a decrease in permeability of the OGAFC mixes and the finding agrees with the results of porosity. Similar trends with varying steel slag content were also reported in another study that used electric-arc furnace steel slag aggregates and evaluated the permeability without using any long-term binder draindown protocol (Pattanaik *et al.*, 2018a).

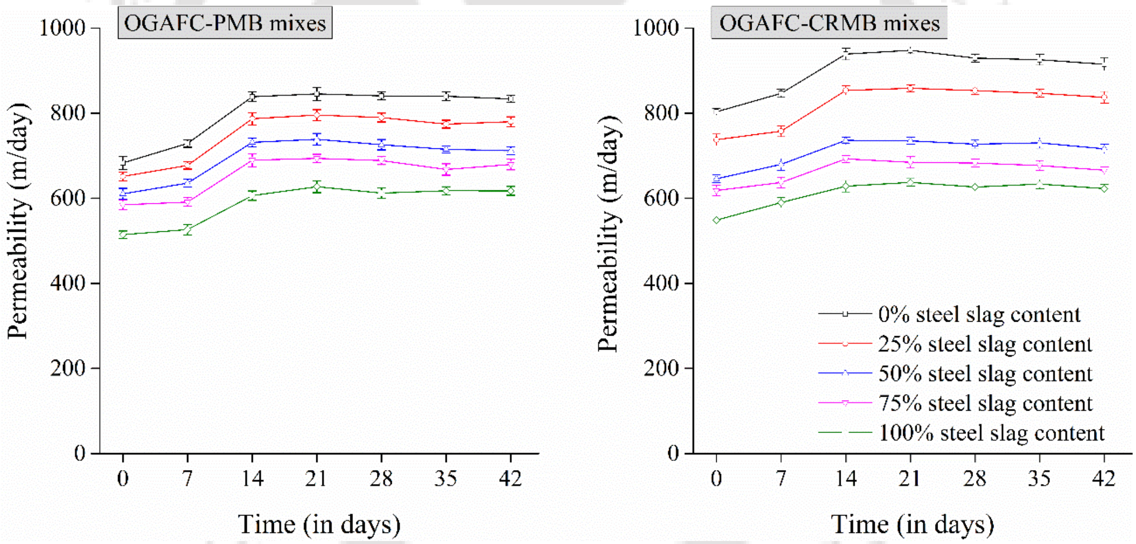


Figure 6.5: Variation of permeability of OGAFC mixes subjected to aging at 60°C.

The expected long-term binder draindown was not well captured through conditioning at 60°C for 42 days; however, this phenomenon has been observed in the field during the life of the OGAFC mixes (Ferguson, 2005; Putman and Lyons, 2015). Therefore, conditioning at a different temperature and time was explored. A review of conditioning procedures to simulate long-term ageing of asphalt mixtures revealed that ageing temperature ranging from 60 to 163°C and ageing duration ranging from 5 hours to 1000 hours have been used (Van der Bergh, 2011). The alternative approach used in this study was to condition the compacted OGAFC mixes at 160°C (a temperature close to the compaction temperature of the mixes) to have a shorter conditioning duration feasible for laboratory evaluation of long-term binder draindown. To prevent any possible specimen distortion at high temperature, the OGAFC specimens were kept confined in Marshall moulds attached with a base plate during the conditioning process. To further check the conditioning duration/protocol, permeability was measured on specimens at every 2 hours interval. Before the permeability measurement, the specimens were first allowed to cool to room temperature. Figure 6.6 shows the decrease in permeability and porosity observed for OGAFC specimens at different steel slag contents for the conditioning period of 8 hours at 160°C as compared to the one for 42 days at 60°C and the unconditioned specimens.

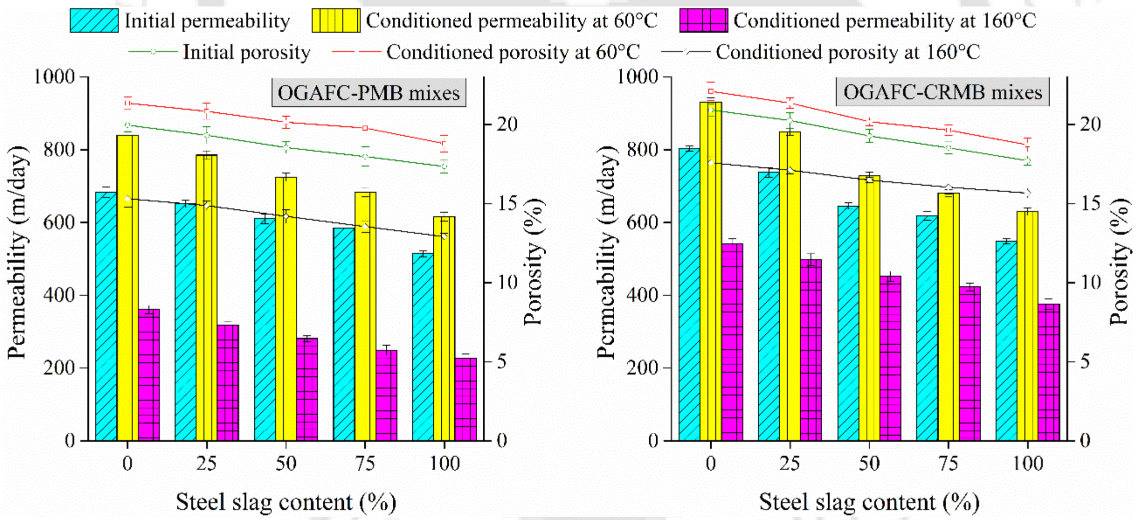


Figure 6.6: Comparison of permeability and porosity values of unconditioned and conditioned (60°C and 160°C) OGAFC mixes.

The permeability values observed for OGAFC specimens at every 2 hours interval under the new conditioning protocol at 160°C for both binders at different slag contents are presented in Figure 6.7. It is seen that permeability of OGAFC mixes now showed a reduction with the conditioning duration and a steady value was attained after 8 hours of conditioning. It may be argued that the selected protocol for long-term draindown simulation (8 hours at 160°C) seems rigorous and will definitely cause the binder draindown through the mix specimen. However, an average drop of about 50% and 30% in the permeability of OGAFC-PMB and OGAFC-CRMB mixes is observed, respectively, compared to the initial permeability at 0 hour. These reductions are close to the reductions in permeability of 31.3–54.5% reported by Lyons and Putman (Lyons and Putman, 2013) where the mixtures were aged at 60°C for 56 days. Therefore, the selected long-term draindown simulation procedure is able to yield similar conditions in OGAFC permeability determination in a shorter time. Furthermore, use of a procedure that assures long-term draindown would be beneficial for comparison of the draindown characteristics with different slag replacement percentages and binder types.

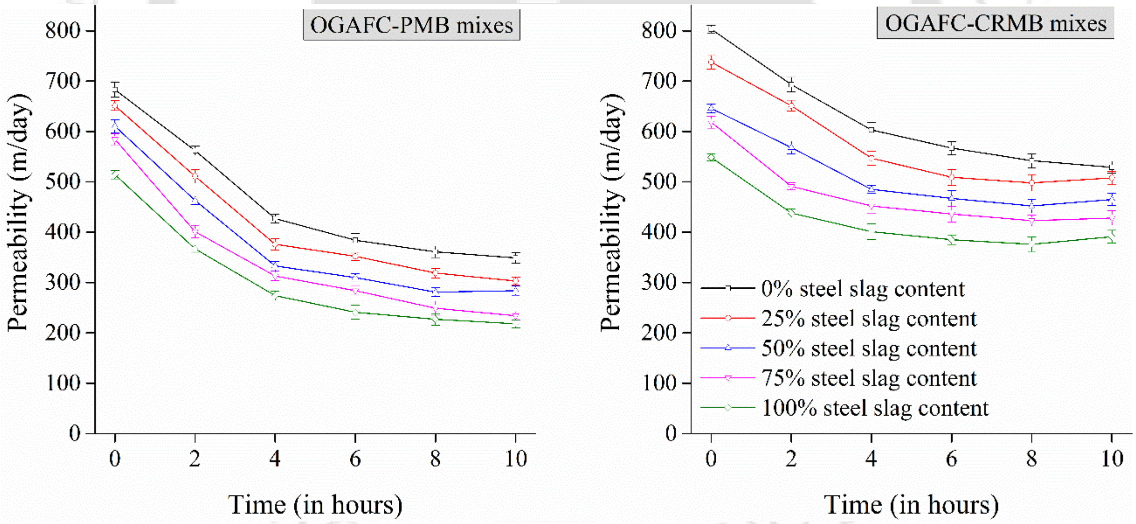


Figure 6.7: Variation of permeability values of OGAFC mixes subjected to conditioning at 160°C.

The lower drop in the permeability values of OGAFC-CRMB mixes (30% reduction) compared to OGAFC-PMB mixes (50% reduction) indicate that CRMB binder provided better resistance to long-term draindown compared to the PMB binder. On conditioning at 160°C, it is expected that binder would flow vertically downwards under the influence of gravity and obstruct the vertical flow of water when the specimen is tested for permeability. The porosity of the long-term conditioning sample is thereby expected to decrease due to the increase in asphalt content in the lower section of the compacted OGAFC specimen. The porosity results exhibited in Figure 6.6 showed a reduced value compared to the initial porosity of the OGAFC specimens. Therefore, the permeability and porosity of the conditioned samples agree with each other.

A qualitative evidence for binder migration through the sample was obtained by inspecting the Marshall baseplate used during long-term draindown conditioning. Figure 6.8(a) shows a baseplate before placing the OGAFC specimen, whereas Figures 6.8(b) – 6.8(e) show the baseplates for control and 100% slag OGAFC specimens with PMB and CRMB binders. The binder migrated down through the specimen as suggested by binder patches on the baseplate. The patches are thinner and lighter for 100% slag incorporated OGAFC when compared with the control. Furthermore, thinner patches can also be observed when CRMB binder is used than PMB binder. It should be stated that the amount of binder patch seen on the baseplate should not be construed as being representative of all binder undergoing the draindown.

(a) (b) (c) (d) (e)

Figure 6.8: Photographs showing drained binder on base plate (4-inch diameter) after long-term draindown conditioning (8 hours at 160°C): (a) base plate before testing, (b) control PMB-OGAFC, (c) 100% slag PMB-OGAFC, (d) control CRMB-OGAFC, and (e) 100% slag CRMB-OGAFC.

Table 6.3 shows the test results of analysis of variance (ANOVA) performed on permeability values obtained after conditioning at 160°C for 8 hours (to simulate long-term binder draindown) at 5% significance level. Both steel slag content and binder type are found to have a significant effect on the permeability values of the mixes. A higher F-value corresponding to binder type indicates that binder type has a greater influence on permeability values. A non-significant interaction obtained between the factors (slag content and binder type) implies that the permeability values follow a similar trend for different steel slag contents for both binders. For the subsequent OGAFC performance tests discussed further (moisture damage test, Cantabro abrasion loss test, and static creep test), the conditioning protocol (160°C for 8 hours) was used to simulate long-term draindown.

Table 6.3: ANOVA test results of long-term aged OGAFc mixes at 5% significance level.

Factors	*Degree of freedom*	*F-value*	*P-value*	*Significance*
Permeability test results at 163°C for 8-h				
Slag content (SC)	4	100.4	<0.001	Yes
Binder type (BT)	1	1048.1	<0.001	Yes
Interaction (SC:BT)	4	1.2	0.327	No
Indirect tensile strength (ITS) test results				
Slag content (SC)	4	22.4	<0.001	Yes
Binder type (BT)	1	2.8	0.102	No
Conditioning (CON)	2	25.7	<0.001	Yes
SC:BT	4	0.1	0.989	No
SC:CON	8	0.4	0.935	No
BT:CON	2	0.2	0.829	No
Cantabro abrasion loss (AL) test results				
Slag content (SC)	4	35.2	<0.001	Yes
Binder type (BT)	1	4.2	0.046	Yes
Conditioning (CON)	2	92.8	<0.001	Yes
SC:BT	4	1.4	0.263	No
SC:CON	8	3.5	0.204	No
BT:CON	2	0.6	0.560	No

6.4.1 Effect of long-term binder draindown on durability characteristics of OGAFC mixes

The effect of long-term binder draindown on the durability of OGAFC mixes was evaluated in terms of its moisture susceptibility, ravelling potential, and rutting resistance through the modified Lottman test, wet abrasion loss test, and static creep test, respectively. The obtained test results are discussed in the subsequent sections.

6.4.1.1 Moisture susceptibility

The results of modified Lottman test conducted for evaluation of moisture susceptibility of the OGAFC mixes after being subjected to long-term binder draindown are presented in Figure 6.9. Tensile split strength along the diametric section of the compacted specimens was evaluated under three environments – unconditioned, conditioned using five freeze-thaw (5FT) cycles (following the specifications stated in AASHTO T283 (2003) and ASTM D7064 (2013)), and a combination of both long-term conditioning (160°C for 8 hours) and 5FT cycles. A clear upsurge in the tensile strength can be observed with each 25% increment in the steel slag content for mixes with both binders under all three environmental conditions. This rise in the split strength of the mixes is attributed to the high strength of the steel slag aggregates and also to the enhanced stone-on-stone contact attained through its better angularity (Suresha *et al.*, 2009a; Pattanaik *et al.*, 2018b, 2019). The rise in split strength can also be due to enhanced bonding between BOF steel slag aggregates and the binders. The split strength is observed to decrease with moisture conditioning due to stripping off of the binder from the aggregate surface. The strength further decreases with subsequent long-term conditioning. As a result of the long-term conditioning, the asphalt film thickness is likely to reduce in the upper half of the compacted OGAFC specimen due to the draindown of the asphalt binder, resulting in a lower split strength.

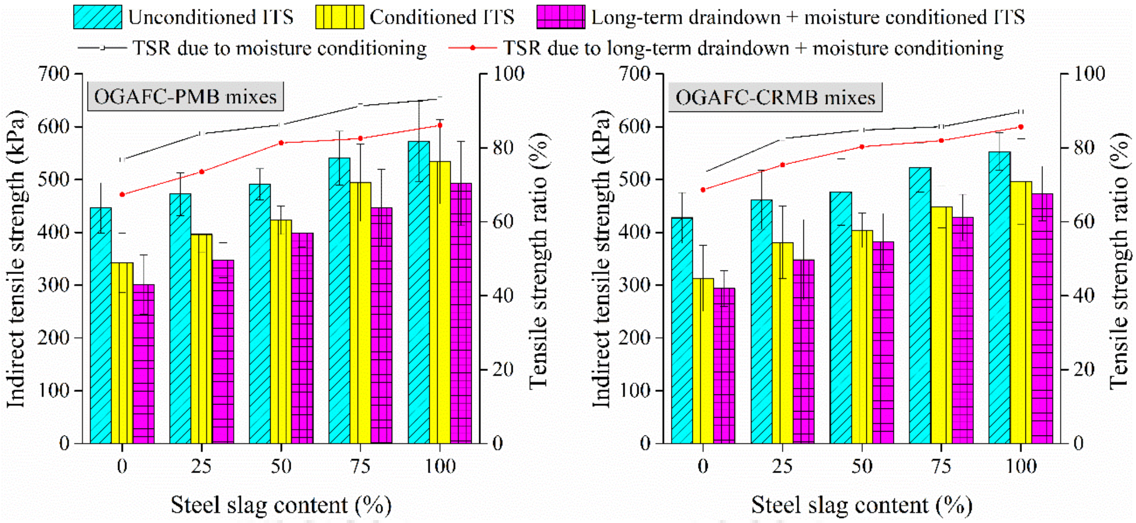


Figure 6.9: ITS and TSR test results from modified Lottman test over long-term conditioned OGAFC mixes.

Tensile strength ratio (TSR) between the conditioned and unconditioned split strength of the mixes was computed under two conditions: firstly, for the moisture conditioned set, and secondly, for the combined long-term and moisture conditioned set. In each case the split strength was compared to that of the unconditioned set. TSR results (Figure 6.9) show that the long-term conditioning of the OGAFC specimens resulted in an average drop of about 5% in the TSR values for all the combination of mixes. The percentage increase in steel slag content had a positive effect on the TSR values, which can be attributed to the improvement in the basicity (higher pH) of the aggregate mixture due to the addition of BOF steel slag. As reported in Table 3.3, steel slag aggregates are rich in CaO with a lower SiO_2 content compared to the natural stone aggregates. The higher CaO/ SiO_2 ratio makes steel slag aggregates more basic compared to the natural aggregates and hence provides better adhesive strength (Xie *et al.*, 2012; Pattanaik *et al.*, 2019). Moreover, rough surface texture and porous nature of steel slag aggregates further enhance the aggregate-binder adhesion/bond. Overall, the TSR values of the OGAFC-CRMB mixes were found to be lower than OGAFC-PMB mixes under both environments. It was observed that OGAFC mixes with steel slag content of 50% and above were only able to meet the usual standard requirement of a minimum 80% TSR.

Table 6.3 also lists the ANOVA results (α = 5.0%) performed on the spilt strength values obtained from the Modified Lottman test under different conditioning regimes. Slag content and mode of conditioning have a significant influence on the test results while binder type creates no difference in the split strength of the mixes. Both slag content and mode of conditioning have comparable F-values indicating that both the factors play almost similar roles/effect on tensile strength. Two-way interactions are non-significant indicating that indirect tensile strength values follow a similar trend for all three possible interactions.

6.4.2 Ravelling potential

The ravelling potential of OGAFC specimens was evaluated through the Cantabro abrasion loss test and the results are shown in Figure 6.10. Two sets of three OGAFC specimens were fabricated with both binder types for this test. Both sets of specimens were subjected to the conditioning of 160°C for 8 hours to stimulate the long-term binder draindown. One set of specimens was further subjected to five freeze-thaw cycles of moisture conditioning as discussed in the Modified Lottman test method. In this way, the test provided a measure of ravelling resistance under combined effect of long-term draindown and moisture damage. Finally, the results were compared with the abrasion loss of the unaged OGAFC specimens obtained during the mix design.

Ravelling is expected to occur either due to adhesive failure at the aggregate asphalt interface or due to cohesive failure within the asphalt film. Figure 6.10 shows ravelling results of OGAFC mixes under all the three conditions (unconditioned, subjected to long-term draindown conditioning, and subjected to long-term draindown and moisture conditioning). When the specimens are conditioned under 160°C, an increase in abrasion loss was observed for all the mixes, which is attributed to the draindown of bitumen when subjected to long-term draindown conditioning, thus resulting in a thinner asphalt film thickness. A thin asphalt film is also expected to enhance the cohesive failure component of ravelling thereby resulting in a higher degree of disintegration in the Cantabro abrasion loss test. The abrasion loss further increased when the effect of moisture conditioning was added to the effect of long-term draindown. An increment in steel slag content resulted in a decrease in abrasion loss. This is attributed to a better bond between the rough surface textured steel slag aggregates and the asphalt binder at the interface that tends to minimise the adhesive failure component of ravelling.

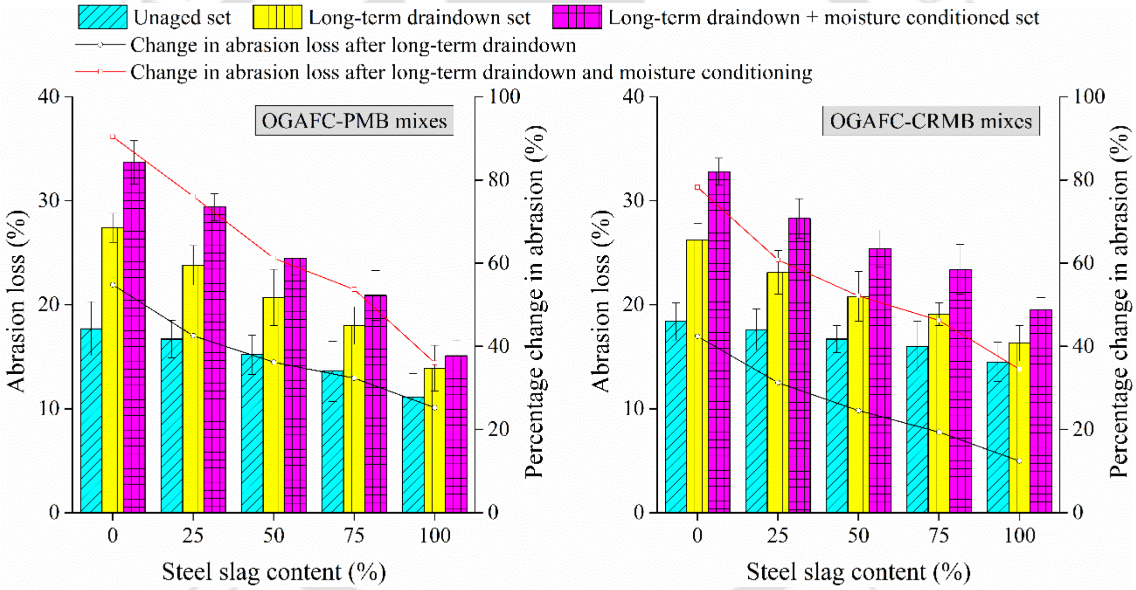


Figure 6.10: Raveling results from Cantabro abrasion loss test over long-term conditioned OGAFC mixes.

For the unaged/ unconditioned specimen set, OGAFC-PMB mixes showed a better resistance to ravelling compared to OGAFC-CRMB specimens. However, when the abrasion loss results of long-term conditioned set of specimens are considered, it was seen that OGAFC-CRMB mixes showed a lower abrasion loss than OGAFC-PMB mixes. The enhanced performance of long-term conditioned OGAFC-CRMB mixes to abrasion loss is due to the better resistance offered by the OGAFC-CRMB mixes to long-term binder draindown. The results are also in agreement with the permeability results observed in the earlier sections. However, when the long-term conditioned OGAFC specimens were further moisture conditioned through 5FT cycles, the abrasion loss of the CRMB mixes were again found to be higher than the PMB mixes. OGAFC-PMB mixes showed better resistance to moisture induced damages compared to OGAFC-CRMB mixes. With the exception of the control mixes (with 0% steel slag content), all other OGAFC specimens showed abrasion loss below the maximum standard permissible limit of 30%. However, it is to be considered that this permissible limit is for Cantabro abrasion loss for specimens tested after ageing only at 60°C for seven days as per ASTM D7064 (2013).

From the results presented in Figure 6.10, it is observed that for long-term draindown conditioned set of samples, the abrasion loss of the control mix increased by about 50% and 40% for PMB and CRMB mixes respectively; while for mixes with 100% steel slag content, an increase of about 15% and 12% was found. An increase in steel slag content therefore reduces the percentage change in abrasion loss under both environmental conditions. For the mixes subjected to both long-term draindown and moisture conditioning, percentage increase in abrasion loss for the control set of specimens with PMB and CRMB binders were 90% and 75% respectively. These values were found to decrease by 35% with both binders when 100% steel slag is used. The use of steel slag in OGAFC mixes thus provided better resistance to the combined action of ravelling, long-term draindown, and moisture-induced damage.

Table 6.3 also presents the two-way ANOVA test results on the abrasion loss values obtained from the Cantabro abrasion loss test. Slag content, binder type, and environmental conditioning are the three different factors considered for the analysis. It is observed that all three factors had a significant influence on abrasion loss of the OGAFC mixes with mode of environmental conditioning having the highest influence on the abrasion loss values followed by slag content and binder type (confirmed by the F-values listed in Table 6.3). All two-way interactions were found non-significant.

6.4.3 Resistance to permanent deformation

The effect of long-term draindown conditioning on OGAFC mixes with and without BOF steel slag aggregates was further studied in terms of permanent deformation through the static creep test conducted in accordance to BS 598-111 (1995), on a universal testing machine (UTM). Figure 6.11 presents the strain versus time graphs obtained in the static creep test of the OGAFC mixes. The test consisted of a loading period of 3600 seconds followed by an equal duration of unloading where the OGAFC specimen was allowed to release the strain. The test was conducted on two sets of specimens: unconditioned set and long-term draindown conditioned (160°C for 8 hours) set. Figure 6.11 shows that for mixes with both binders, a well-defined drop in both total strain and permanent strain was observed with an increase in steel slag replacement percentage. This decrease in the accumulated strain with increase in steel slag percentage is due to its higher angularity and strength along with the rough surface texture and better interlocking mechanism of the steel slag aggregates (Pasetto and Baldo, 2010; Pattanaik *et al.* 2021).

Figure 6.12 illustrates the permanent strain developed in the mixes for both unconditioned set and long-term draindown conditioned set of specimens. Percentage increment in the permanent strain of these mixes decreased with an increase in the steel slag content. The permanent strain of the control mix (with 0% steel slag aggregates) increased by 1.5 times (for both type of binders) when conditioned at 160°C for 8 h. On the other hand, for mixes with 100% steel slag replacement, the permanent strain increases by 28% and 18% for OGAFC-PMB and OGAFC-CRMB mixes respectively. The lower percentage increment in the permanent strain confirms better deformation resistance of OGAFC mixes under long-term draindown with the use of BOF steel slag aggregates.

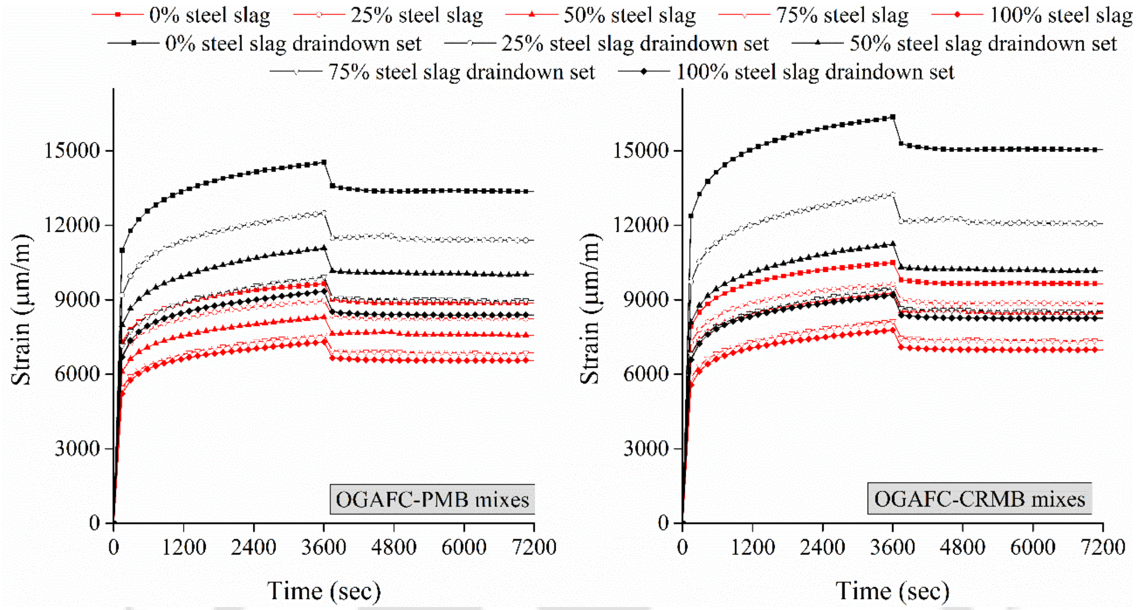


Figure 6.11: Static creep test results of long-term conditioned OGAFC mixes.

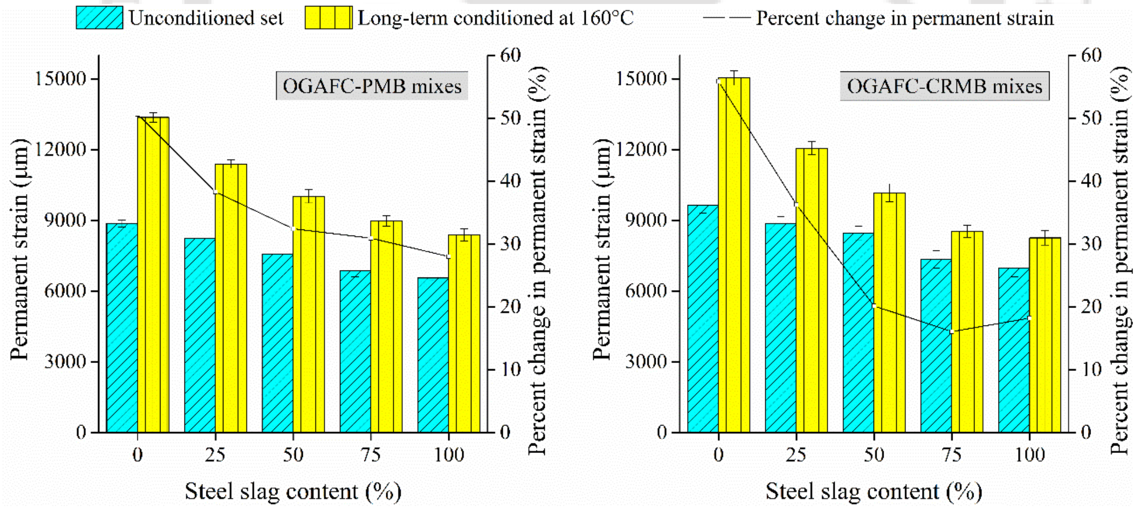


Figure 6.12: Permanent strain results from static creep test over long-term conditioned OGAFC mixes.

6.5 Summary

In this chapter, the durability of OGAFC mixtures with different aggregate types (natural stone aggregate, BOF steel slag, and combinations of both) and modified binder types was presented in terms of moisture susceptibility and long-term binder draindown potential. OGAFC mixes with five replacement percentages (0, 25, 50, 75, and 100%) of BOF steel slag and two types of modified binders (PMB and CRMB) were prepared and subjected to moisture susceptibility and long-term binder draindown test protocols. Moisture susceptibility evaluation was performed under different environments (neutral and acidic) by varying the pH of the conditioning water. For the evaluation of moisture damage characteristics, OGAFC mixtures were subjected to modified boiling water test, modified Lottman test, wet abrasion loss test, and permeability measurements. Results showed that an acidic environment exacerbated the moisture damage, however, OGAFC mixtures containing BOF steel slag showed better performance than the control mixture (with natural aggregates only). Inclusion of BOF steel slag in OGAFC mixtures enhanced resistance to moisture damage under both pH environments. OGAFC mixes with 100% BOF slag content performed the best considering all moisture damage tests performed under both conditioning environments. Further, OGAFC mixes prepared with PMB binder reported a better resistance to moisture damages than OGAFC-CRMB mixes.

To evaluate the long-term binder draindown of OGAFC mixes with both natural aggregates and BOF steel slag, compacted OGAFC specimens were prepared and subjected to different long-term conditioning procedures to simulate the downward migration of asphalt binder in the mixes. Two different conditioning approaches were considered — at 60°C for 42-days and at 160°C for 8-hours. Long-term binder draindown was established by evaluating the drainability properties (porosity and permeability) of the conditioned OGAFC specimens. It was found that a higher conditioning temperature (160°C) and lower conditioning procedures time (8-hours) was able to capture the long-term binder draindown of the OGAFC mixes experienced during its service life.

Later, the OGAFC specimens with long-term binder draindown, were subjected to the modified Lottman test, wet abrasion loss test, and static creep test, respectively to evaluate the effect of long-term binder draindown on the moisture susceptibility, ravelling potential, and rutting resistance of OGAFC mixes. The results revealed that OGAFC mixes with higher BOF steel slag content showed better moisture, ravelling, and rutting performance compared with the control mix after being subjected to long-term draindown. The inclusion of BOF steel slag up to 100% in OGAFC mixes produced encouraging results, with overall improvement in performance. Moreover, OGAFC mixes with CRMB binder were found less susceptible to long-term binder draindown compared to OGAFC mixes with PMB binder. The use of BOF steel slag in OGAFC mixes showed a positive influence on its durability even when subjected to combined moisture and long-term draindown conditioning.

Chapter 7: Performance Properties of OGAFC Mixes with BOF Steel Slag Aggregates

7.1 General

OGAFC mixes are predominantly used as a functional layer and are not considered as structural layers. Therefore, majority of the existing studies on OGAFC have mainly focused on the functionality and durability aspects of these mixes, with a limited interest on their mechanical properties/characteristics. However, for comparison among different OGAFC mix combinations with the incorporation of BOF steel slag, various performance characteristics of the OGAFC mixes were evaluated under this study. The mechanical properties of OGAFC mixtures were evaluated for five percentage replacements (0, 25, 50, 75, and 100%) of coarse natural aggregates with BOF steel slag with PMB and CRMB binders. Mixes were prepared at the designed optimum binder content of 6.0%. Mechanical performance of the OGAFC mixes with and without BOF steel slag was evaluated for rutting resistance (dynamic creep test and Hamburg wheel tracking device test), cracking potential (indirect tensile strength test, cracking tolerance index test, and semi-circular bending test), fatigue life (indirect tensile fatigue test), and modulus properties (indirect tensile stiffness modulus test and resilient modulus test). The detailed description for the procedure adopted and parameters determined under the different performance tests were presented in Chapter 3. The results of the aforementioned tests are discussed in details in this chapter.

7.2 Dynamic creep test

The dynamic creep test simulates the rutting potential of a mix subjected to repeated stress loading. The test was conducted as per BS DD 226 (1996) using a universal testing machine (UTM) at a test temperature of 40°C. The accumulated strain versus time graphs for all combinations of OGAFC mixes for a total of 10,000 loading cycles are illustrated in Figure 7.1.

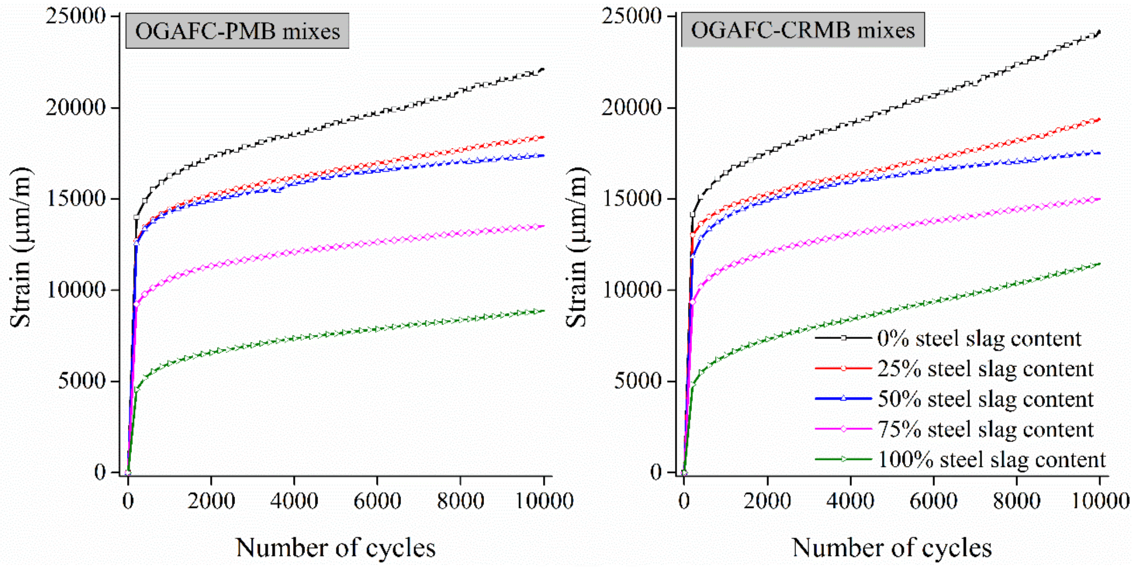


Figure 7.1: Dynamic creep test results.

The accumulated strain value throughout the loading cycles was found to decrease with an increase in steel slag content for both OGAFC-PMB and OGAFC-CRMB mixes. Incorporation of steel slag aggregate into the OGAFC mixtures resulted in a decrease in the accumulated strain varying from 17–60% and 20–53%, respectively for OGAFC-PMB and

OGAFC-CRMB mixes, compared to the control mix. The decrease in the strain observed with increase in steel slag content is attributed to the better strength and higher angularity of the steel slag aggregates. Similar improvements have been reported in other studies (Shen *et al.*, 2009; Suresha *et al.*, 2009b). OGAFC-CRMB mixes reported a marginally higher strain values compared to OGAFC-PMB mixes corresponding to each percentage substitution of steel slag.

7.3 Hamburg wheel tracking device test

The HWTD test evaluates the rut depth accumulated over an asphalt mix due to the combined action of moisture and repeated wheel loading at high pavement service temperatures and was performed as per the AASHTO T324 (2017) specifications. Figure 7.2 illustrates the cumulative rut depth corresponding to the number of wheel passes for OGAFC-PMB and OGAFC-CRMB mixes when tested at 40°C. The rut depth was found to decrease with percentage increase in BOF steel slag substitution in OGAFC mixes. For OGAFC-PMB mixes, the rut depth after 20,000 HWTD passes was found to decrease by about 35% for every 25% increment in the steel slag content while for OGAFC-CRMB mixes this decrease in rut depth was recorded to be about 25%. This indicates that OGAFC mixes with steel slag aggregates are less susceptible to rutting.

Overall, for any particular slag content, the rut depth recorded for OGAFC-PMB mixes at the end of the test period was slightly (about 0.5 mm) lower than OGAFC-CRMB mixes. The increase in the resistance to rutting with an increase in the steel slag content for both OGAFC-PMB and OGAFC-CRMB mixes also agrees with the results of dynamic creep test. Further, none of the mixes showed stripping throughout the 20,000 passes as no inflection point was observed in Figure 7.2. The higher resistance of OGAFC mixes with BOF steel slag to moisture damage may be attributed to the rough surface texture and basicity of BOF steel slag as presented earlier in the Figure 3.3 and Table 3.3, respectively, which imparts better adhesion with asphalt binder. Similar improvements in moisture resistance with BOF steel slag application in asphalt mixtures have been reported by other researchers (Xie *et al.*, 2012, 2013, 2014).

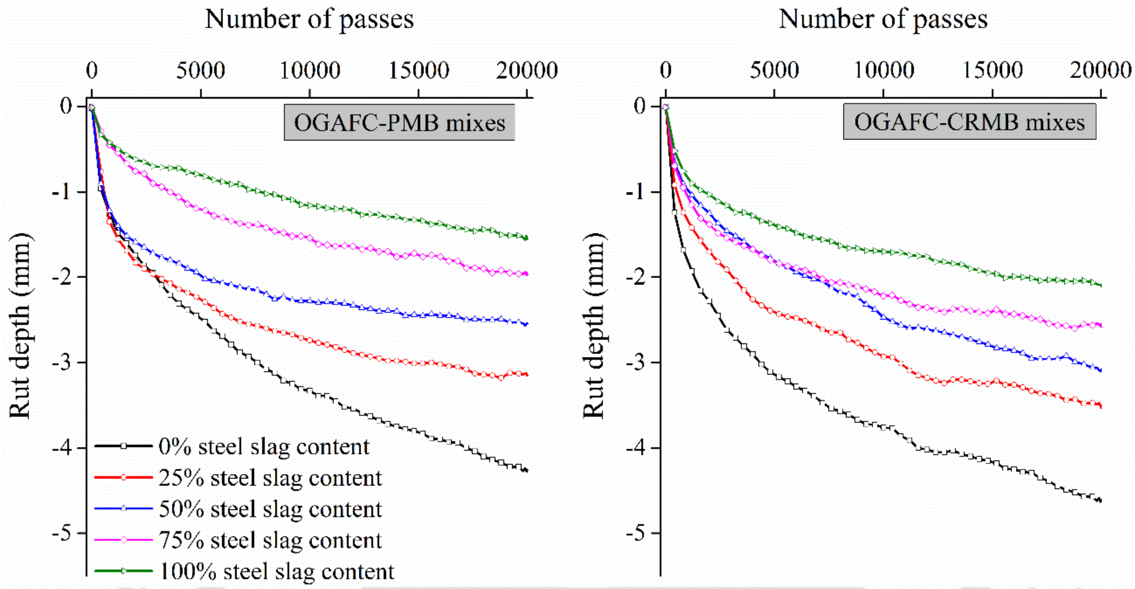


Figure 7.2: Hamburg wheel tracking device (HWTD) test results.

7.4 Indirect tensile strength test

The indirect tensile strength (ITS) determination was made at 25°C in accordance with ASTM D6931 (2017) on 150 mm diametric cylindrical OGAFC specimens. The specimens were diametrically compressed at 50 mm/min loading rate and the maximum load at which the specimen failed was used to compute ITS as per Equation 3.15. The indirect tensile strength (ITS) values of OGAFC-PMB and OGAFC-CRMB mixes are presented in Figure 7.3. The ITS values of the OGAFC mixes were found to range between 456–552 kPa and 432–531 kPa for OGAFC-PMB and OGAFC-CRMB mixes respectively. An enhancement in the ITS values with the incorporation of BOF steel slag is an indication of increase in the mix strength and cohesiveness.

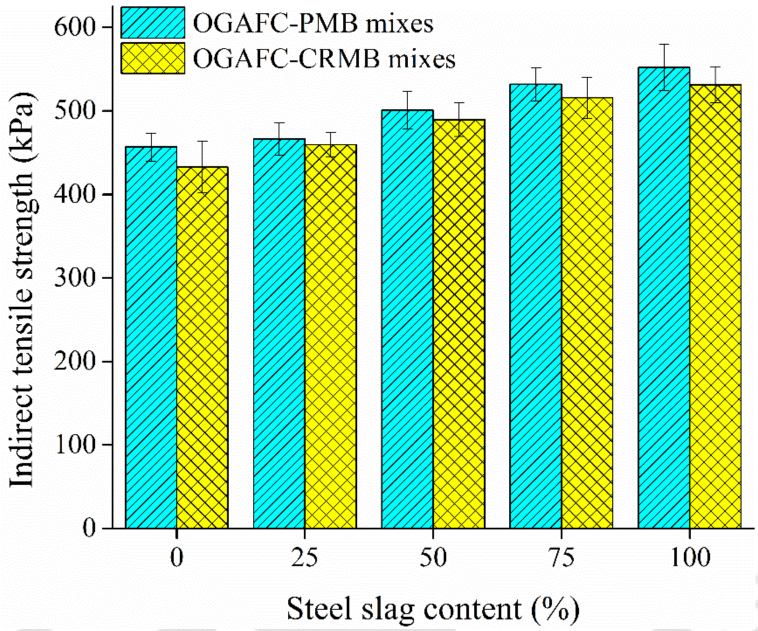


Figure 7.3: Indirect tensile strength (ITS) test results.

7.5 Cracking tolerance index test

The resistance of the OGAFC mixtures to cracking was determined through the cracking tolerance index (CT_{Index}) which was obtained from the load-displacement curve of the ITS test, in accordance with ASTM D8225 (2019). Figure 7.4 illustrates the cracking tolerance index (CT_{Index}) values of the OGAFC mixes obtained through the ITS test and computed using Equations 3.18–3.21 at 25°C. The CT_{Index} (unitless) values were observed to range from 1019–1927 and 888–1806 for OGAFC-PMB and OGAFC-CRMB mixes, respectively. A higher value of this index corresponds to a better cracking resistance. Usually for dense-graded asphalt mixes the CT_{Index} values are found in the range of 31–255 (ASTM D8225, 2019), due to a higher peak load and a lower displacement. However, OGAFC mixes showed a lower peak load and higher maximum displacement compared to dense-graded asphalt mixes due to the open aggregate structure.

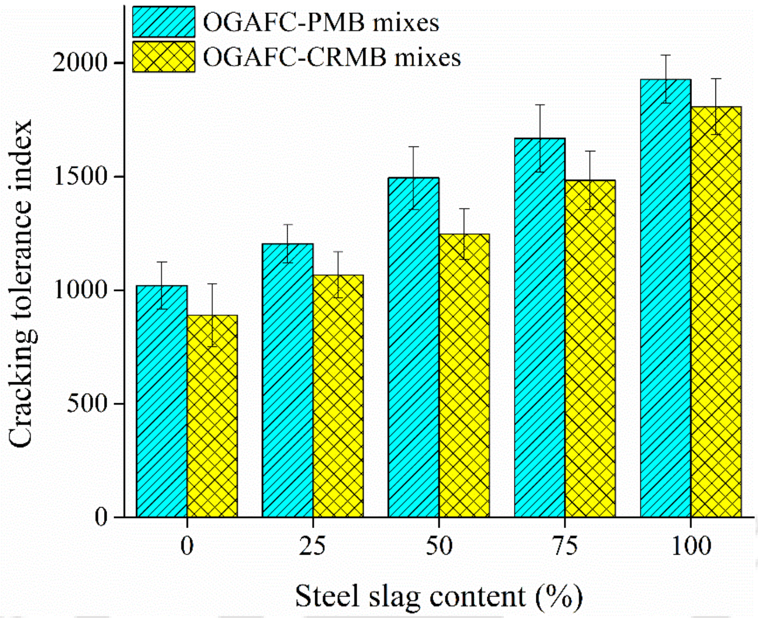


Figure 7.4: Cracking tolerance index (CT_{Index}) test results.

Figure 7.5 illustrates a typical load-displacement curve for the cracking tolerance index test which illustrates the difference in the behaviour of a dense graded asphalt mix and an OGAFC mix. This difference in the behaviour results in a higher work of failure (W_f) and subsequently higher CT_{Index} value for OGAFC mixes. Similar high values of CT_{Index} for OGAFC mixes have also been reported by other researchers (Zhang *et al.*, 2021). The CT_{Index} values were observed to increase with an increase in the steel slag replacement indicating a higher resistance to cracking with the incorporation of BOF steel slag. It can be observed that the cracking resistance of OGAFC mixes with 100% steel slag aggregate is almost double the cracking resistance of the control mixes (with 0% steel slag). This can be attributed to the better interlocking of the OGAFC mixes with the incorporation of BOF steel slag aggregates, which have higher angularity and rough surface texture. Further, CT_{Index} values of OGAFC-PMB mixes were found to be slightly higher than OGAFC-CRMB mixes (about 7–15% higher).

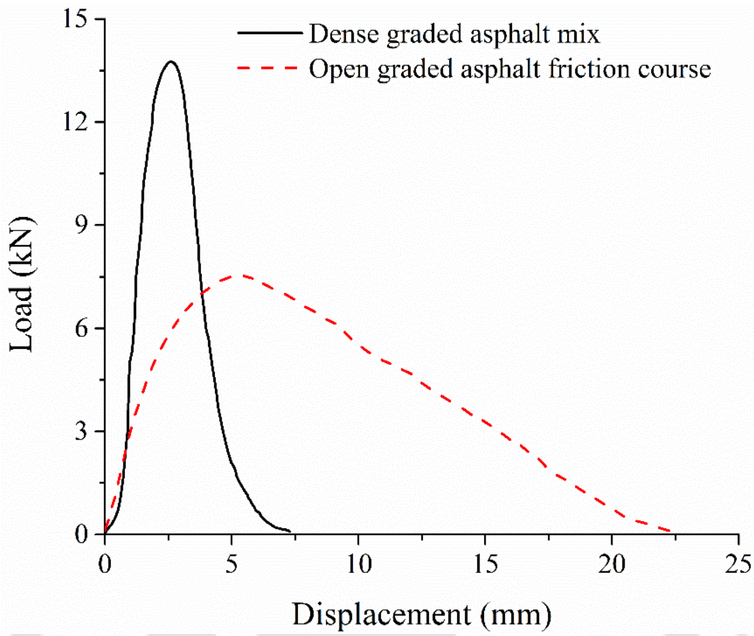


Figure 7.5: A typical load-displacement curve for dense graded asphalt mix and OGAFC mix.

7.6 Semi-circular bend test

The semi-circular bend (SCB) test was conducted per ASTM D8044 (2016) at 25°C to characterise the fracture resistance of asphalt mixtures in terms of J-integral (J_c) as per Equation (3.22). The J-integral (J_c) of the OGAFC mixes obtained from the semi-circular bend test at three different notch depths (25, 32, and 38 mm) is presented in Figure 7.6. A gradual increase in the value of J-integral is observed with an increase in the BOF steel slag content indicating that the incorporation of BOF steel slag results in a higher cracking resistance of the OGAFC mixes. The test results agree with the CT_{Index} test results and suggest that the enhanced surface morphology (rough and porous surface texture), good shape characteristics (superior interlocking through enhanced angularity) and higher adhesion with asphalt binder of BOF steel slag aggregates assists in better cracking resistance under static loading. The J-integral values of OGAFC-PMB mixes were also found slightly higher than the OGAFC-CRMB mixes.

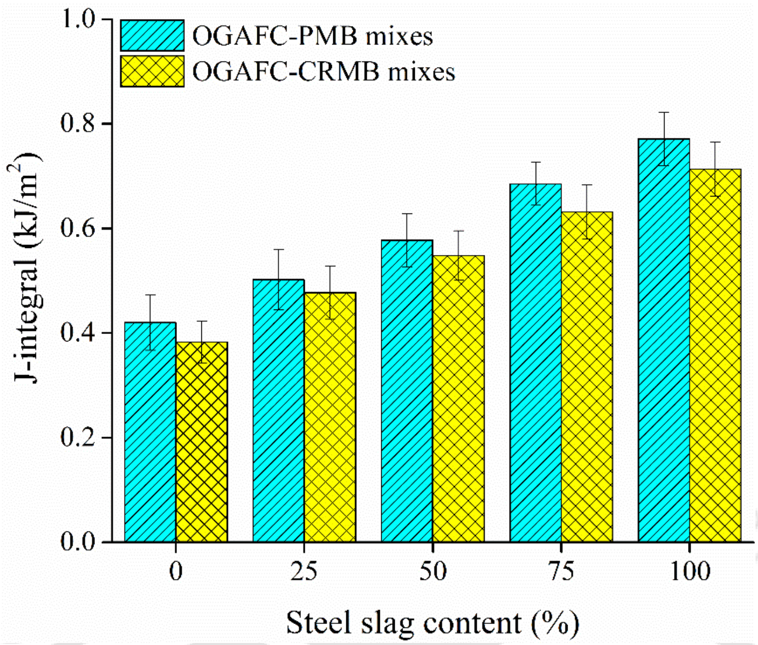


Figure 7.6: Semi-circular bend test results.

7.7 Indirect tensile fatigue test

The Indirect tensile fatigue (ITF) test was conducted at 20°C to determine the number of cycles prior to complete fracture of the test specimen as per BS EN 12697-Part 24 (2012) guidelines. Specimens were subjected to repetitive stress of 200 kPa along the diametrical plane to attain a strain in the range of 100–400 με. The load was applied in a haversine form with a 2 Hz frequency (0.1 s load duration and 0.4 s rest duration).The number of cycles resisted by a mix specimen before failure were used to compare the fatigue life of different OGAFC mix combinations with BOF steel slag aggregates. The failure life results of OGAFC-PMB and OGAFC-CRMB mixes obtained at 20°C for the five percentages of steel slag substitution are presented in Figure 7.7. The fatigue life of the OGAFC mixes increased with an increment in the steel slag substitution. OGAFC mixes with steel slag aggregates showed higher fatigue life before complete fracture when compared to the control mixes (with 0% steel slag). The fatigue life showed an improvement by 55–200%

and 53–197% respectively for OGAFC-PMB and OGAFC-CRMB mixes for varying percentages (0-100%) of steel slag content. The increase in the fatigue lives of the OGAFC mixes with steel slag has been attributed to the better adhesion between the steel slag aggregates and asphalt binder compared to natural aggregate (Qazizadeh *et al.*, 2018). Also, OGAFC-PMB mixes had a higher fatigue life than OGAFC-CRMB mixes at any particular steel slag content indicating that the use of PMB binders provided better fatigue life of OGAFC mixes when compared with those having CRMB binders.

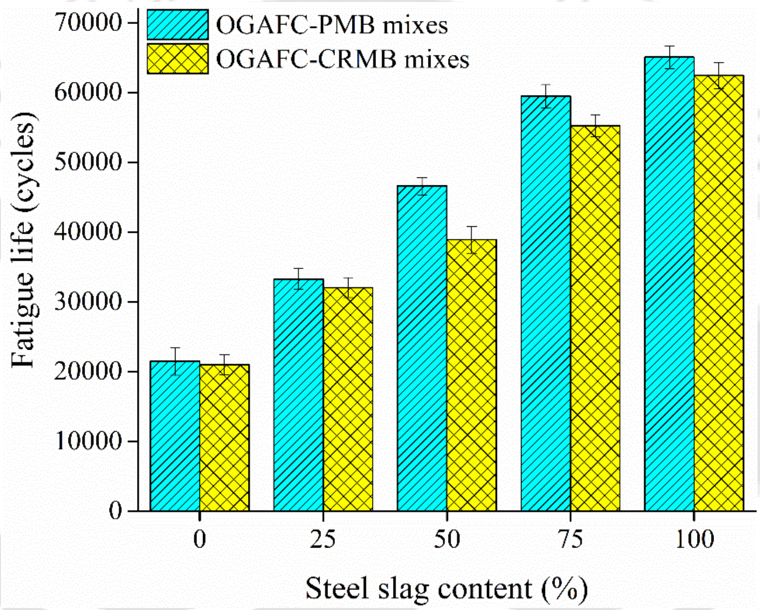


Figure 7.7: Indirect tensile fatigue (ITF) test results.

7.8 Indirect tensile stiffness modulus test

Stiffness modulus is a measure of the resistance to deformation and thus enables to determine the ability of an asphalt layer to distribute the vehicular traffic load (Gómez-Meijide *et al.*, 2016; Tahami *et al.*, 2019). The stiffness modulus of the OGAFC mixes with varying steel slag content and the two binder types was measured in accordance with BS EN 12697-Part 26 (2012) at 20°C. Figure 7.8 illustrates the variation of stiffness modulus with BOF steel slag content and binder type. For OGAFC mixes with both PMB and CRMB binders, stiffness modulus was found to increase with an increase in the steel slag content.

Stiffness modulus increased in the range of 21–52% and 30–59% for OGAFC-PMB and OGAFC-CRMB mixes (compared to the control mix), respectively, with percentage increment in the steel slag content.

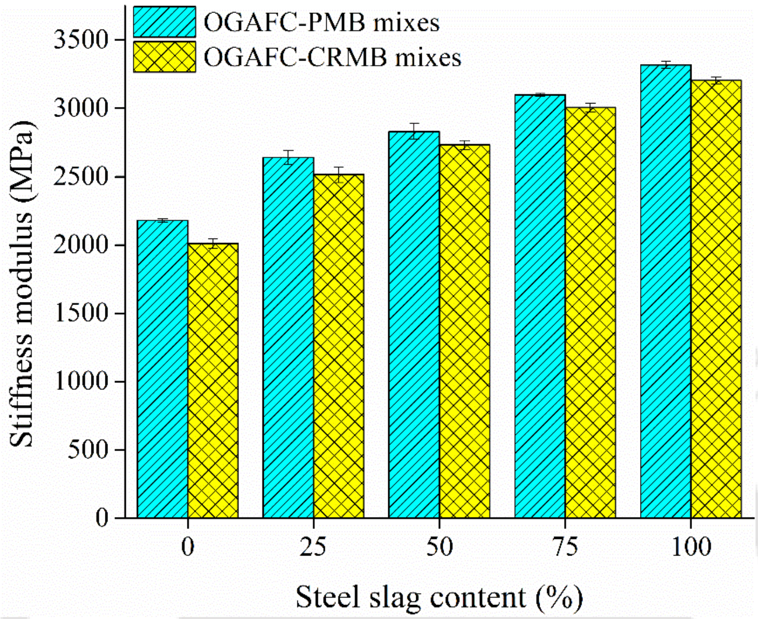


Figure 7.8: Indirect tensile stiffness modulus (ITSM) test results.

7.9 Resilient modulus

The resilient modulus (RM) test was performed per AASHTO TP31 (1996) specifications at 40°C using a cyclic stress where a seating load was applied at a fixed amplitude for 0.1 s loading period followed by 0.9 s rest period. This is also an important mix parameter and is used in the mechanistic-empirical pavement design procedure currently followed in India for flexible pavements. The variation of resilient modulus of the OGAFC mixes with varying steel slag contents and binder types is presented in Figure 7.9. The resilient modulus values of OGAFC mixtures were found to increase with an increase in the percentage increment of steel slag content. Application of BOF steel slag aggregates resulted in an increase in the resilient modulus compared to the control mix varying from 9–52% and 18–60% respectively for OGAFC-PMB and OGAFC-CRMB mixes. These results indicate that use of BOF steel slag aggregates enhance the vehicular load resisting capacity of an OGAFC mixture. Further, for any particular steel slag content, OGAFC-PMB mixes showed a higher modulus than OGAFC-CRMB mixes.

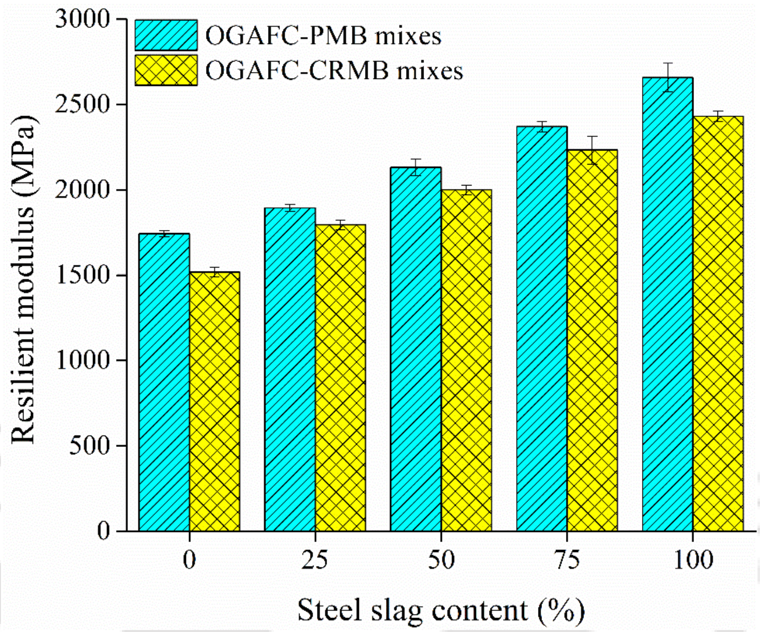


Figure 7.9: Resilient modulus test results.

7.10 Statistical analysis

The results of the study were statistically analysed through analysis of variance (ANOVA) at 5% significance level. The main and the interaction effects of the two factors: slag content (SC) and binder type (BT) were evaluated for the following responses – accumulated strain obtained from the dynamic creep at the end of the 10,000th cycle, rut depth obtained from the HWTD test at the end of the 20,000th pass, ITS, CT_{Index}, J-integral value obtained from the SCB test, fatigue life obtained from the ITF test, modulus value obtained from ITSM, and the RM test. Table 7.1 presents the test results of ANOVA performed on the response variables, showing that the two factors were significant for each test result with an exception of binder type on ITS and J-integral values. The two-way interaction (SC:BT) was found to be non-significant in all cases indicating that the effect of slag content on the response variable is independent of binder type in the various mix performance properties considered.

Table 7.1: Analysis of variance test results of the OGAFC mix performance properties at 5% significance level.

Factors	*DC*	*HWTD*	*ITS*	*CT_{Index}*	*SCB*	*ITF*	*ITSM*	*RM*
	p-value	*p-value*	*p-value*	*p-value*	*p-value*	*p-value*	*p-value*	*p-value*
	S/NS	*S/NS*	*S/NS*	*S/NS*	*S/NS*	*S/NS*	*S/NS*	*S/NS*
Slag Content (SC)	<0.001, S	<0.001, S	<0.001, S	<0.001, S	<0.001, S	<0.001, S	<0.001, S	<0.001, S
Binder Type (BT)	0.003, S	<0.001, S	0.129, NS	0.006, S	0.085, NS	<0.001, S	<0.001, S	<0.001, S
SC:BT	0.444, NS	0.522, NS	0.981, NS	0.941, NS	0.986, NS	0.092, NS	0.264, NS	0.763, NS

Note: 'DC' stands for 'dynamic creep', 'HWTD' stands for 'Hamburg wheel tracking device', 'ITS' stands for 'indirect tensile strength', 'CT_{Index}' stands for 'cracking tolerance index', 'SCB' stands for 'semi-circular bend', 'ITF' stands for 'indirect tensile fatigue', 'ITSM' stands for 'indirect tensile stiffness modulus', 'RM' stands for 'resilient modulus', 'S' stands for 'significant', and 'NS' stands for 'not significant'.

7.11 Summary

The mechanical strength performance test results of OGAFC mixes with varying contents of BOF steel slag were presented in this chapter. The performance properties of the OGAFC mixes were evaluated in terms of rutting resistance, cracking potential, fatigue life, and modulus properties. The mechanical properties of the OGAFC mixes improved with the application of BOF steel slag for both OGAFC-PMB and OGAFC-CRMB mixes and the improvement was mainly attributed to the rough surface texture, better angularity, higher strength, and basicity of BOF steel slag aggregates. OGAFC mixes with BOF steel slag aggregates showed higher rutting and cracking resistance, which further increased with an increase in BOF steel slag content. Fatigue life of OGAFC mixes prepared with 100%

BOF steel slag aggregate were found to increase by about three times compared to the fatigue life of OGAFC mixes prepared with 0% BOF steel slag (control mix). The modulus properties also showed a reasonable improvement with an increase in BOF steel slag replacement percentages. Further, OGAFC-PMB mixes exhibited better mechanical performance than OGAFC-CRMB mixes. Overall, it can be stated that the incorporation of BOF steel slag improves the mechanical performance of OGAFC mixes.

Chapter 8: Summary and Conclusions

8.1 Summary

Open graded asphalt friction course (OGAFC) is a special bituminous course (generally 25–50 mm thick) laid over an existing impermeable/dense graded surface to enhance functional performance and safety of roadways, especially under wet-weather conditions. It consists predominantly of single-sized coarse aggregates (having a coarse aggregate fraction of about more than 90% of the total aggregate weight) with a relatively high air voids content (minimum 18% of mix volume) and permeability (more than 100 m/day). The network of interconnected air voids permits rainwater runoff to travel within the OGAFC overlay laterally until it is discharged through the pavement edges. OGAFC mixes offer several advantages including reduced hydroplaning and splash and spray of rainwater runoff (Dell'Acqua *et al.*, 2011; Praticò *et al.*, 2013; Kandhal, 2016; Watson *et al.*, 2018), enhanced friction under both dry and wet surface conditions (Adam and Shah, 1974; Bruner, 1975; Huddleston *et al.*, 1993; Pattanaik *et al.*, 2017), improved visibility of road markings (Tappeiner, 1993; Liu *et al.*, 2010; Rungruangvirojn and Kanitpong, 2010), reduced wet-weather surface glare (Lefebvre, 1993; Kandhal, 2002), and lower tyre-pavement interaction noise (Bendtsen and Andersen, 2005; Ongel *et al.*, 2009; Liu *et al.*, 2016). Driving safety is significantly improved by ensuring adequate surface skid resistance (Kuttesch, 2004) especially under wet weather conditions. A higher percentage of road accidents is reported during wet weather conditions, and one of the prime causes of these accidents is hydroplaning, accounting for about 13.5% of fatal accidents and 25% of the total road accidents globally (Kuemmel *et al.*, 2000). Studies conducted in the State of Louisiana (United States of America) and Japan revealed that accidents related to wet weather conditions significantly reduced with OGAFC mixtures' application (Kabir *et al.*, 2012, Shimeno *et al.*, 1997).

OGAFC mixes demand good quality aggregates to distribute the traffic loads through stone-on-stone contact while allowing the high void structure to perform the requisite drainage functions. Meanwhile, along with the negative environmental impact of stone excavation, the availability and accessibility to good quality road aggregates has continually become challenging. Being aware of the challenges related to availability and cost of good quality road construction aggregates, researchers are continuously exploring alternative aggregates for an environment friendly and sustainable construction.

Steel slag, a by-product/co-product of the steelmaking industries, can be one such material for use as a sustainable alternative to the conventional natural aggregates. Steel slag is obtained as a co-product during the conversion of molten pig iron or steel scrap to steel either in the presence of highly pure oxygen in a basic oxygen furnace (BOF) or with the aid of electricity in an electric-arc furnace (EAF). Based on the furnace used for the conversion of steel, steel slag is classified as BOF or EAF steel slag. India is the second largest producer of crude steel in the world with an annual production of 108.5 million tonnes (MT) in the year 2019 (World Steel, 2020). Around 12 MT BOF steel slag and 8 MT EAF steel slag are estimated to be generated annually in India that mostly lie unutilised near the various steel manufacturing units (Indian Bureau of Mines, 2018b). Steel slag is associated with desirable physical (shape and strength), chemical (hydrophobic nature), and morphological (rough surface texture) characteristics which make it a candidate for possible exploration in road construction activities. Steel slag has been tried/explored for use in dense-graded bituminous mixes (Motz and Geiseler, 2001; Xue *et al.*, 2006; Xie *et al.*, 2013; Chen *et al.*, 2014; Lin *et al.*, 2015; Chen *et al.*, 2015; Chen and Wei, 2016; Amelian *et al.*, 2018; Teixeira *et al.*, 2019; Guo *et al.*, 2020; Díaz-Piloneta *et al.*, 2021; Zhao *et al.*, 2021). However, there are lack of studies to explore their use in OGAFC mixes.

With this background, the present study was performed with the main aim to explore the use of BOF steel slag as coarse aggregate in the preparation of OGAFC mixes with different asphalt binders. The aim of the study was achieved through the following objectives: (1). Characterisation of natural stone aggregate, BOF steel industry slag, and modified binders (PMB and CRMB) selected for the study, (2). Determination of volumetric and design parameters of OGAFC mixes with varying percentages of BOF steel slag aggregates as a replacement of natural coarse aggregates, (3). Evaluation of functionality of OGAFC mixes with and without BOF steel slag aggregates in terms of permeability, clogging, and frictional characteristics, (4). Assessment of durability of OGAFC mixes with and without BOF steel slag aggregates in terms of moisture susceptibility and long-term binder draindown characteristics, and (5). Evaluation and comparison of performance properties of OGAFC mixes with varying BOF steel slag content in terms of rutting resistance, cracking potential, fatigue life, and modulus measurements.

To achieve the framed objectives, one type of natural stone aggregate, one type of BOF steel slag, two types of modified binders, and one type of cellulose fibre (as additive) were used for the fabrication and evaluation of OGAFC mixes. BOF steel slag aggregate was used in five varying percentage replacements — 0% (control mix), 25%, 50%, 75%, and 100% for the coarse natural aggregate (greater than 2.36 mm). The mixes were first designed for the determination of optimum binder content (OBC) in terms of stone-on-stone contact, air voids content, binder draindown, unaged and aged abrasion loss. After the OBCs of the mixes were finalised, the mixes were evaluated for functional characteristics through permeability, clogging potential, and frictional properties. The mixes were then examined for durability in terms of moisture susceptibility and long-term binder draindown potential. Finally, the mixes were evaluated for performance properties in terms of rutting resistance, cracking potential, fatigue life, and modulus properties.

8.2 Conclusions

OGAFCs are associated with better hydraulic, acoustic, and frictional performance that contribute to better road safety, especially under wet weather conditions compared to conventional dense graded hot mix asphalts. The present study investigated the design, functionality, durability, and performance characteristics of OGAFC mixes prepared with incorporation of BOF steel slag with two types of modified binders. The BOF steel slag replaced natural stone aggregate in the percentages of 0, 25, 50, 75, and 100%. Based on the experimental results and analysis, the conclusions corresponding to different key aspects of OGAFC mixes are presented as follows:

- ***Characterisation of BOF steel slag aggregates:*** Physical properties of BOF steel slag met the standard requirements of aggregates as per ASTM D7064 (2013) and were also found superior to those of natural stone aggregate especially in terms of shape, angularity, abrasion resistance and strength. BOF steel slag used was found to have a rough surface texture with the presence of pitted and vesicular surface features. The presence of high concentrations of CaO and FeO/Fe_2O_3 in BOF steel slag helped in providing it hydrophobic nature and better strength, respectively. When examined for the swelling and leaching potential, BOF steel slag showed results within the permissible limits as well as no leaching of harmful elements was observed.

- ***Design of OGAFC mixes:*** In the design of OGAFC mixes with BOF steel slag with both modified binders, the angular shape and rough surface texture of BOF steel slag aggregates helped to enhance the stone-on-stone contact. Rough surface texture, higher basicity and porosity of BOF steel slag helped to form stronger bond with binders and thus enhanced the ravelling resistance of OGAFC mixes. At 6.0% binder content, all combinations of OGAFC mixes were found to meet the specified requirements for all design parameters as per ASTM D7064 (2013). Hence, the same binder content was selected as the OBC of the OGAFC mixes with different replacement/substitution percentages of BOF steel slag for determination of different characteristics (functionality, durability and mechanical strength). Steel slag content, binder content and binder type had significant effect on OGAFC mixes in terms of air voids content, stone-on-stone contact, binder draindown and ravelling resistance.
- ***Functional characteristics of OGAFC mixes:*** All OGAFC mix combinations showed initial permeability values quite higher than the minimum requirements of 100 m/day stipulated by ASTM D7064 (2013). With the incorporation of BOF steel slag, the initial permeability and porosity of the OGAFC mixtures decreased with an increase in the binder content and steel slag substitution percentage. Permeability

values of OGAFC-CRMB mixtures were found to be slightly higher than OGAFC-PMB mixtures.

Clogging (surface-clogging) of the OGAFC mixtures reduced the initial permeability by about 25%. However, initial clogging rate of OGAFC mixtures decreased with an increase in steel slag substitution percentage. After attempting de-clogging through vacuum pressure and reverse flushing, OGAFC-PMB mixtures were able to regain about 85% of the initial permeability while OGAFC-CRMB mixtures were able to regain about 90% of the initial permeability. Secondary (step-wise) clogging rate was found to be lower than the initial clogging rate. The angularity as well as sharper edges and surface features of BOF steel slag helps to delay the rate of disruption/blockage of interconnected void channels and therefore steel slag incorporated OGAFC mix-showed lower values of initial and secondary clogging rates.

Porosity and permeability of the OGAFC mixtures decreased with moisture conditioning (through modified boiling water test) and repeated loading (through dynamic creep test). Deformation-related clogging had a higher effect on the drainability of OGAFC mixes compared to stripping related clogging as the percent reductions in porosity and permeability caused by deformation were higher than those caused by stripping. Higher strength, rough texture and the basicity of BOF steel slag provided a better adhesive and cohesive strength to OGAFC mixes resulting in improved performance under both stripping and deformation related clogging.

The incorporation of the BOF steel slag led to a significant improvement in the mean texture depth (MTD) of OGAFC mixes. Overall, each 25% increment in steel slag content resulted in an approximate increase of 0.3 mm in the MTD. MTD values of OGAFC-CRMB mixes were slightly higher than OGAFC-PMB mixes. The results of the British pendulum test indicated that the incorporation of BOF steel slag enabled a significant improvement in the skid/frictional resistance of OGAFC mixtures under all three surface conditions (dry, wet, and ponding). The BPN values under the dry surface condition showed an increase from 70 to 117 and 74 to 122 with increment of the steel slag content from 0 to 100% for OGAFC-PMB and OGAFC-CRMB mixes respectively. From the analysis of the BPT results, it was observed that the adhesion component of skid resistance contributed to about 17% to 26% of the total skid resistance. Both adhesion and hysteresis components increased with an increase in the BOF steel slag content. Under dynamic friction tests, the friction coefficients also showed an increase by about 0.15 for every 25% increment in BOF steel slag content. OGAFC mixes with BOF steel slag showed a higher polishing resistance than natural stone aggregate and are therefore expected to retain their surface frictional resistance/ characteristics for a longer time.

- ***Durability assessment of OGAFC mixes:*** A change in the conditioning water environments from a neutral (pH=7.0) to acidic (pH=4.9) resulted in a lower performance of OGAFC mixes in terms of abrasion loss and tensile strength ratio (TSR). Incorporation of BOF steel slag enhanced the moisture damage resistance of OGAFC mixtures in terms of abrasion loss, indirect tensile strength, and stripping index under both pH environments. Statistical analysis through ANOVA showed that steel slag content and conditioning environment had significant effect on functionality and drainability characteristics.

As conditioning period of 42 days at 60°C was not able to capture the long-term binder draindown potential of OGAFC mixes during their service life, an alternative conditioning protocol of 160°C for 8 hours was used. OGAFC mixes with BOF steel slag showed a lower long-term binder draindown when compared to those with natural aggregates alone (control mixes). OGAFC mixes with CRMB binder were found less susceptible to long-term binder draindown compared to OGAFC mixes with PMB binder. OGAFC mixes with BOF steel content greater than 50% only were able to give TSR of 80% when subjected to a combined action of long-term binder draindown and moisture conditioning. Abrasion loss/ravelling was found to increase under combined action of long-term binder draindown and moisture conditioning. However, OGAFC mixes with steel slag content of 25% and above showed abrasion loss lower than the maximum value of 30%, as recommended in ASTM D7064 (2013) specifications. Long-term binder draindown also decreased the permanent deformation resistance/strength, determined through static creep test, of the different OGAFC mix combinations. The inclusion of BOF steel slag helped to improve the rutting resistance of the OGAFC mixtures.

- ***Performance properties of OGAFC mixes:*** In comparison to control mixes with natural aggregates alone, OGAFC mixes with BOF steel slag exhibited higher rutting resistance, higher cracking resistance and a lower moisture damage, and the performance improved further with an increase in BOF steel slag content. OGAFC-PMB mixes showed better performance compared to OGAFC-CRMB mixes in all performance tests including dynamic creep test, Hamburg wheel tracking device test, indirect tensile strength test, cracking tolerance index test, semi-circular bend test, indirect tensile fatigue test, indirect tensile stiffness modulus test, and resilient modulus test. In the dynamic creep test, the incorporation of steel slag aggregate into the OGAFC mixtures resulted in a decrease in the accumulated strain varying from 17–60% and 20–53% respectively for OGAFC-PMB and OGAFC-CRMB mixes, compared to the control mix. None of the OGAFC mix combinations showed stripping throughout the 20,000 passes during the Hamburg wheel tracking tests. During the determination of cracking tolerance index (CT_{Index}), OGAFC mixes showed a lower peak load and higher maximum displacement compared to dense-graded asphalt mixes due to their open aggregate structure. The CT_{Index} values were found to increase with an increase in the BOF steel slag replacement percentage indicating a higher resistance to cracking of these mixes. Fatigue life of the OGAFC mixes, measured as the number of cycles prior to complete fracture of the test specimen in the ITFT test, increased by about three times with 100% BOF steel slag aggregates.

Enhancement in the mechanical strength parameters/performance of OGAFC mixes with increase in BOF steel slag content is attributed to the better strength, higher angularity of the steel slag aggregates along with a higher cohesion of mix due to better adhesion between BOF steel slags aggregates and asphalt binder. With an exception of the results of indirect tensile strength values and the J-integral values from SCB test, where binder type was not found as a significant factor, BOF steel slag content and binder type were found to be statistically significant factors for all other mechanical tests conducted in this study.

OGAFC mixes with 100% BOF steel slag substitution exhibited the best results in terms of functionality, durability and performance. OGAFC mixes with CRMB binder showed better results in terms of permeability, skid resistance, and resistance to long-term binder draindown. OGAFC mixes with PMB binder reported superior results in terms of moisture susceptibility and performance characteristics (rutting resistance, cracking potential, fatigue life, and modulus properties). With BOF steel slag replacement percentages of 50% and above, all the different parameters evaluated under various standard and extreme/severe test conditions/environments adopted in this study, the requirements laid by ASTM D7064 (2013) for OGAFC mixes were met. Utilisation of BOF steel slag, an industrial waste, in OGAFC mixes showed a positive effect on the properties of OGAFC mixes, and it will be a promising avenue to tackle the unprecedented shortages of natural aggregates in highway construction and a sustainable approach to utilise an industrial by-product/co-product as a road making aggregate.

8.3 Recommendations for Future Research

The thesis evaluated (at laboratory scale) the utilisation of BOF steel slag aggregates in preparation of OGAFC mixes with modified binders in terms of its design, functionality, durability, and performance parameters. Field trial sections of OGAFC mixes with BOF steel slag aggregates (having substitution percentages of about 50% and above) are recommended for being constructed to gain further confidence. These sections can be then regularly monitored especially for their functional characteristics in terms of drainability and frictional resistance. Studies can be also conducted on OGAFC mixes with BOF steel slag and different binder types, to evaluate their effect on noise and glare reflection reduction characteristics.

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LIST OF PUBLICATIONS

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1. Pathak, S., Choudhary, R., and Kumar, A. (2022). A state-of-the-art review on utilization of steel slag aggregates in open graded asphalt friction course mixes, *Journal of Materials in Civil Engineering.* (Submitted)

2. Pathak, S., Choudhary, R., Kumar, A., and Kumar, B. (2022). Mechanical Properties of Open Graded Asphalt Friction Course Mixtures with Basic Oxygen Furnace Steel Slag as Coarse Aggregates, *Journal of Materials in Civil Engineering.* (Under Review)

3. Pathak, S., Choudhary, R., and Kumar, A. (2022). Drainability and Clogging Behavior of Open Graded Asphalt Friction Courses with Basic Oxygen Furnace Steel Slag Aggregates, *Transportation Research Record: Journal of the Transportation Research Board.* (Accepted, In-Press)

4. Pathak, S., Choudhary, R., Kumar, A., and Pattanaik, M. (2022). Friction Characteristics of Open Graded Asphalt Friction Courses with BOF and EAF Steel Slag Aggregates, *Journal of Materials in Civil Engineering*, *34*(6), 04022087. DOI: 10.1061/(ASCE)MT.1943-5533.0004222

5. Pathak, S., Choudhary, R., and Kumar, A. (2022). Effect of Long-term Binder Draindown on Performance of Open Graded Asphalt Friction Courses with BOF Steel Slag Aggregates, *Journal of Materials in Civil Engineering*, *34*(1), 04021383. DOI: 10.1061/(ASCE)MT.1943-5533.0004022

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5. Pathak, S., Choudhary, R., and Kumar, A. (2020). Moisture Damage Investigations of OGAFC Mixtures with BOF Steel Slag as Coarse Aggregate under Different pH Environments, *Transportation Research Board (TRB) 99th Annual Meeting, 12-16 January, 2020, Washington, D.C., USA.*
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7. Pathak, S., Choudhary, R., and Kumar, A, (2019). Effect of Basic Oxygen Furnace Steel Slag on Moisture Sensitivity Characteristics of Open Graded Asphalt Friction Course, *18th Annual International Conference on Asphalt Pavement Engineering & Infrastructure, Liverpool John Moores University, 27-28 February, Liverpool, UK.*