



UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

OPTIMISATION OF MICROSTRUCTURAL PROPERTIES AND MECHANICAL PERFORMANCE OF ASPHALT MIXTURES

BY

SELINAH BUSANG



A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS OF
THE
DEGREE OF

Philosophiae doctor in Civil Engineering

in the

FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION
TECHNOLOGY

UNIVERSITY OF PRETORIA

December 2021

THESIS SUMMARY

OPTIMISATION OF MICROSTRUCTURAL PROPERTIES AND MECHANICAL PERFORMANCE OF ASPHALT MIXTURES

SELINAH BUSANG

Supervisor: Professor J W Maina

Department: Civil Engineering

University: University of Pretoria

Degree: Philosophiae Doctor (Civil Engineering)

SUMMARY

Excellent gradation with good strength aggregate morphology and quality binder significantly affect the microstructural properties, which affects the mechanical performance of asphalt pavements. Selection of aggregate gradation with optimised complex geometric morphologies and contact point of interaction of aggregate particles to provide good interfacial interactions between aggregate and asphalt binder, which complies with specification requirements, is a lengthy trial and error procedure. Most successful mix designs were obtained based on the experience of the designer. This study's first aim is to understand the influence of the chemical properties, texture, shape, strength, and, consequently, the microstructural properties and its resultant mechanical behaviour. The second aim is to optimise gradation and aggregate packing with idealised air voids without testing the microstructure in the laboratory. The materials selected in this study were three types of aggregate: granite 1(GD 1), granite 2 (GD 2) and limestone (GD 3), TK fibre and bitumen pen grade 40/60 and 70/80. MATLAB and Particle Flow Code (PFC3D) were used in this study to achieve and optimise the parameters that influence the stability of the aggregate skeleton, including highly detailed aggregate clumps, aggregates clump size range (gradation), and the packing density by using optimum air voids as an indicator. The virtual aggregate skeleton

microstructure was built, and a triaxial test in the PFC3D was used. The anisotropic mechanical properties of the virtual aggregate skeleton, such as the normal contact force and void fabric, were measured using a scan line void method established along the angle θ using fabric vectors and were obtainable using PFC3D. Additionally, the asphalt mixtures were prepared from three different aggregate sources to evaluate the influence of aggregates' physical and chemical properties on microstructural properties. The microstructural properties were captured using a Charge-Coupled Device (CCD) digital camera and analysed using Image Process Analysis System (iPAS) software. The effect of the daily temperature variation of the environment on the corresponding temperature gradient through the depth of the asphalt mixtures layers was assessed. Tests including Marshall stability, wheel tracking, three-point bending beam and double tension-compression at two periods were conducted to investigate the relationship between the structural performance of the asphalt mixtures and their microstructural properties. Additionally, the normal contact fabric tensor (F) was developed to evaluate the interlocking of aggregate in asphalt mixtures, and a correlation with the mechanical performance was performed. Also, all the bitumen grades were modified with various percentages of Teak (TK) fibre contents to evaluate rheological properties through rutting, penetration, thermal conductivity, and multiple stress creep recovery tests. Base and teak modified binders were soaked in the sodium carbonate (NaCO_3) salt solutions for different conditioning times to simulate rheological performance in semi-arid areas. The Kruskal-Wallis test, a non-parametric test, was used to statistically study the effect of stress level, and TK addition and the mean wise comparisons at a 95% confidence level were determined. Grey relational analysis was selected to evaluate the asphalt mixture's performance through chemical characteristics, strength, shape, microstructural properties, and modified binder. Parameters that influence the microstructure stability, such as aggregate size fraction range, shape percentage, Dominant Aggregate Size Range (DASR), aggregate densities, and Destructive Factor (DF), were optimised for all gradations using PFC3D. The results suggest a linear correlation between the evolution of normal contact fabric and void fabric. A scan line approach successfully identified and quantified the wall and loosening effects by quantifying the voids' shape and orientation. The results showed that aggregate' chemical oxides such as sodium oxide (Na_2O) + potassium oxide (K_2O) + calcium oxide (CaO) + silicon (SiO_2) have a major effect on the electrical conductivity of granite samples at high temperatures and pressure. The results indicated that the higher amount of sodium oxide (Na_2O) + potassium oxide (K_2O) + calcium oxide (CaO) + silicon (SiO_2) in the aggregate, the better the aggregate texture and the higher the number of contact points. In addition, high

numbers of contact points have a notable impact on the Marshall stability, rutting resistance, dynamic stability, stiffness modulus and complex Poisson's ratio at high and low temperatures. A good linear correlation between F and Marshall stability, dynamic stability and stiffness modulus was demonstrated. TK fibre modified bitumen provided greater rutting resistance, lower penetration, and lower thermal conductivity than the base bitumen binders. Compared to base bitumen, TK modified bitumen demonstrated reduced shear strain, higher recovery, and higher non-recoverable creep compliance. The TK fibre-modified bitumen binders had better resistance to the action of salt than the base bitumen. However, increased shear strain, reduced recovery, and increased non-recoverable creep compliance were observed for samples soaked in increasing salt concentration. The base bitumen and TK modified bitumen showed excessive softening and negative recovery at stress levels from 0.5k Pa due to increased soaking duration and salt content. The fabric tensor presented in this study is another approach that can evaluate the packing of aggregate in asphalt mixtures. The study concluded that aggregate contact properties directly influence the Marshall, rutting, and bending stiffness modulus for both low- and high-temperature performance of asphalt mixtures. The results for F and the number of aggregate contact points were similar. Therefore, F can also be used to evaluate the internal structural index. This investigation established that adding TK fibre to bitumen enhanced its toughness, which could improve asphalt fatigue performance, with the optimum level of TK fibres being 2% by mass of bitumen.

LIST OF PUBLICATIONS

1. Busang S., Maina, J. (2021). “Laboratory simulation and mechanical performance of asphalt materials under the action of saline”. *Construction and Building Materials*, Volume 333: Published
2. Busang S., Maina, J. (2021). “Influence of aggregate properties on microstructural properties and mechanical performance of asphalt mixtures”. *Construction and Building Materials*, Volume 318. Published
3. Busang S., Maina, J. (2022). Optimisation of the mechanical performance of asphalt mixture using fabric tensors and grey relational analysis, 1st International Data Science for Pavements Symposium, March 22 – 24, 2022, Turner-Fairbank Highway Research Center, McLean, VA, USA: Accepted
4. Busang S., Maina, J. (2021). Compatibility of fly ash and African teak (*Pterocarpus angolensis*) with bitumen mastic: Submitted to *International Journal of Integrated Waste Management, Science and Technology*: Submitted
5. Busang S., Maina, J. (2021). Numerical modelling of anisotropy of microstructural properties asphalt mixture: Submitted to *Road Materials and Pavement Design Journal*
6. Busang S., Maina, J. (2021). Influence of African Mokolwane palm fibre on rheological and thermal properties of bitumen: Submitted to *International Journal of Integrated Waste Management, Science and Technology*
7. Busang S., Maina, J. (2021). Using the mapping of constituents to quantify the porosity and directional permeability of asphalt mixtures: Submitted to *Road Materials and Pavement Design Journal*

DECLARATION

I, the undersigned hereby declare that

- I understand what plagiarism is and I am aware of the University's policy in this regard;
- the work contained in this thesis is my own original work;
- I did not refer to the work of current or previous students, lecture notes, handbooks or any other study material without proper referencing;
- where other people's work has been used, this has been properly acknowledged and referenced;
- I have not allowed anyone to copy any part of my thesis, and
- I have not previously – in its entirety or in part – submitted this thesis at any university for degree purposes.

DISCLAIMER:

The work presented in this thesis is that of the student alone. Students were encouraged to take ownership of their projects and to develop and execute their experiments with limited guidance and assistance. The content of the research does not necessarily represent the views of the supervisor or any staff member of the University of Pretoria, Department of Civil Engineering. The supervisor did not read or edit the final report and is not responsible for any technical inaccuracies, statements or errors. The conclusions and recommendations given in the report are also not necessarily that of the supervisor, sponsors or companies involved in the research. In addition, most of the work conducted in this thesis was published in or submitted to international engineering journals as shown in the list of publications.

Signature of student:



Name of student: Selinah Busang

Student number: 2070827

Date: 17/01/2021

ACKNOWLEDGMENTS

Firstly, and above all, I would like to show gratitude and praise to the Almighty God for giving me the opportunity and strength to study, and complete my Doctor of Philosophy (PhD), by His grace and mercy, He saw me through the impossible, difficult and tough situations.

I would also like to express my heartfelt appreciation to my supervisor, Professor James Maina, for his endless supportive guidance, advice, and patience from the first until the final day. He moulded my research skills and broadened my capabilities through their presence, mentoring, and monitoring. This work would be incomplete without his efforts and teamwork. I am blessed and privileged to have worked under his supervision. He opened networking channels and advanced my writing, analytical, and communication skills. His work ethic and expertise played a crucial role in helping me complete this research. Furthermore, his words of encouragement and consistency in checking up on me gave me strength. I am forever grateful to have learned a lot from him.

Botswana International University of Science and Technology (BIUST), University of Nottingham and University Lisbon are acknowledged for providing laboratories equipped with advanced equipment to aid my research. I would like to thank BIUST, University of Nottingham and University Lisbon departments; Civil & Environmental, Chemical, Materials & Metallurgical, Mining & Geological, Physics & Astronomy and Earth & Environmental Sciences, for allowing me to use their laboratories, chemicals, and equipment. My thanks are extended to Sasol for the provision of x-ray CT.

Special thanks to Tosas Botswana and SAMBIT Botswana for providing Pen 40/60 and 50/ 70 bitumen. Botswana Institute for Technology Research and Innovation (BITRI) is thanked for availing of its SEM. Lastly, I would like to appreciate the support and generosity of the Australian Road Research Board (ARRB) for helping with the shipping samples and Wheel tracking test at their own cost.

Finally, but most importantly, I sincerely appreciate my husband, Martins B Albanese and my mother-in-law Joyce B Albanese for their continuous support during the entire period of this research.

DEDICATION

I dedicate this work and thesis to the soul of my father James, my husband Martin, and my children.

TABLE OF CONTENTS

Chapter 1 : INTRODUCTION	1
1.1 BACKGROUND.....	1
1.1 Pavement structure	2
1.2 Problem statement.....	4
1.3 Objectives of the study	5
1.4 Scope of the study	6
1.5 Approach and methodology	6
1.6 Organisation of the thesis.....	7
CHAPTER 2 :LITERATURE REVIEW	10
2 OVERVIEW.....	10
2.1 Asphalt mixture	10
2.1.1 Characterisation fatigue mechanism in asphaltic mixtures.....	10
2.1.2 Characterisation rutting mechanism in asphalt mixture.....	15
2.1.3 Blistering of asphalt pavement under the action of salt	17
2.1.4 Mechanical performance	19
2.2 Material characteristics	24
2.2.1 Influence of bitumen binder	24
2.2.2 Influence of aggregate	25
2.3 Use of microstructure to predict the mechanical performance	26
2.3.1 Aggregate grading.....	27
2.4 Aggregate packing.....	28
2.4.1 Packing fractions and densities	29
2.4.2 Bailey method of gradation analysis and asphalt mix design	30
2.4.3 Dominant Aggregate Size Range (DASR).....	31
2.5 Compaction methods.....	32
2.6 Laboratory mechanical performance testing.....	33
2.6.1 Testing of rheological properties of a binder	33
2.6.2 Laboratory fatigue testing	35
2.6.3 Laboratory permanent deformation testing.....	36

2.7	Microstructural analysis	37
2.7.1	Fabric tensor	37
2.7.2	X-ray computed tomography (X-ray CT)	40
2.7.3	Discrete elementary method (DEM)	41
2.7.4	Hydraulic conductivity tensors.....	43
2.8	Clump.....	44
2.9	Bitumen modification.....	45
2.9.1	Use of fibre on bitumen modification	45
2.9.2	Use of fibre to improve performance under action of salts.....	48
2.10	Discussion.....	48
CHAPTER 3: METHODOLOGY		50
3 NUMERICAL MODELLING OF ANISOTROPY OF MICROSTRUCTURAL PROPERTIES ASPHALT MIXTURE W OF THE GRADATION		50
3.1	Objective(s) and scope	50
3.1.1	Creating the realistic aggregate particles shapes.....	51
3.1.2	Aggregate gradation	54
3.1.3	Virtual packing and sample testing	55
3.2	Microstructure analysis by fabric by scan line approach	58
3.2.1	Normal contact and scan line void fabric tensors	58
3.3	Hydraulic conductivity tensors.....	59
3.4	Preliminary results and discussions	60
3.4.1	Anisotropy microstructural properties	60
3.4.2	Porosity.....	61
3.5	Discussion	67
CHAPTER 4: MATERIALS AND DATA		68
4 MATERIALS AND CHARACTERISATION		68
4.1	Aggregate (rock mineral in Botswana)	68
4.2	Bitumen	72
4.3	Teak fibre	73
4.3.1	Thermogravimetric analysis.....	73

4.4	Daily environmental	76
4.5	Discussion	77
CHAPTER 5: LABORATORY TESTING		78
5	EXPERIMENTAL PROCEDURES	78
5.1	Comparison of modelled and laboratory permeability	78
5.2	Bitumen modification using TK fibres	79
5.2.1	Multiples stress creep recovery	84
5.3	The anisotropy of asphalt mixture	86
5.3.1	Marshall stability	88
5.3.2	Wheel tracking test	89
5.3.3	Three Bending test	90
5.3.4	Complex modulus and complex Poisson's ratio	92
5.3.5	Image analysis and microstructural analysis	93
5.4	Contact mapping analyses by fabric tensors	96
5.4.1	Grey relational analysis method	97
5.5	Preliminary results	99
5.5.1	Comparison between dem and laboratory porosity in different depths ...	99
5.5.2	The directional permeability	100
5.6	Discussions	101
CHAPTER 6: RESULTS FROM EXPERIMENTAL WORK		102
6	RESULTS INTERPRETATION AND DISCUSSION	102
6.1	Overview of research methodology	102
6.2	Mechanical performance of teak fibre modified bitumen.	103
6.2.1	Penetration	103
6.2.2	Rutting factor	103
6.2.3	Thermal conductivity	104
6.2.4	Multiple stress creep recovery test (MSCR)	105
6.3	Case study	112
6.4	Influence of aggregate properties on microstructural properties and mechanical performance of asphalt mixtures	117

6.4.1	Influence of chemical properties to angularity, strength and shape.....	117
6.4.2	Thermal conductivity and volumetric heat capacity	120
6.4.3	Influence of angularity to mechanical properties.....	123
6.4.4	Complex Poisson's ratio.....	127
6.4.5	Grey relational grade	130
6.5	The significance of the research.....	133
CHAPTER 7: CONCLUSION.....		134
7	CONCLUSIONS AND RECOMMENDATIONS.....	134
7.1	Numerical modelling of anisotropy of microstructural properties asphalt ..	134
7.2	Rheological properties of TK fibre modified butemen mastic.....	134
7.3	Influence of aggregate properties on microstructure properties and mechanical properties	135
7.4	Remarks and recommendations	136
7.5	Future works	136
References.....		137

LIST OF TABLES

Table 2-1: Penetration and Viscosity graded bitumen	33
Table 2-2: Main findings for reinforcing asphalt mixture using fibres	46
Table 3-1: Main micro-properties	56
Table 3-2: DASR–IC Parameters for AC gradation	64
Table 4-1: Gradation scope 1 of 3 types of aggregate.	69
Table 4-2: Gradation scope 2 of 3 types of aggregate.	69
Table 4-3: Particle size distribution for the control of the shape	70
Table 4-4: Chemical composition of aggregate	70
Table 4-5: Aggregate particles properties.....	71
Table 4-6 Bitumen properties	72
Table 4-7: Bitumen properties	72
Table 4-8: Properties of TK fibres	74
Table 4-9: TK fibre parameters.....	74
Table 4-10: The crystallinity index of TK fibre.....	74
Table 4-11: Mechanical properties of TK fibre	76
Table 5-1: Experimental programme	81
Table 5-2: Stress levels for the MSCR test.....	84
Table 5-3: Number of replicates per test.....	88
Table 5-4: Symbol list for Grey relational analysis method	98
Table 5-5: Directional permeability for samples	101
Table 6-1: Kruskal-Wallis test.	108
Table 6-2: Pair-wise comparison of recovery for TK fibres (%).....	109
Table 6-3: Pair-wise comparison of Jnr for Recovery TK Content	111
Table 6-4: Number of contact points and mechanical properties	124
Table 6-5: Data normalization	132
Table 6-6: Grey relational coefficient.....	132
Table 6-7: Grey relational degree	132

LIST OF FIGURES

Figure 1-1: Cross-section of Roman roads	1
Figure 1-2: Cross-section of McAdam roads	2
Figure 1-3: Change in pavement layer thickness with time	2
Figure 1-4: Typical flexible pavement	3
Figure 1-5: Graphical study flow chart	9
Figure 2-1: Examples of fatigue on asphalt pavement	11
Figure 2-2: Response of elastic, viscous and viscoelastic material under constant stress loading	13
Figure 2-3: Elastic and viscoelastic behaviour under loading and unloading conditions	14
Figure 2-4: Hysteresis loop	14
Figure 2-5: Phase lag between the applied load and the measured strain	15
Figure 2-6: Permanent deformation (rutting) (google picture)	16
Figure 2-7: Permanent deformation under repeated loading	17
Figure 2-8 a: Illustration of heat transfer coupled with salt transport, (b): example of blistering on the asphalt layer	18
Figure 2-9: The effect of rest periods during a fatigue test	20
Figure 2-10: Stress-Temperature deformation mechanism map of 50 Pen bitumen in tension	25
Figure 2-11: Aggregate stone skeleton	26
Figure 2-12: Wheeltracking apparatus	36
Figure 2-13: Illustration of wall and loosening effects and line scan void	43
Figure 3-1: Chapter flow chart	51
Figure 3-2: X-ray CT images (a) actual aggregate (b) scanner	52
Figure 3-3: Quadrangle and STL model	53
Figure 3-4: STL files	53
Figure 3-5: Clumps simulating realistic shapes	54
Figure 3-6: Clumps library	54
Figure 3-7: sample thickness of virtual sample	Error! Bookmark not defined.
Figure 3-8: Scan line approach	59
Figure 3-9: Development of fabric variances αt and αvs under vertical axial strain	61

Figure 3-10a and b: Relationship between αt and αvs for all samples, 5L500_0.5. The solid line relates to a linear regression through the origin, and the two light visible characterise 95% confidence level.....	61
Figure 3-11: Recorded porosity for various binary mixes for GS 1- Error! Bookmark not defined.	
Figure 3-12: Recorded porosity for various binary mixes for GS 2- Error! Bookmark not defined.	
Figure 3-13: Porosity at different depths for mixture 1	65
Figure 3-14: Porosity at different depths for mixture 2	66
Figure 3-15: Gradations	67
Figure 4-1: Thermograms of TK fibre at various particle sizes.....	75
Figure 4-2: TK fibre SEM.....	76
Figure 5-1: Prepared laboratory samples using modelled gradation	79
Figure 5-2 and 5-3b: A picture of upper and lower portions of the bubble tube constant head permeameter, and 5-3c: Bubble tube constant head permeameter	79
Figure 5-3:Flow chart of the chapter	80
Figure 5-4: Dynamic shear rheometer	82
Figure 5-5: A Hilton heat transfer.....	83
Figure 5-6: Multiples stress creep recovery (Anton Paar MCR 302 DSR)	85
Figure 5-7: Servopac gyratory compactor	86
Figure 5-8: The section flow procedure and plans	87
Figure 5-9: Marshall testing machine	89
Figure 5-10: Wheel tracking test	90
Figure 5-11: Three bending test.....	91
Figure 5-12: Cylindrical samples set for axial and radial strain measurements	93
Figure 5-13:Illustration of sawed samples	94
Figure 5-14: Illustration of slice on a scan scanner	94
Figure 5-15: Image analysis and processing focus on coarse aggregate particles (a) an example section of UTA-10 with green filter, (b) zoomed binary image, (c) contact judgment processing, (d) definition of the contact indices, (e) orientation	95
Figure 5-16: Vectors that describe the microstructure of asphalt mixture.....	97
Figure 5-17: Comparison of laboratory and estimated porosity at different depths for mixture 1	99

Figure 5-18: Comparison of laboratory and estimated porosity at different depths for mixture 2	100
Figure 6-1: Penetration of base and modified bitumens	103
Figure 6-2: Rutting factor of base and modified bitumens (Busang and Maina 2021)	104
Figure 6-3: Thermal conductivity of base and modified bitumens	105
Figure 6-4: Creep-recovery curves of base and modified bitumens	106
Figure 6-5: Percent recovery at all stress levels (Busang and Maina 2021).....	107
Figure 6-6: Non-recoverable creep compliance at all stress levels	107
Figure 6-7: Creep-recovery curves of base (Pen 40/60) and TK 1 bitumen at all salt contents and ageing times	114
Figure 6-8: Creep-recovery curves of Base (Pen 50/70) and TK 1 bitumens at all salt contents	Error! Bookmark not defined.
Figure 6-9: Percentage recovery of base (Pen 40/60) and TK 1 bitumens at all salt contents and different ageing times.....	115
Figure 6-10: Range of contact orientation of different gradations	119
Figure 6-11: Range of contact length for different gradations	119
Figures 6-12a, b and c: The highest and lowest the daily surface temperature: (upper) difference of the thermal conductivity in summer, (bottom) difference of the volumetric heat capacity in summer	123
Figure 6-13: The urban heat island impact, solar radiation, and air temperature for all mixtures	123
Figures .6-14, b and c: Correlation between F and Marshal stability, dynamic stability and stiffness modulus	127
Figures. 6-15: Master curves of the complex Poisson's ratio of GD 1, GD 2 and GD 3 asphalt (a)mixtures for norm and (b) phase angle.....	128
Figure 6-16: Correlation between fatigue accumulative strain with stiffness modulus and creep strain for (a) GD 1, (b) GD 2 and (c) GD	130

LIST OF SYMBOLS/ VARIABLES

N_f	number of cycle to failure,
ε, σ	tensile strain or stress repeatedly applied,
A, b, C, d	material coefficients, derived by fitting the data from laboratory testing.
i	course range
j	fine range
r_i	volumetric fractions of course range
r_j ,	volumetric fractions of fine range
ϕ_i	packing densities of course range
ϕ_j	packing densities of fine range
ϕ_i^*	packing density of the binary aggregate skeleton mixture when size course is predominant
ϕ_j^*	packing density of the binary aggregate skeleton mix when size fine range is dominant
$E(\mathbf{n}_{vc})$	directional distribution of the vector density
a_{vc}	non-dimensional second-order tensor,
vc	numbering the void vectors
$\overline{E^0}$	average directional distribution of the vector density
$\mathbf{n}_{vc}$	vectors joining the centre of the void cell and the contacts,
k_{vc}	numbering of the void vectors,
N_{vc}	total number of void vectors
V	volume
$(\mathbf{n}, -\mathbf{n})$.	two unit vectors are established on the main axis.
$\otimes$	tensor product
$\mathbf{N}_t$	number of vectors,
θ and φ	spherical coordinates of the vector $\mathbf{n}_t$
α_t	highest principal values for the contact normal fabric
α_{vs}	lowest principal values) for the void fabric
K_{ij}	hydraulic conductivity
$g^{\theta\varphi}$	weight factor.
N	total number of particles of the mix,
V_i	volume of subset i of a given z^* ,

A_{tot}^*	total area of the mix,
A_i	cross-sectional area of subset i,
z^*	height of the subset,
Δz^*	small increment of dimensionless height.
V_{TM}	total volume of a mix,
VMA	voids in mineral aggregate.
μ	friction coefficient
k_n ,	normal contact stiffness
k_s ,	shear contact stiffness
pb_nstren	parallel bond normal
pb_sstren	shear strength
pb_kn	parallel bond normal
pb_ks	shear stiffness
V_{be}	effective volume of asphalt binder
W_T	total weight of the mixture,
P_b	percentage of the amount of bitumen or water content by mass of the total of the mixture
Abs	absorption,
P_{AGG}	aggregate percentage by mass of total mixture,
G_b	specific gravity of bitumen binder,
SA	surface area of fine aggregate,
PF_{AGG}	percentage of fine aggregate by mass of total mixtures.
a_{ij}	loosening effect coefficient
b_{ij}	wall effect coefficient
c_{ij}	wedging effect coefficient
i_{th}	void vector with respect to θ ,
$\mathbf{n}^{\varphi, \theta}$	unit vector of the i_{th} void scan line.
i_{th}	void tensor can be measured as an area
N^θ	sum of scan line segment inclination angle $\theta\varphi$,
$g^{\theta\varphi}$	weight factor,
φ, θ	direction of the unit vector in 3D.
$F_{\text{lk}}^{\text{AVS}}$	fabric of APS
δ_{im}	identity tensors.

I_{002}	crystallographic counter reading, and
I_{am}	amorphous phase counter reading at 2θ in the specimen
$R(\%)$	percentage recovery
ε_1	strain value at the end of the creep portion
ε_{10}	strain value at the end of the recovery portion
d_1	extent of deformation at the time t_1
d_2	extent of deformation at the time t_2 ;
N	rapidity of tire 42 passes per 60 seconds
$C1$	coefficient of the alteration connected to the machine
$C2$	coefficient of alteration connected to the samples
R_B	flexural tensile strength
ε_B ,	maximum flexural tensile strain
L	length
b ,	width
h	height of the samples,
P_B	maximum load at the time of sample failure,
d	mid-span deflection at the time of breakage
S_B	bending stiffness modulus
σ_1	axial stress
ε_1	axial strain
ε_2	radial strain
t	function of time
E^*	complex modulus
ν^*	complex Poisson's ratio
f	frequency
σ_{01}	stress
ε_{01}	axial strain
ε_{02}	radial strain,;
$\phi_{\sigma 1}$	Phase angle stress
$\phi_{\varepsilon 1}$	axial
$\phi_{\varepsilon 2}$	radial strain
j^2	complex number
$ E^* $	The norm

ϕ_E	phase angle of the complex modulus
$ v^* , \phi_v$	complex Poisson's ratio
$x_i(k)$,	after normalisation i series k. value, $x_i^0(k)$ =i series k,
$\min x_i^0(k)$	minimum value in i series,
$\max x_i^0(k)$	maximum value in i series,
x^0	desire deal value,
x_i	m series with x^0 series,
ξ	a coefficient between (0,1),
$\Delta_{\min}$	minimum value in the series,
$\Delta_{\max}$	maximum value in the series,
$\Delta_{0i}(k)$	k value in the series,
$\gamma(x_0, x_i)$	grey relation degree in i. rank,
W_k	total weight .

LIST OF ABBREVIATIONS

SADC	Southern African Development Countries
DASR	Dominant Aggregate Size Rang
HMA	Hot mix asphalt
WMA	Warm Mix Asphalt
iPAS	Software Image Processing Analysis System
DIP	Digital image processing
2D	Two-dimensional
CCD	Charge-Coupled Device
PFC3D	Particle Flow Code
TK	Teak fibre
MSCR	Multiples Stress Creep Recovery
DEM	Discrete Element modelling
LEFM	linear elastic fracture mechanics
NLFM	Nonlinear fracture mechanics
NaCl	Sodium chloride
NaHCO ₃	Sodium hydrogen carbonate
PMB	Polymer Modified Binder
ESAL	standard axle loading,
RAP	Recycled asphalt pavement
QA	Quality assurance
QC	Quality control
SMA	Stone Matrix Asphalt
NMAS	Nominal Maximum Aggregate Size
HS	Half Size
PCS	Primary Control Sieve
SCS	The secondary Control Sieve
TCS	Tertiary Control Sieves
OP	Oversize pluggers
EFT	Effectictive sample thickness
IC	Excessive
DF	Disruption Factor
X-ray CT	X-ray computed tomography
STLS	STereoLithography

APS	Areal Pore Size
SBR	Styrene-Butadiene Rubber
SBS	Styrene-Butadiene-Styrene
PE	Polyethylene
CaCl ₂	Calcium chloride
BTCHP	Bubble Tube Constant Head Permeameters
PAV	Pressure ageing vessel
TTSP	Time-temperature superposition principle
FAR	The fine aggregate represents the fineness of the IC
CFA	The coarse portion of the fine aggregate
FFA	The fine portion of the fine aggregate.
F	Fabric tensors
SATS	Saturation Ageing Tensile Stiffness

1 : INTRODUCTION

1.1 BACKGROUND

Recent development has shown the need for quality and efficient transportation infrastructure for a better life. Across the world, roads are one of the essential modes and very affordable transportation systems. In the past roads were made for wagons; therefore, most had short live services because of poor paving and drainage structure. Roman-built straight three-layered roads to enjoy the shortest marching paths over the past two centuries. Their layers had three sizes of stones: from the large to the smallest size, and some side ditch drainages to minimise road damages by stormwater. Figure 1-1 is an illustration of Roman roads.

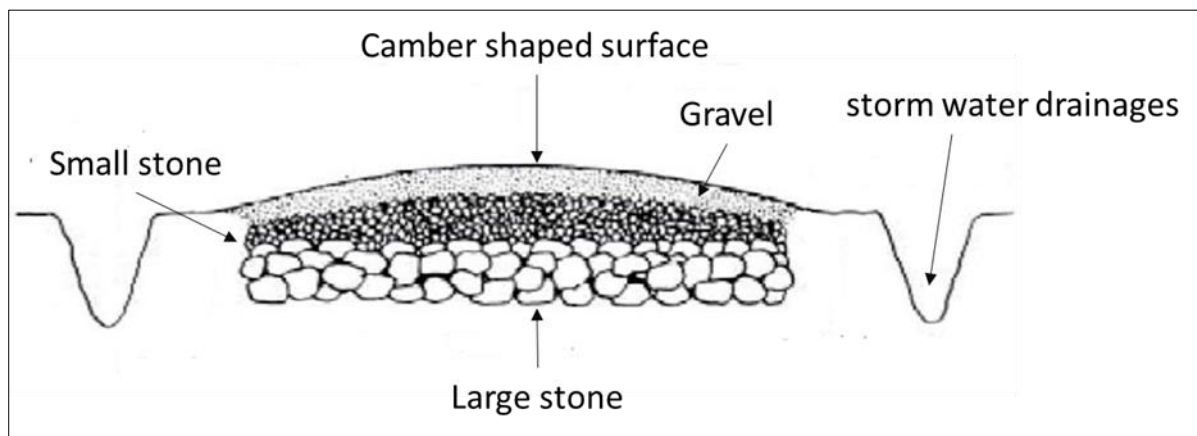


Figure 1-1: Cross-section of Roman roads (Britannica, 2021)

In the 18th century, the Roman roads attracted some ideas in France by Tresaguet and in the United Kingdom by Thomas Telford (1757-1834) and John Loudon McAdam (1756-1836) to develop some construction designs. Most importantly, engineer John Loudon McAdam introduced road construction design using compacted angular stones. The stones, smaller than the ones used by the Romans, were laid symmetrical, with a top layer of small stone to a hard surface, as shown in Figure 1-2. Like the recent roads, McAdam's course layers were formed from compacted angular stones that interlocked to provide the strength and stiffness of the road. The name "Macadam roads" is an honour for McAdam's designs, known for thinner layers. The layer thickness changed with time due to the aim to improve the performance of the roads, as illustrated in Figure 1-3 (Interaction, 2008).

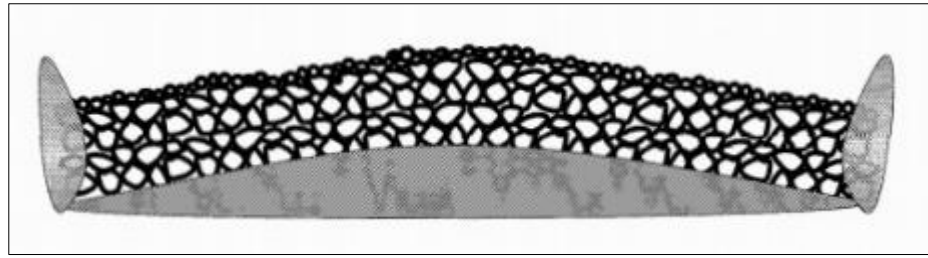


Figure 1-2: Cross-section of McAdam roads (Read, 1996)

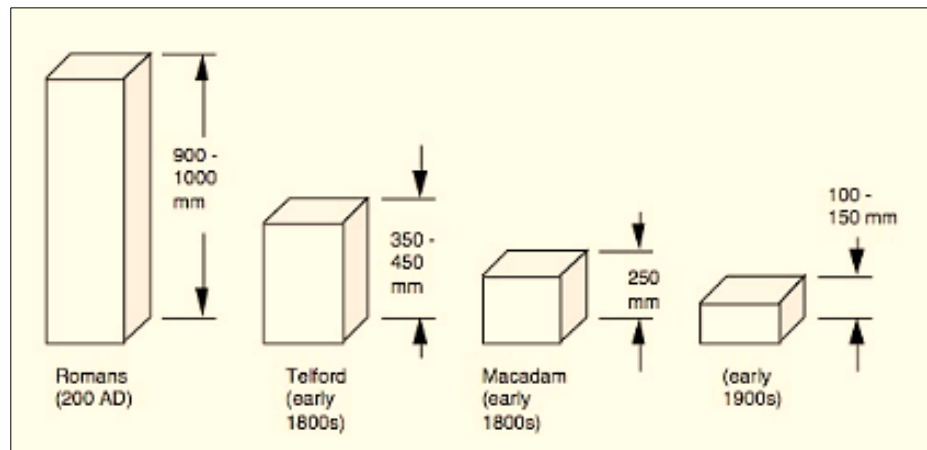


Figure 1-3: Change in pavement layer thickness with time (Interaction, 2008)

Towards the 20th century, many nations, including South Africa, adopted asphaltic material for road constructions to cater to more vehicle use and reduce dust for health purposes. Afterwards, most SADC countries visited South Africa and invited some experts with an aim to benchmark and adopt some manuals and methodologies to construct their pavements. At first, the use of tar was introduced, and later, a by-product of petroleum, namely bitumen, was widely adopted worldwide (Taherkhani, 2006a).

1.2 Pavement structure

In general, roads are designed to carry traffic safely, economically and conveniently throughout their design life. The road pavement consists of three layers compacted mainly to offer easy movement and a solid and smooth surface for road users. The three types of pavement characterised by the nature of the material used include,

- flexible pavement is built using asphaltic materials,
- rigid pavement is made using a concrete slab, and
- composite pavement is constructed from both asphaltic material and a concrete slab

The study focuses on flexible pavement, consisting of asphalt layers such as surface course, binder course, and base coarse, as illustrated in Figure 1-4 (Taherkhani, 2006b).

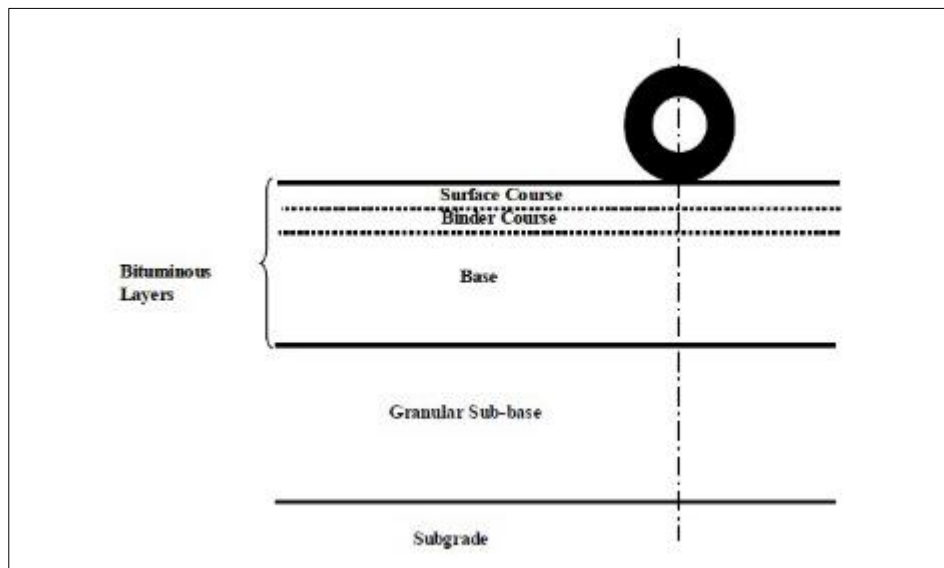


Figure 1-4: Typical flexible pavement (Taherkhani, 2006a)

The endeavour, demand, and developments in promoting easy trading between Southern African Development Countries (SADC) have renewed interest in constructing highways to international standards. The main aim of these international standards is to build a surface course that provides a protected and smooth surface for vehicles with adequate skid resistance at their low cost, good durability, accessibility, convenient construction and ease of maintenance and repair compared to cement concrete (Chen, Huang and Shu, 2013). A good quality surface course acts as a waterproof to the sub-layers. The skid resistance of a surface course depends on the microtexture and macrotexture mixture. However, due to the increased traffic volume and vehicle load, particularly the influencing factors of traffic overload, which damages asphalt pavement frequently in its early use. Also, with the endeavour and demand for the long-distance transportation of bulk freight, the roads are subjected to different service lives due to variations in construction materials and climatic changes. These damages reduce the life service of the pavement and increase the maintenance expenses. There is a need to develop asphalt mix designs with good mechanical performance, which is very important for infrastructure with high concentrations of heavy trucks.

1.3 Problem statement

The study concerns are factors that affect the mechanical performance of asphalt design mixes, such as aggregate gradation and packing, aggregate properties, and quality of binders. Aggregate gradation has a significant influence mechanical performance of asphalt mixtures. Horak *et al.*, (2017) stated that the aggregate packing and particle orientation are supposed to withstand the repeated traffic load since they are the highest asphalt mixture, constituting a volume of about 85% on average of the total asphalt mix. The methods such as the Bailey method and Dominant Aggregate Size Rang (DASR) (Kim, 2006) were established with the aim to optimise the aggregate gradation packing and enhancing load-bearing microstructure in Hot/ Warm Mix Asphalt (HMA/WMA). Also, packing density models were developed to improve aggregate packing (Wong and Kwan, 2014; Kwan, Wong and Fung, 2015). They accounted for a wall effect coefficient b induced by “dominant fine aggregate range” and a loosening effect coefficient a induced by “dominant coarse aggregate range”. Besides all various attempts to optimise the aggregate gradation to enhance microstructural properties, there is insufficient knowledge on how to optimise aggregate gradation in asphalt mixtures design and hence mechanical performance.

Currently, the use of modifiers to improve the rheological properties of the binders is increasing (Behbahani, 2007; Christy and Tensing, 2010; Subhy *et al.*, 2021). The use of fibres can expressively enhance bitumen mechanical properties such as penetration and viscosity (Weise and Zeissler, 2016; Mohammed, Parry and Grenfell, 2018). Fibre properties are length, adhesion, absorption, swelling and however, and how these properties influence bitumen is not well understood.

On the other hand, several SADC countries are semi-arid. They experience blistering, a common phenomenon, as one distress mechanism caused by different detrimental salts causing poor bonding at the interface of aggregate and bitumen (Busang and Maina, 2021). When hot moisture evaporates and reaches this delaminated interface, it can result in blistering due to heat and thermal expansion (Busang and Maina, 2021). There is an increasing interest in the semi-arid areas to use fibre to enhance the mechanical properties of asphalt mixtures to obtain durable and sustainable pavements (Busang and Maina, 2021). The use of fibre to remediate salt damages is not well understood.

Furthermore, factors affecting microstructural and mechanical properties are aggregate gradations, aggregate properties, binder quality (Arambula, 2007; Elshaer and Daniel, 2018). However, not much has been done to understand the influence of aggregate properties on

microstructure properties and mechanical properties. Fabric tensors have been used widely to assess the microstructure of granular material. However, not much has been done to determine the anisotropy of the asphalt mixture.

1.4 Objectives of the study

The study optimises the microstructural properties to obtain durable, flexible pavements with high fatigue and rut resistance. The three primary objectives are outlined for this research:

- Numerical modelling of anisotropy of microstructural properties asphalt mixture
 - a. To simulate the realistic particles shape and triaxial test for compaction
 - b. To analyse the virtual microstructural properties such as inter-aggregate contact and voids in the x,y,z – directions using the statistical distribution vectors by applying the DEM (the void scan line). Afterwards, to measure the air voids' size, shape and orientation based on second-order fabric tensors. To determine the correlation between the contact normal fabric tensor and void fabric tensor.
 - c. The void fabric tensors were used to calculate the porosity of the virtual microstructure. Also, the porosity binary mixtures in a microstructure according to the Bailey method were determined and, most importantly, DASR
- Laboratory simulation and mechanical performance of unmodified and teak modified bitumen under the action of saline
 - a. To assess the effect of TK fibres on the rheological properties of the bituminous binders and,
 - b. To investigate the stress sensitivity of bitumens to assess adhesion loss due to the action of salt, i.e. NaHCO₃ solution.
- To evaluate the influence of aggregate properties on microstructural properties and mechanical performance of asphalt mixtures
 - a. To use the Image Processing Analysis System (iPAS) software centred on obtaining the asphalt mixture's microstructural properties. A two-dimensional (2D) image processing approach based on a Charge-Coupled Device (CCD) uses digital cameras to capture the cross-sectional images of the microstructures.

- b. Constructed Fabric tensors were used to evaluate aggregate interlocking in the asphalt mixture.
- c. Use the testing parameters including Marshall stability, dynamic stability and bending stiffness modulus, and complex Poisson's ratio to assess the influence of aggregate' chemical and physical properties on the mechanical performance of the asphalt mixtures using gradation obtained from objective one and TK fibre modified bitumen mastic.

1.5 Scope of the study

The focus of the study is to use parameters that influence the microstructure stability, such as aggregate size fraction range, shape percentage, Dominant Aggregate Size Range (DASR), aggregate densities, and Destructive Factor (DF) optimise all gradations using PFC3D. To use the scan line approach to identify and quantify the wall and loosening effects by quantifying the voids' shape and orientation. Also, to determine the correlation between normal contact and void fabric evolution.

In addition, the scope of the assessment includes tests on rutting factors, penetration, as well as the multiple stress, creep recovery (MSCR) on the base and TK fibre-modified bitumens. Then the mechanical properties of base and TK fibre-modified bitumens under auction of salt were determined using MSCR.

Furthermore, use the testing parameters including Marshall stability, dynamic stability and bending stiffness modulus, and complex Poisson's ratio to assess the influence of aggregate' chemical and physical properties on the mechanical performance of the asphalt mixtures using gradation obtained from objective one and TK fibre modified bitumen mastic

1.6 Approach and methodology

The study's aim is to optimise microstructure and mechanical properties using fabric tensors. The schematic showing the flow chart of the methodology adopted is shown in Error! Reference source not found. The details are as follows.

- Use MATLAB and PFC3D were used to achieve the high details clumps to simulate natural aggregate shapes,
- Optimise aggregate gradation by considering indices such as fraction size ranges based on the Bailey method fractions description and their densities, the

porosity of binary mixes, including dominant aggregate size range DASR, optimising the IC control DF using PFC3D,

- Apply a triaxle test on clump microstructure and use the DEM method to develop void and normal contact fabric tensors and calculate porosity based on the scan line method,
- Rheological properties of a base and TK modified bitumen mastic were determined through rutting, penetration, thermal conductivity, and MSCR tests and significance was determined using ANOVA,
- Rheological properties of a base and TK modified bitumen mastic under the action of salt were simulated using the MSCR test,
- The microstructural properties were captured using a CCD digital camera and analysed them using iPAS software. The effect of the daily temperature variation of the environment on the corresponding temperature gradient through the depth of all asphalt mixtures layers was assessed,
- Marshall, wheel tracking, three-point bending beam, double tension-compression fatigue tests at two periods were conducted to investigate any relationship between the structural performance of the asphalt mixtures and their microstructural properties and
- The grey relations analyses method determined the correlation of various properties' influence on microstructure and mechanical performance.

1.7 Organisation of the thesis

Chapter 1 contains the background of the thesis, which begins by discussing the increasing traffic volumes, which inevitably lead to increased axle loading and harsh climatic conditions resulting in premature damages to asphalt pavement. The global interest and demand in enhancing the mechanical performance transportation of asphalt pavement are presented and thus contribute to the rationale or motivation for this study. The chapter also comprises the objectives, methodology and scope of the study.

Chapter 2 contains the literature review of the thesis. It commences with an explanation of the two major damages found on asphalt mixture, followed by factors that influence resistance to fatigue and permanent deformation, and laboratory tests methods. After that, the chapter covers the science and performance of modified binders in asphalt mixtures. Afterwards, the chapter covers methods and principles to enhance aggregate gradation and

packing. The chapter ends with a discussion that argues and presents the gap in knowledge related to using fabric tensors to understand the anisotropy of microstructure.

Chapter 3 contains a description of and discussion of the aggregate gradation and packing using PFC3D. Then followed by the use of Discrete Element Modelling (DEM) and characterisation of the microstructure using a scan line approach. The characterisation involves the anisotropy of the microstructure, such as void fabric tensor and normal contact fabric tensor.

Chapter 4 consists of three sections: the first section introduces and characterises aggregate and closes off with gradation and shape control from results in Chapter 3. The second section introduces and characterises bitumen grades and TK fibres, followed by a laboratory simulation and mechanical performance of TK fibre modified bitumen mastic. The chapter closes with a case study: an improvement of rheological properties of binder under the action of salt using TK fibre.

Chapter 5 comprises the experimental work of the study, samples preparation, methodologies, and a brief discussion of each stage and the number of replicates of the tests, procedures and preliminary results.

Chapter 6 comprises the results from the analysis and interpretation thereof with discussions specific to the influence of fibre on the rheological properties of bitumen and the influence of aggregate properties on microstructure and mechanical performance.

Chapter 7 comprises the study's conclusions and provides recommendations for future studies on the use of fibre in bitumen binders and fabric tensors and on aggregate grading and microstructural analysis.

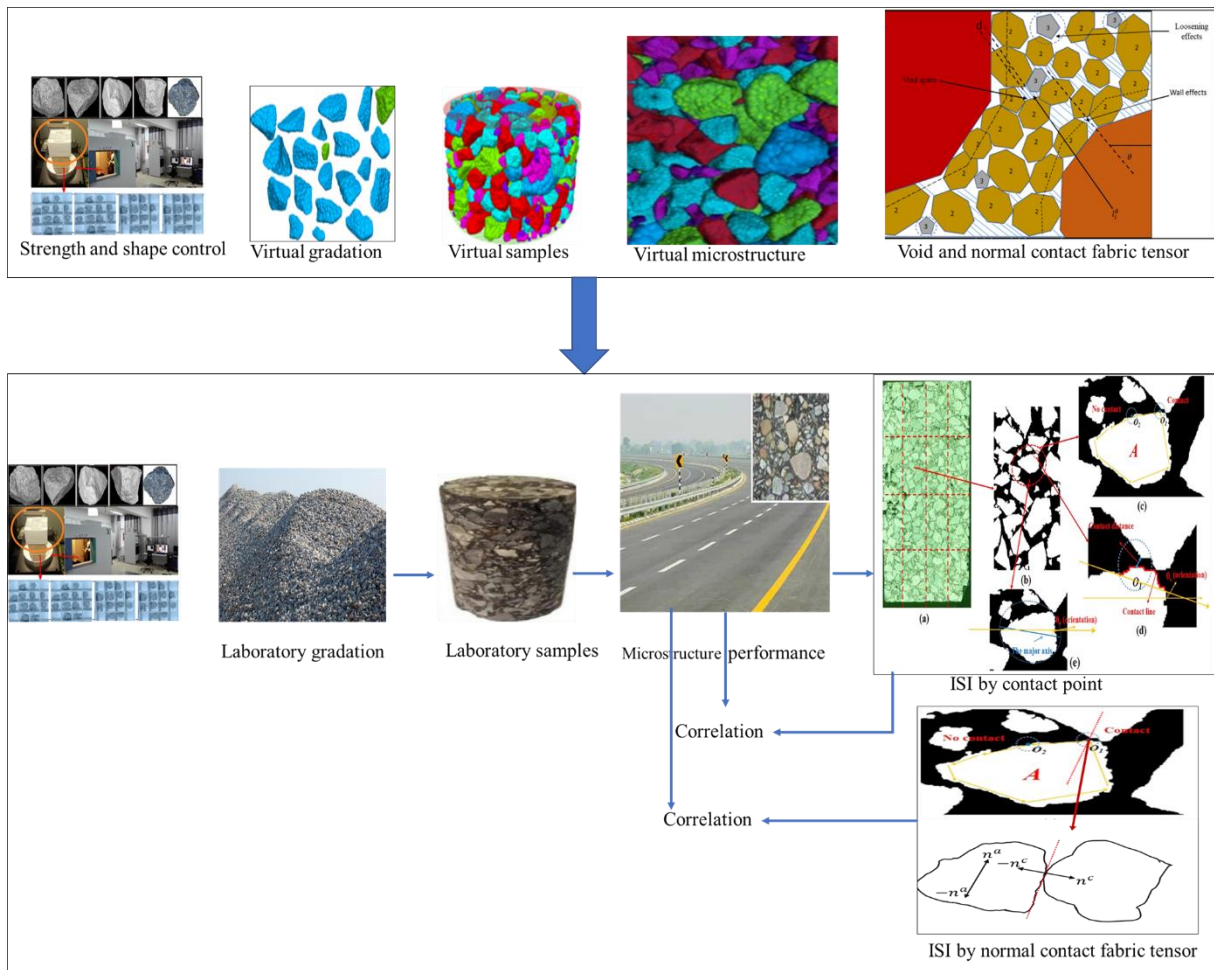


Figure 1-5: Graphical study flow chart

CHAPTER 2 : LITERATURE REVIEW

2 OVERVIEW

This chapter reviews various issues associated with the asphalt mixture's microstructural properties and mechanical performance. The first section discusses the mechanism of two major damages related to asphalt pavement, followed by a discussion on blistering of the pavement caused by salt in semi-arid areas. The factors that influence fatigue resistance and permanent deformation are also discussed in this section. The second section reviews the frequent laboratory experimental tests/ methods used to assess fatigue performance and permanent deformation in the asphalt mixture. The third section discusses the asphalt mixture's related packing theories and characterisation. The Bailey method and DASR, packing fractions and density model for angular aggregate particles in a binary mix, sample thickness and destructive factor will be reviewed in this section as well. The fourth section introduces different methods of analysing the microstructural properties. Finally, fibres used to improve the mechanical properties asphalt mixture are shown.

2.1 Asphalt mixture

Asphalt mixture is constituted of bitumen binder, mineral filler, aggregate and voids. Its mechanical performance is influenced by the interactions of its various constituent materials, such as the interaction between bituminous binder and filler and the interaction between bitumen mastic and aggregate. The major damages related to asphalt pavement are fatigue cracking, which happens at intermediate and low temperatures, and rutting at high temperatures. Another common phenomenon in a semi-arid area is blistering, a distress mechanism induced by detrimental salts causing the loss of adhesion at the interface of aggregate and bitumen.

2.1.1 Characterisation fatigue mechanism in asphaltic mixtures

Cracking in asphalt concrete pavement is cumulative fatigue damage, as shown in Figure 2-1. Three categories of fatigue behaviour are as follows:

- the phenomenological approach,
- the fracture mechanics approach, and
- the energy-based approach.



Figure 2-1: Examples of fatigue on asphalt pavement

2.1.1.1 Phenomenological approach

The fatigue properties of asphaltic mixes can be determined as a correlation between the actual stress or strain and the repeated loading amount. The association usually ignores pavement mechanics' theoretical analysis (Khodary, Hamed and Straßenwesen, 2010). Results from fatigue tests are characteristically expressed as using Eqs. 2-1 and 2-2, all depends on the loading mode:

in strain control mode using Eq. (2-1)

$$N_f = A \left(\frac{1}{\varepsilon} \right)^b \quad 2-1$$

in stress control mode using Eq. (2-2)

$$N_f = C \left(\frac{1}{\sigma} \right)^d \quad 2-2$$

N_f = Number of cycle to failure, ε , σ = Tensile strain or stress repeatedly applied, and A, b, C, d = Material coefficients, derived by fitting the data from laboratory testing.

The phenomenological approach is the most common traditional, ignoring the repetitive load's accumulated damage in the mixture. In addition, the strain fatigue life is a linear association to the accumulated damage. However, (Vavrik *et al.* (2001) indicated that

primarily incorrect at low strain/damage conditions (Carpenter *et al.*, 2003). The phenomenological approach is influenced by material and loading.

2.1.1.2 Fracture mechanics

Fracture mechanics is a cracking mechanism that leads to the fatigue life of asphalt mixtures. Asphalt materials are inhomogeneous in the sense of the hypothesis in the phenomenological approach. They are categorised by pre-existing internal flaws (microcracks) in air voids, surface irregularities and inner shortcomings. For example, cracking can be categorised into crack initiation, propagation, and failure. The first stage refers to the formation and growth of pre-current microcracks. In the process of crack propagation, the cracks begin to propagate at a distinct state of stress and reach critical dimensions and patterns until failure.

The two main groups of fracture mechanics are Linear Elastic Fracture Mechanics (LEFM) and Nonlinear Fracture Mechanics (NLFM). In the LEFM, the concentration of the stress area close to the crack is determined by employing the “stress intensity factor”, and it is a linear function of the stress, the crack and the pavement's geometry. Additionally, the LEFM defines fracture behaviour mainly for fragile materials, and asphalt becomes brittle at low temperatures.

2.1.1.3 Dissipated energy concepts

Asphalt is regarded as a viscoelastic material, which refers to its dissipating (loading and relaxation) energy under mechanical work. Its mechanical performance is influenced by temperature and loading situations; thus, the elastic character at low temperatures and short loading time conditions depicts a vicious character with long loading time conditions at high temperatures. Figure 2-2 illustrates the behaviour of asphalt induced to a constant load. After removing the load, the elastic material describes a complete recovery behaviour to the initial position. In contrast, the strain increases over time with the applied load in the viscous material, and their permanent deformation remains after removing the load. From the naked eye the material looks like it has returned original position but holds a residual deformation on it (Khodary, Hamed and Straßenwesen, 2010).

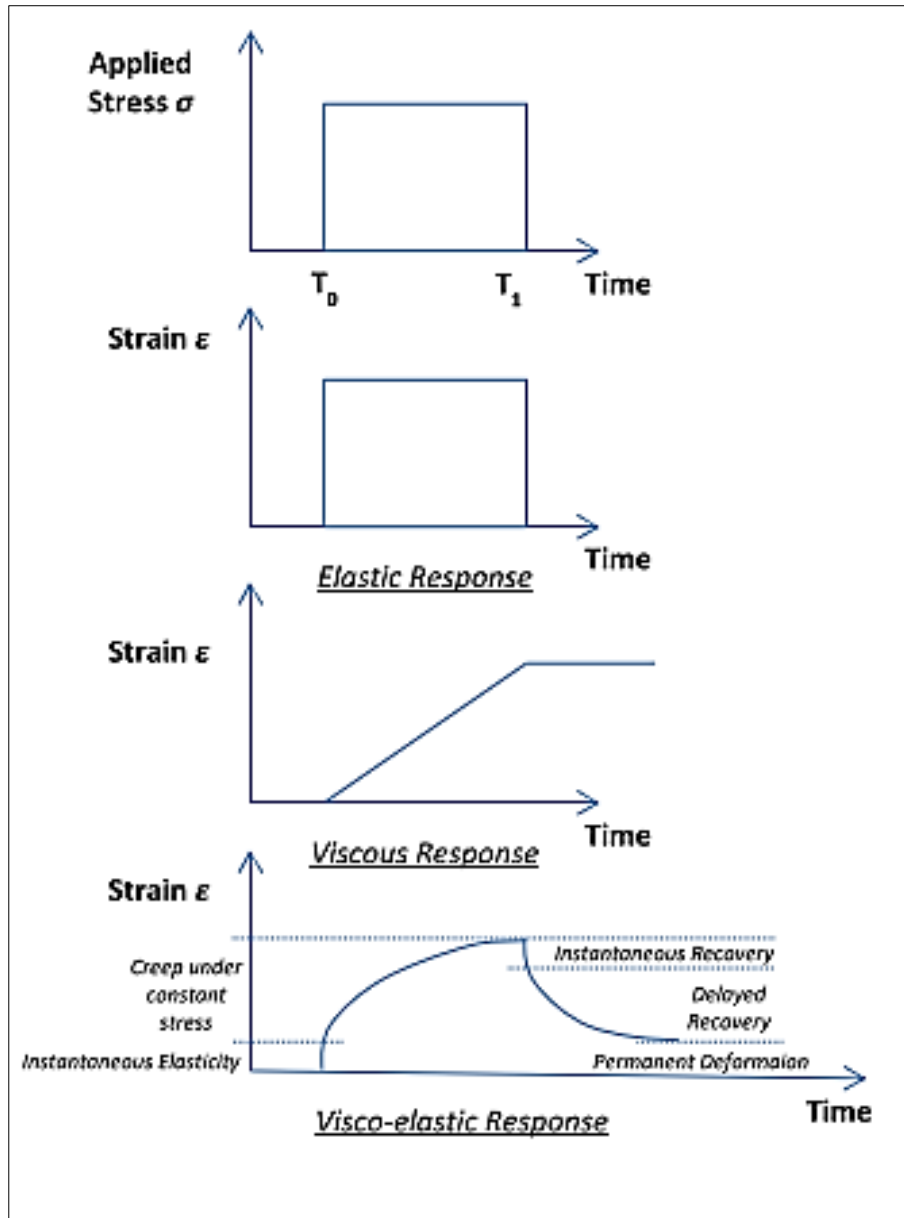


Figure 2-2: Response of elastic, viscous and viscoelastic material under constant stress loading (Khodary, Hamed and Straßenwesen, 2010)

Energetically, the energy is stored in the system when the load is applied to an elastic material. The energy recuperates when the load is removed; in this situation, the dumping and the loading curve harmonise. A hysteresis loop is a perfect way to characterise the viscoelastic materials because the unloaded material follows various transverse to that when loaded, then stage break is measured between the induced stress and the recorded strain); leading to energy dissipating in mechanical work, heat generation, or damage from Figure 2-3 to Figure 2-5.

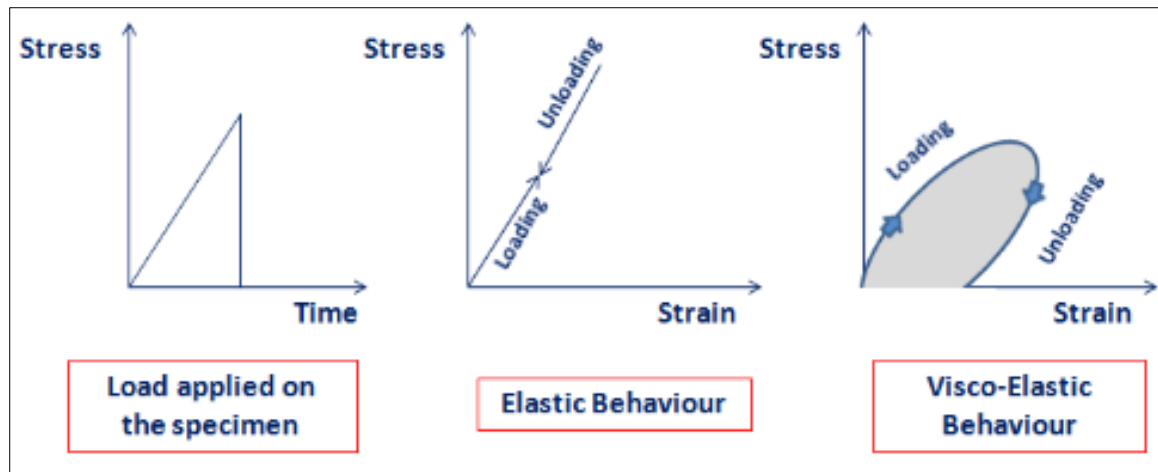


Figure 2-3: Elastic and viscoelastic behaviour under loading and unloading conditions (Rowe, 1996)

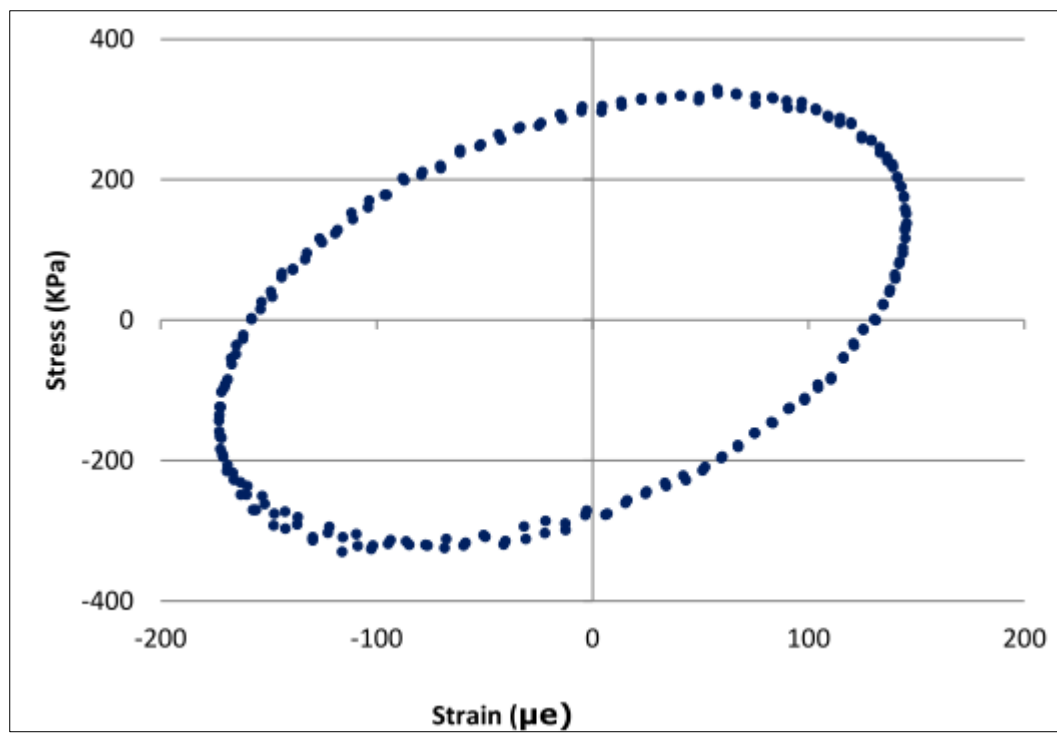


Figure 2-4: Hysteresis loop (Maggiore, 2014)

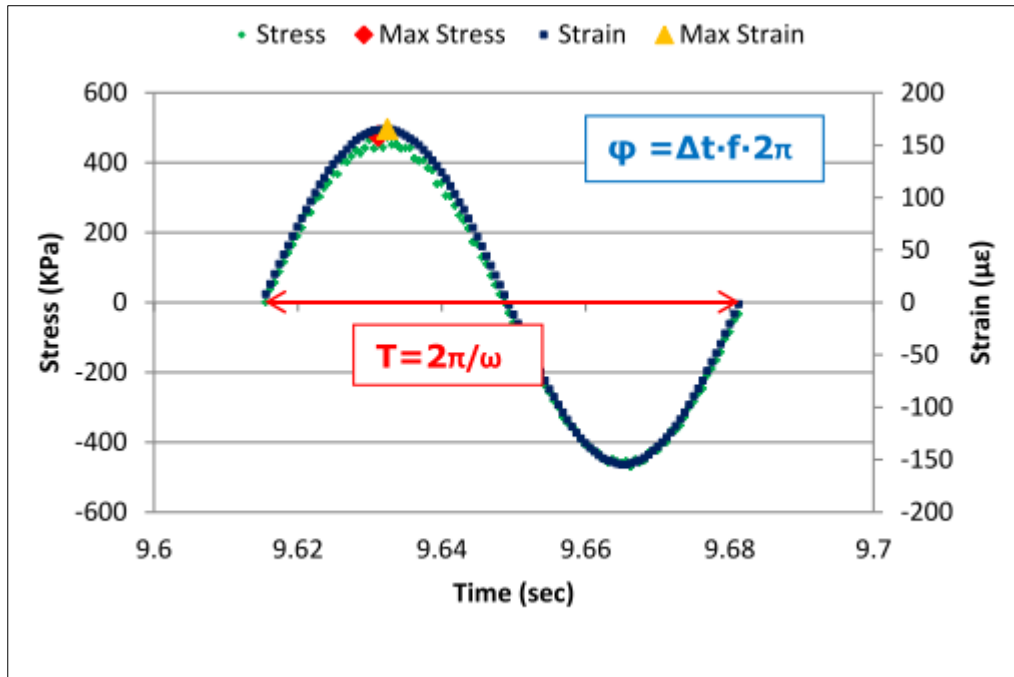


Figure 2-5: Phase lag between the applied load and the measured strain
(Maggiore, 2014)

2.1.2 Characterisation of rutting mechanism in asphalt mixture

Permanent deformation is a major type of damage that degrades asphalt pavement and is distressing for the world. It usually starts in the form of rutting in the wheel track produced by accumulated strains due to repeated traffic loading or a combined densification and shear deformation, as illustrated in Figure 2-6. They are two concepts of rutting mechanism that occurs on the pavement.



Figure 2-6: Permanent deformation (rutting)

2.1.2.1 Densification

Densification is a decrease in volume immediately after pavement due to compaction by first traffic when the binder is still soft and fresh (un-aged).

2.1.2.2 Shear displacement

Shear displacement is a movement of the material without volume changing. Several laboratory investigations support the primary reason for rutting as shear displacement. Shear displacement is a process over time with the pavement's lifespan (Khanzada, 2000). A wheel load applied to asphaltic material in the pavement cause deformation in the material. The degree of the deformation relay on the material properties, amount of load, loading duration, and temperature. After removing the load, some deformation recovers and the rest of the permanent deformation remains in the material. The deformation recovery is associated with a bitumen binder's elastic and delayed elastic properties. In contrast, the permanent deformation is due to a bitumen binder's plastic and viscous properties. Each load passing contributes to a small value of permanent deformation. Due to the small accumulation of these small deformations, consequences lead to high asphaltic material deformities, as illustrated in

Figure 2-7 (Dunhill, 2002). In most well-compacted asphaltic mixtures during construction experiences, only shear deformation is the leading cause of rutting (Hofstra and Klop, 1972).

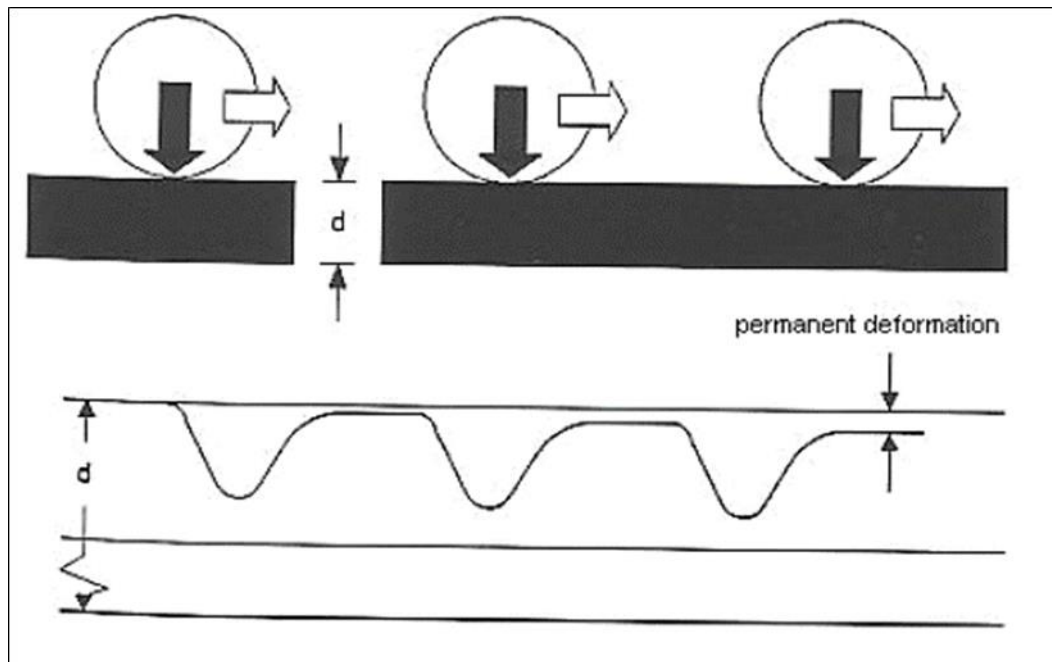


Figure 2-7: Permanent deformation under repeated loading (Taherkhani, 2006a)

2.1.3 Blistering of asphalt pavement under the action of salt

General knowledge suggests that, in arid areas, a build-up of either volatile gases or moisture vapour from the underlying layers of the asphalt pavement that accompanies an increase in surface temperature cause blisters in asphalt pavements. As illustrated in Figure 2-8a, salt-containing moisture evaporates through the pores of the subgrade up to the upper asphalt layers resulting in asphalt blisters during high temperatures; the example is shown in Figure 2-8b. Dry climates with saline materials and saline groundwater or surface water induce salt damage in these areas. Several investigations have suggested that blistering and deformation of asphalt pavement are due to concentrated salts in moisture from underlying layers of the asphalt pavement (Abo-Qudais and Al-Shweily, 2007; Croll, 2008; Z. Wang *et al.*, 2019). Blistering could also be due to interaction between the salts and the mineralogy from aggregate sources in the asphalt materials. This means certain mineral phases might be particularly detrimental and result in blistering (Abo-Qudais and Al-Shweily, 2007; Apeagyei, Grenfell and Airey, 2014; Zhang *et al.*, 2017).

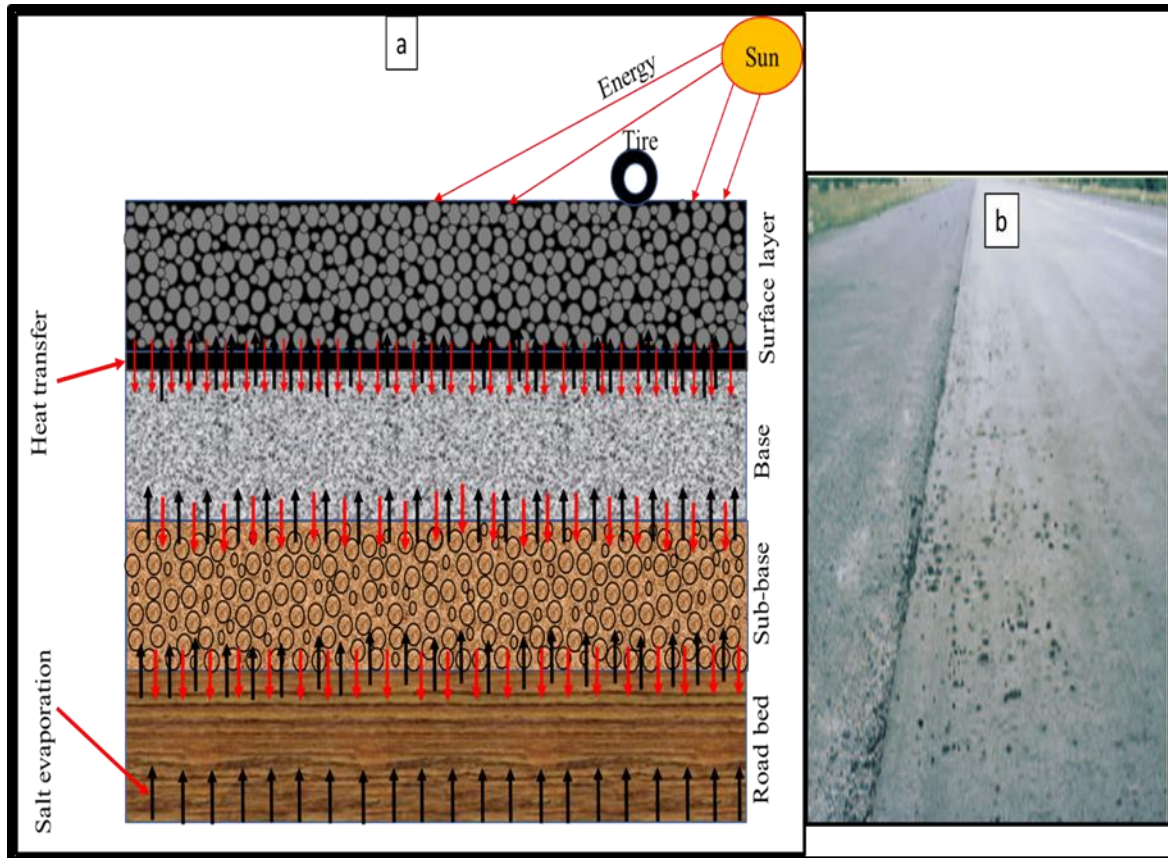


Figure 2-8 a: Illustration of heat transfer coupled with salt transport, (b): example of blistering on the asphalt layer (Busang and Maina, 2021)

More than two-thirds of the total land area of Botswana contains sodium chloride (NaCl) and NaHCO_3 in the soil (Ministry of Works, Transport & Communications Botswana 2001). Reported locations damaged by the action of salts in Botswana include Sua Pan airstrip, Nata-Maun Road (km 0-45), Sebina Nata, Phikwe runway and Sekoma-Kang road (Trans-Kgalagadi road) (Ministry of Works, Transport & Communications Botswana, 2001). Therefore, it is essential to develop a detailed understanding of the effect of the action of salt on the performance of asphalt mixtures, especially in semi-arid regions.

McAloney *et al.* (2001) verified that nano-modified asphalt could remove cryoprotectants (antifreeze compounds and antifreeze proteins) that degrade asphalt mixtures. In their study, the indirect tensile test was performed on unmodified and nano-modified asphalt mixture specimens treated with NaCl solution, and one of the findings was that chloride salts reduced the strength of the asphalt mixture. Similarly, Cooley *et al.* found that antifreeze agents, especially those containing chloride salts, had adverse effects on the aggregate and the asphalt mixture (Cooley, Brown and Watson, 2000). They found that different antifreeze concentrations degrade asphalt mixtures by freezing and thawing more

than pure water. The study by (Yu *et al.*, 2013) analysed the master curves of complex modulus and phase angle and the ultimate fatigue temperature of a long-term aged unmodified and polymer-modified bitumen after soaking in various salt solutions. The study concluded that salt reduces asphalt mixtures' low-temperature and fatigue resistance properties. The study also found that salt enhances the high-temperature properties of the aged bitumen, which portrays poor sensitivity to salt effects on complex modulus and phase angles at low frequencies for both unmodified and Polymer Modified Binder (PMB) bitumens. Özgan *et al.* (2013) highlighted specimens soaked with a de-icing solution exhibited low Marshall Stability and flow values.

2.1.4 Mechanical performance

2.1.4.1 Resistance to fatigue of asphaltic mixtures

Numerous factors that influence the fatigue performance include the method of samples compaction method and energy, the rest periods, and the material properties. Also, factors such as traffic volume and traffic loading (axle loads, modes and patterns) and environmental variables (temperature, ageing, healing, etc.) are crucial to fatigue performance. All construction variables and material properties can be governed based on the standards and specifications, but traffic load and environmental variables are dynamic.

2.1.4.1.1 Traffic loading

Traffic loading forms a part of essential inputs in a design procedure (others are subgrade strength and temperature). For the concept of designing, it is crucial to converting every actual traffic load (different wheel loads magnitudes and repetitions) into an equivalent number of a standard axle loading, ESAL (same as 80 kN single axle load) (HRB, 1962). Multiple loading waveforms are utilised to simulate traffic loading in the laboratory with relevant available technologies. The most appropriate technique is sinusoidal; it can approximate more convincingly the traffic load projected on the road. Read highlighted that the loading frequencies and duration significantly impact the fatigue life (Read, 1996). For example, a high frequency or short period of load pulse increases the stiffness; consequently, the fatigue life increases.

2.1.4.1.2 Temperature

Annual and daily climate variations such as surrounding temperature, solar radiation, wind speed, and precipitation influence the mechanical performance of the pavement. Asphalt pavement as viscous material changes with the change of temperature. For example, at low temperatures, it becomes stiffer and softer at a higher temperature. Olard *et al.* (2003) indicated that the asphalt pavement layer loses stiffness at high temperatures and increases when the temperatures drop.

2.1.4.1.3 Rest period

A rest period is a phenomenon that can be shown during dynamic tests. Continuous cycles of loading cycles are applied when rest is avoided. Over the last two decades, several studies considered elapsing time between two successive axles of either the identical or various vehicles (Si, Little and Lytton, 2002; Read and Whiteoak, 2003; Castro and Sánchez, 2006). All those who concluded that fatigue life increases when the rest period is incorporated during fatigue tests had demonstrated a growth in the fatigue life when a rest period is introduced during a fatigue test. In particular, the improvement in fatigue life is shown in Figure 2-9.

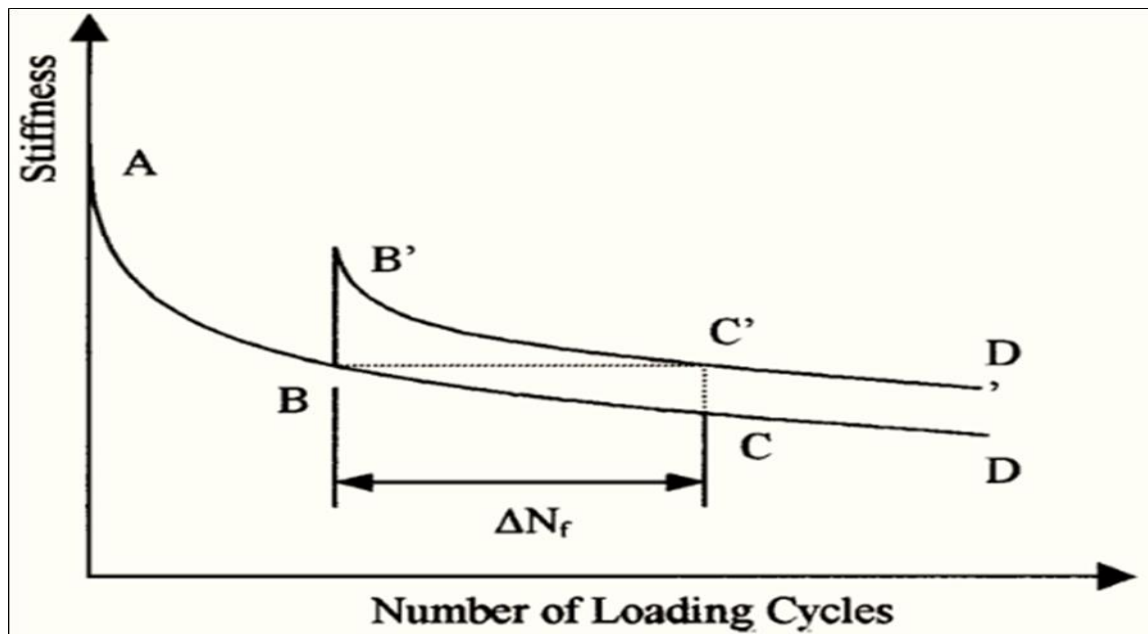


Figure 2-9: The effect of rest periods during a fatigue test (Castro and Sánchez, 2006)

The illustration (curve ABD) shows a decreased stiffness modulus. The stiffness modulus recovers after removing the load during the break/ rest period. Thus, during the rest

period, the material has a chance to heal. After the rest, the stiffness modulus reductions (curve B'C'D') when the load is applied again to the samples.

2.1.4.1.4 Material properties/characteristics

Volumetric properties such as binder and air-void contents, binder grade, binder modification, gradation, Recycled Asphalt Pavement (RAP) content, ageing, and adhesion between asphalt and aggregate are fundamental to fatigue performance (Company, 1978; Tsai, Harvey and Monismith, 2002; Li *et al.*, 2008; Hu, Zhou and Scullion, 2011). In the case of graded mixes, air-void and binder contents are two significant factors influencing the fatigue cracking performance of asphalt mixtures. A mixture with low air void content will have a high amount of binder and will experience an improved cracking performance of asphalt pavements. Sreedhar and Coleri evaluated the effects of bitumen binder content in mixture on asphalt mixture fatigue cracking and rutting resistance. The results suggest that the binder content significantly influenced the flexibility index measured 0.7%, increase in binder content increased the flexibility index 1.07 – 2.63 times (Sreedhar and Coleri, 2018). Increased binder content improved the cracking performance, suggesting that increasing the binder content of asphalt mixtures currently used in Oregon can create significant savings by improving pavement longevity.

2.1.4.1.5 Ageing

. Bitumen hardening due to ageing has a significant influence on fatigue life in asphalt material. One major challenge associated with the bituminous binder is ageing, increasing the bitumen viscosity and stiffening the mixture. During construction, bitumen can be exposed to the loss of volatile components and oxidation of the bitumen, which is regarded as short-term ageing. With time after construction, progressive oxidation can occur during material life service called long-term ageing. Airey (2003) indicated that short-term and long-term ageing could change the fatigue resistance in asphalt mixtures.

2.1.4.2 Resistance to permanent deformation of asphaltic mixtures

Resistance to permanent deformation is significantly reliant on both internal and external factors. Internal factors are attributes of properties of the materials used for mixing the mixture. A good asphalt mix design involves selecting and proportioning quality aggregate and binders to obtain the microstructural properties and desired mechanical performance

(Hamed, Sakanlou and Sohrabi, 2019). The external factors that affect resistance to permanent deformation are traffic loading, daily temperature variation, and moisture (Kim and Koh, 2012; Pérez-Jiménez *et al.*, 2013) and the content of raw materials used on the asphalt mixture. Additionally, requirements related to resistance to permanent deformation are linked with QA/QC systems. Based on different cases, these requirements can be directly addressed through performance-based tests or indirectly, using optimum mixture volumetrics. The microstructural properties of the asphalt mixture have been used successfully to simulate or predict the mechanical performance to obtain decent quality pavement (Mohammed *et al.*, 2020).

2.1.4.2.1 Traffic loading

Due to the growth of the SADC economy, the volume of good has drastically increased, which has led to truck overload in road transportation, which speed up the premature failure of pavement structural (Ismael, Fattah and Jasim, 2021). Abu Al-Rub *et al.*, (2012) researched to develop a rutting prediction model of asphalt pavement under repeated loading and various loading conditions. Their study investigated the anticipated rut depth using numerical simulation. A study by Lu *et al.* indicated that the subgrade could vibrate due to heavy-duty trucks with various axle weights, suggesting that heavy trucks can cause high vibration on the subgrade and result from more damage to pavement structures than other small vehicles (Lu *et al.*, 2018).

2.1.4.2.2 Temperature

The daily temperature is one of the major factors influencing the high-temperature resistance to asphalt pavement rutting. The temperature changes are known of causing expansion/ contraction as well as changing the viscoelastic characteristics of the asphalt mixture, which then cause the permanent deformation of the pavement (Ji *et al.*, 2019). Pouranian *et al.* investigated the influence of temperature on the rutting performance of Stone Matrix Asphalt (SMA). Their results indicated a decrease in stress sensitivity of rutting performance of SMA asphalt mixture when the test temperature increases. The other observation was that temperature significantly influences the flow number of the SMA mixture (Pouranian, Imaninasab and Shishehbor, 2020). The further study observed that deformation in the asphalt mixtures' was influenced significantly individually or both by thermal deformation and the thermo-susceptibility of the viscoelastic material (Souza and

Castro, 2012). Wasage *et al.* (2003) conducted a study to evaluate the effect of the high-temperature rutting on the mechanical performance of asphalt mixture using the same gradation and various bitumen binder. The study concluded that the increase of test temperature significantly influenced the rut depth. Thus, the asphalt binder is not easy to bond (Goli *et al.*, 2019). That indicates that the environmental temperature is an important input to design a good asphalt pavement performance.

2.1.4.2.3 *Material properties/characteristics*

Resistance to rutting on asphalt pavement depends significantly on pavement structure, material properties, and pavement construction quality (Vaitkus and Paliukaite, 2013). Aggregate gradation selection is a critical factor that influences the rutting resistance of the asphalt mixture. A study by (Dukatz, 1989) indicated that a mix with a poor aggregate gradation of high-quality material could experience poor rutting resistance. Rutting resistance of asphalt mixtures was evaluated using aggregate gradation. The results indicated that the mechanical performance was directly linked to properties of mineral aggregates, such as primarily gradation, particle shape, and absorption (Topal and Sengoz, 2005). Pouranian *et al.* (2020) studied the effect of coarse aggregate shape properties on the compaction performance of asphalt mixtures, and a decreased compaction slope was obtained on a mix with round stones. In contrast, the regularity of coarse aggregate experienced an increased compaction slope (Pouranian, Shishehbor and Haddock, 2020). Another observation was that coarse aggregate had significant high-temperature stability in asphalt mixtures as it is a critical factor in asphalt mixtures' rutting resistance performance (Behbahani, 2007).

2.1.4.2.4 *Microstructural properties*

Asphalt mixtures consist of discrete aggregate glued with asphalt binder and air voids. Pouranian and Haddock, (2018) mentioned that the voids in the mineral aggregate play an essential role in the design of asphalt pavement, especially when it comes to ensuring the pavement's durability and resistance to rutting the pavement. A study by (Airey *et al.*, 2008). DASR concept was used by (Guarin *et al.*, 2013) to determine the influence of binder content changes due to void content in the mixture less than DASR on the rutting resistance's asphalt mixture. Also, results from (Zhang *et al.*, 2018) indicated that in a mix, the distribution of the void ratio has a significant effect on the rutting resistance of the asphalt mixture, and the void ratio is the result of the mixture's gradation. An analytical model was developed for fine and

coarse aggregate binary mixtures in asphalt to regulate air volume between binary mixtures' aggregate and packing density. Furthermore, (Pouranian and Haddock, 2021) suggested using the numerical simulations model as an advanced design method to improve the mechanical performance of asphalt mixtures . Thus, designing an asphalt mixture with optimum voids is vital for rutting performance.

2.2 Material characteristics

2.2.1 Influence of bitumen binder

Fundamental to evaluating the performance of asphalt mixture is identifying the mechanical behaviour of bitumen. Oil companies initiated the interest in understanding bitumen behaviour in the nineteenth century due to its widespread use in pavement construction. Bitumen is a visco-elastic material. Over past decades, various studies on bitumen mechanical properties showed that the stiffness of an asphalt mixture might be influenced by the binder properties such as penetration and softening point (Van der Poel, 1954). Van der Poel nomograph is a valuable model developed summary of findings of bitumen mechanical behaviour correlated to loading time, and temperature is illustrated in Figure 2-10 (Van der Poel, 1954). That attracted interest to simulate the bitumen linear behaviour based on rheological models (Jongepier and Kuilman, 1969; Hall, 2007), and the assumption made was only valuable for minor strains and stresses. Numerous studies characterised the stress-strain of pure bitumen as very complex (Cheung and Cebon, 1997; Cheung and Cebon, 1997a, 1997b). Bitumen becomes elastic solid at low temperature and viscous liquid at high temperature (Brown, 1958). Visco-elastic behaviour has been observed in the transition zone.

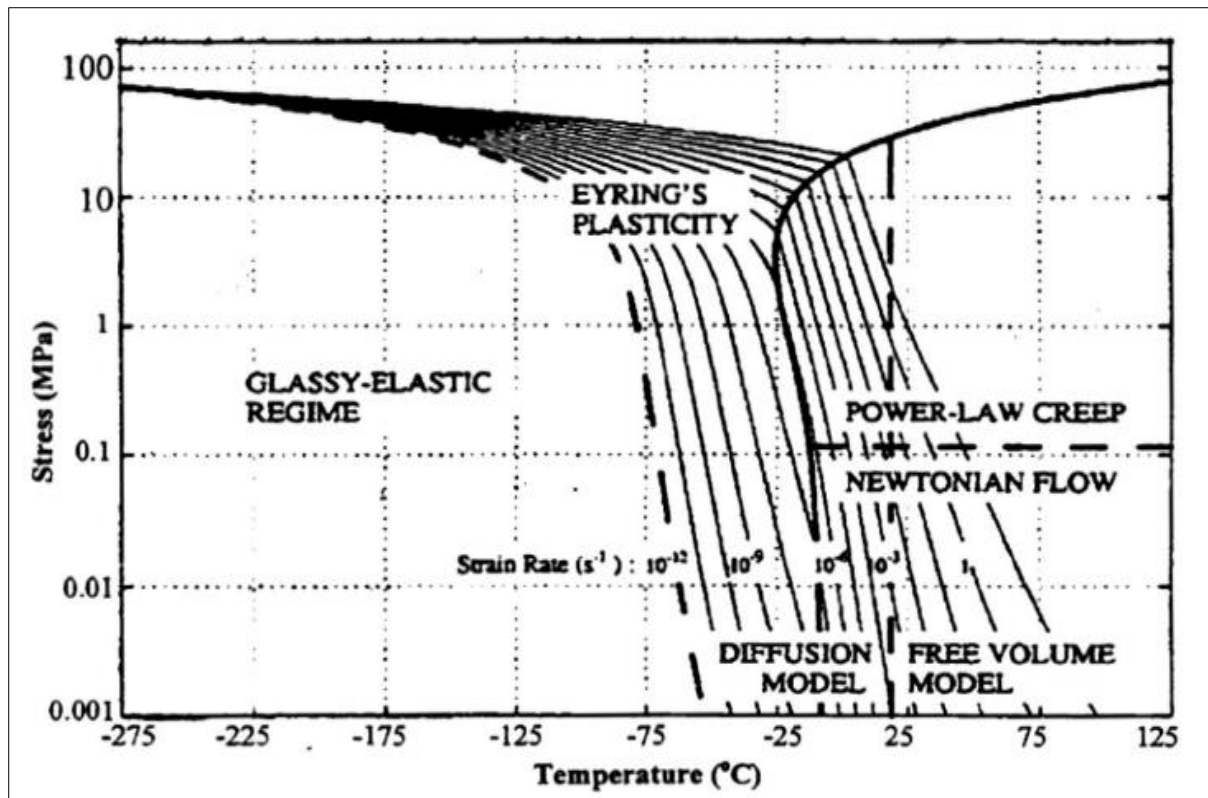


Figure 2-10: Stress-Temperature deformation mechanism map of 50 Pen bitumen in tension (Cheung, 1995)

2.2.2 Influence of aggregate

Road engineers regard aggregate as discrete particles or elements that interlock together to aggregate a pavement's skeleton structure (microstructure) (Valdés-vidal *et al.*, 2015). Several researchers characterised the morphology of aggregate as size, surface texture, angularity, and morphology of the particles and concluded that they significantly influence the mechanical behaviour of asphalt mixtures (Zhang, Huang and Zhao, 2012; Diógenes *et al.*, 2021; Busang and Maina, 2022). Each type of aggregate has a different rock origin and chemical composition. Thus, different strengths, sizes, surface textures, and shapes make it very difficult to determine their influence on the microstructure of asphalt mixtures (Valdés-vidal *et al.*, 2015; Vidal, Floody and Alonso, 2019). The physical properties of aggregate rely on the mineralogy and the shredding process (Golalipour *et al.*, 2012; Cui *et al.*, 2014; Valdés *et al.*, 2014). The internal friction and the ability to withstand the traffic loads depend on morphology and coarse aggregate gradation (Moreno and Rubio, 2013). Studies have shown that the microstructural properties and fatigue cracking, and rutting resistance are influenced by morphological characteristics (Golalipour *et al.*, 2012; Özgün, Serin and Kap, 2013).

Furthermore, different crushers produce different aggregate morphology. Numerous investigations studies indicated that the effect of the crusher with a vertical axis produces different cubic particles sizes (Özgan, Serin and Kap, 2013). In contrast, various morphologies are made on a cone crusher depending on the size range (Bengtsson and Evertsson, 2006). Under traffic loads, flat and elongated aggregate demonstrated high vulnerability to break, adjusting aggregate distribution and original properties of asphalt mixtures (Chen, Chang and Lin, 2005; Topal and Sengoz, 2005). When the diameter ratio of aggregate is close to 1 in a crusher, there is a high possibility of producing cubic crushed aggregate, and cubically shaped aggregate is known for having better behaviour of asphalt mixtures (Chen, Chang and Lin, 2005). Cubic shape aggregates were recommended to used because it demonstrated excellent resistance to rutting (Chen, Chang and Lin, 2005). They can interlock into a structure with limited rotation and aggregate movements (Moriyoshi *et al.*, 2014). The typical aggregate shapes are shown in Figure 2-11.

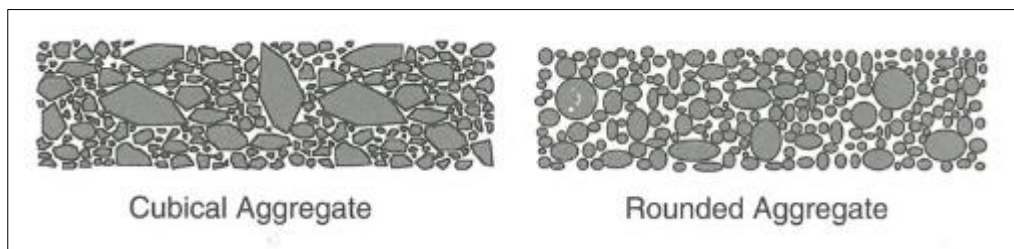


Figure 2-11: Aggregate stone skeleton (Institute, 2007)

2.3 Use of microstructure to predict the mechanical performance

The microstructure of the asphalt mixture has been used successfully to simulate or predict the mechanical performance to obtain decent quality pavement (Mohammed *et al.*, 2020). Several studies highlighted that the aggregate chemical and physical properties (such as aggregate size, orientation, morphology, texture, shape) have a significant influence on microstructural properties, hence the mechanical response and performance of asphalt mixture (Chen, Huang and Shu, 2013; Rajan and Singh, 2017; Hassan *et al.*, 2021). Han *et al.* conducted a study on the effect of microstructure with different aggregate morphology on the dynamic modulus of asphalt mixture (Han, Yuan and Hu, 2021). They found that aggregate morphology has a major influence on the dynamic moduli of asphalt mixture. Yang studied the effects of the shape and angularity of coarse aggregate on the microstructure as well as the mechanical performance of asphalt mixtures (Yang, Bi and Zhang, 2016). They found that asphalt mixtures containing aggregate with higher shape indexes and lower angularity have higher creep deformation and low dynamic modulus. Kuang *et al.*, (2019) mentioned that the

average angular coefficient on microstructure demonstrates a positive linear correlation between the dynamic stability and freeze-thaw split strength ratio of the asphalt mixture. Angularity coefficient is the aggregate particle shape evaluation method. It is mainly the quantitative characterisation of the angularity and roughness of aggregate particles. The mean angularity coefficient of several aggregate particles is obtained from the void ratios of aggregate particles tamped based on different times. Gao *et al.*, (2020) highlighted that a microstructure with more aggregate particles with high angularity is harder to compact the asphalt mixture but that it provides better skid resistance. Ge *et al.*, (2018) used microstructures of coarse aggregate with various particle sizes and shapes under different abrasion cycles. They discovered that the small size ranges of aggregate have an excellent surface texture, but they quickly get damaged during the abrasion cycles process. Wang *et al.*, (2016) examined the influence of morphological properties of coarse aggregate on the microstructures. They found that the aggregate particles' fractal dimension which was measured by the slit island method, has a better linear correlation with the dynamic stability of asphalt mixtures at high temperatures. The coarse aggregate with higher angularity has shown more robust resilience at high temperatures.

Porosity is a geometric property of asphalt mixture that influences such properties as permeability and mechanical properties of pavements. Permeability is a quantitative measurement of the ability of pavement layers to conduct fluid flow, whereas mechanical properties include resilient modulus and shearing strength of the asphalt layer. The aggregate geometry, contact points and voids have a major role in the microstructure. These important individual parameters lead to spatial statistics ideas, and recent researchers have adopted stochastic modelling. Stochastic models have benefits such as providing details about the mixtures regarding porosity, geometric quantities involving distinct internal surfaces, particle contact distributions, and correlation functions.

2.3.1 Aggregate grading

Aggregate gradation is an orientation of particle size in an asphalt mixture and is determined by the percent passing each standard sieve. Recent designers pay attention to improving aggregate gradation to obtain desirable required mechanical performance. The Superpave mix design provided specification of a band in a gradation called 'restricted zone'; it advises that the gradation should comply with the restricted area to resist fatigue and permanent deformation better. Kandhal and Cooley, (2001). define the restricted zone as the

maximum density line between the intermediate particle size (4.75 or 2.36 mm), which relies on the Nominal Maximum Particle Size (NMPS) and the 0.3 mm. The restricted zone was developed based on Superpave, but a study has shown that a good mixture performance can be obtained by passing the gradation over the zone. Various gradations and NMPS to evaluate the influence of the restricted zone on mechanical properties of a dense-graded Hot Mix Asphalt mixture (HMA) (Kandhal and Cooley, 2001). The study used two nominal maximum sizes (9.5 and 19.0 mm) and five gradations. Three gradations were passed through the restricted zone, and the other two were not. Various tests methods such as Asphalt Pavement Analyzer (APA), Superpave shear tester, and repeated load confined test were used to assess the permanent deformations. Results suggested that mixtures with gradations passing through the restricted zone presented similarly to or slightly better than the one falling outside the restricted zone for all nominal maximum sizes. In the study by (Kennedy *et al.*, 1996), asphalt mixtures of the same aggregate with the same rock origin but different gradations were evaluated. The asphalt mixtures were made from granite, limestone, and gravel passing below, through, and above the Superpave restricted zone. They found that mixtures of granite and limestone aggregate, gradations that passed below the restricted zone, presented the worst rutting resistance, followed by the gradations passing through the zone. At the same time, the best performance was obtained for grading passed over the restricted zone.

2.4 Aggregate packing

Different aspects and approaches were brought to the board to improve understanding of designing complexities, hence developing such a good load-bearing aggregate skeleton with optimum porosity. Methods such as the Bailey and DASR were established to help optimise the aggregate grading packing. Also, models, including the linear packing density model (Stovall, Larrard and Buil, 1986), Furnas model and compressible packing model (Roquier, 2016), as well as many other reworked models together with the density, have been used to determine the porosity on granular materials (Moutassem, 2016; Bolin, Zhiqiang and Qian, 2017). These methods effectively analyse these mixtures' spatial particle distributions and packing densities but cannot be used for various aggregate sizes. Further, even though these procedures are significant for increasing new knowledge on determining porosity at the microscopic level, estimating a media's porosity with various aggregate sizes, shapes, and grain-scale information using a phenomenological model is too complex and difficult to define.

Over the years, several advanced constitutive models were developed for granular materials, which provided a better definition of the major features of the materials. These models include (Drucker, 2013), the Cam-Clay, and the modified Cam-Clay (Roscoe, Schofield and Wroth, 1958; Burland, 1970). Researchers can now subdivide several models recently used with the aid of laboratory experiments to estimate porosity for various granular mixtures into slit models and capillary tubes (Bachmat, 1992), network models (Laranjeira and Mata, 2009), fractal models (Pape *et al.*, 2009), permeation models (Chatzis and Dullien, 2014), stochastic reconstruction models (Dullien, 1979), grain models and Kendall, 2013), and diagenetic models (Hilfer, 2007).

2.4.1 Packing fractions and densities

Laboratory samples for pavement layers can be described by the x, y, z coordinates of all packed aggregate. Gradation is mainly a trial and error process. Still, adequate packing of aggregate grading is primarily influenced by a volume fraction of Nominal Maximum Aggregate Size (NMAS) and the DASR or how well fine size aggregate fits in the voids created by coarse aggregate. Studies by (Hainin, Cooley and Prowell, 2003) show from 8% and 8.5% air void content, the Hot Mix Asphalt (HMA) / Warm Mix Asphalt (WMA) become highly permeable. The effect of NMAS on the permeability of HMA /WMA was observed when using NMAS (12.5mm and 9.5mm), which provided a low void content of less than 6%. Cooley *et al.*, (2002) results suggested overly permeable pavement at 4% and 8% void content for NMAS of 25mm and 9.5mm, respectively. Fractions of aggregate size ranges for a mix are called aggregate skeleton subsets and voids for these aggregate packing subsets, and their densities can be determined separately. The aggregate packing subsets can be classified into coarse, medium and fine aggregate. The aggregate skeleton for each subset is estimated by area fraction (Lee and Hogan, 2021).

Another critical parameter frequently used to measure permeability is bulk density. Also, density is one of the main parameters for pavement layers' quality assurance (QA) measures. Density is associated with the permeability of the asphalt mixture and the voids in the mix. In terms of durability, using permeability is more accurate than the density of individual pavement layers. This concept was proven by (Khosla, Paul, 2005) when permeability gave them better results than the density of HMA/WMA mixes.

Recently, numerous researchers developed main packing density models (Kwan, Wong and Fung, 2015; Roquier, 2016) that accounted for a wall effect coefficient b induced

by “dominant fine aggregate range” and a loosening effect coefficient a generated by “dominant coarse aggregate range”. The wedging effect coefficient c happens in both cases. When the coarse aggregate is dominant, the wedging effect occurs when some isolated fine aggregate is entrapped in the voids between the coarse aggregate instead of filling into the voids, wedging the coarse aggregate apart. When the fine aggregates are dominant, the wedging effect occurs when some void between the coarse aggregates are too narrow to accommodate one complete layer of fine aggregate, leading to only isolated fine aggregate at the voids wedging the coarse aggregate apart. The wall effect describes the supplement of volume fraction unoccupied at a coarse particle’s interface that surrounds the fine aggregate.

The loosening result is a volume fraction of voids that happens when the fine aggregates are large enough to fill the voids and push the coarse aggregate apart (Kwan, Wong and Fung, 2015). A binary mix comprises two aggregate size ranges: course range i and fine range j . The volumetric fractions of course range i and fine range j are r_i and r_j , respectively (where, $r_i + r_j = 1$), and ϕ_i and ϕ_j refer to the packing densities of course range i and fine range j , respectively. The packing density of the binary aggregate skeleton mixture when size range i is predominant (indicated by ϕ_{i*}) the packing density of the binary aggregate skeleton mix when size range j is dominant (denoted by ϕ_{j*}) are given, respectively by (Fung and Kwan, 2014).

2.4.2 Bailey method of gradation analysis and asphalt mix design

The Bailey method became a fruitful industrialised approach to examining HMA gradations. The technique was developed to design an excellent aggregate interlock by selecting a suitable volume of coarse and fine particles. Vavrik *et al.*, (2001) presented the method to provide a perfect mix design, and this is correlated with two concepts:

1. An advanced essential methodology to differentiate between coarse and fine particles must be established.
2. The aggregate particles' appropriate volume has been combined to attain a good aggregate interlock coarse particles.

Pavement engineering context regards particles greater than 4.75mm as coarse particles. Fine particles are smaller than 4. Development by (Vavrik et al., 2001) adjusted this definition to enhance the analysis method to understand the aggregate interlocking in the mixture. The primary role of coarse and fine particles is presented in the previous section to develop the concept. According to (Varvrik *et al.*, 2001) study, the coarse particles refer to

large aggregate that leaves some voids when put together in a unit volume. In contrast, fine aggregate is simply the small aggregate that fills the void generated between the coarse aggregate. There is a clear indication that absolute can be defined for coarse and fine aggregate (Vavrik *et al.*, 2001).

The essential correctness of the volumetric ratio recommended by the Bailey method and compliance worldwide to improve good asphalt mix designs (Vavrik *et al.*, 2001) make the Bailey method an ideal reference system in the analysis of grading envelopes. The Bailey method terminology is used throughout to describe specific aspects of the grading envelope. The definitions of various Bailey control sieves and associated ratios are described as follows (Vavrik *et al.*, 2001):

- As per the Superpave definition, Maximum Nominal Particles Size (NMPS): “One size larger than the first sieve that retains more than 10% aggregate,”
- Half Size (HS) refers to the sieve size closest to or equal to half the NMPS,
- Primary Control Sieve (PCS) is the sieve size closest to $0.22 \times \text{NMPS}$,
- The secondary Control Sieve (SCS) is the sieve size closest to $0.22 \times \text{PCS}$, and
- Tertiary Control Sieve (TCS) is the sieve size closest to $0.22 \times \text{SCS}$.

In literature, additional aggregate size range descriptors and terminology are often used as follows:

- Interceptors: The size range between HS and PCS,
- Pluggers: In the original Bailey method description (Vavrik 2001), they are defined as all aggregate fractions larger than half size. However, “Pluggers” can be divided into, and
- Pluggers up to NMPS (PN). The size ranges between HS and NMPS. Horak *et al.* (2017a&b) referred to this as Pluggers.

Oversize pluggers are larger than NMPS (PO). The oversized aggregate is larger than NMPS. (Horak *et al.*, 2017) referred to this as Oversize

2.4.3 Dominant Aggregate Size Range (DASR)

Two decades ago, Kim developed a conceptual and theoretical approach to evaluate the coarse aggregate microstructural properties based on the gradation (Kim, 2006). The main aim of the process was to recognise the size range DASR of aggregate in the asphalt mixture to carry the load. Also, the DASR porosity concept was brought as a strategy to calculate the porosity of a range of adjacent aggregate fractions in series that do not overlap. Porosity can

enhance the packing of dominant particles in the aggregate mixture. Similarly, (Kim, 2006) used the porosity approach to improve dominant particles for the asphalt mixtures. Roquier (2016) advised that any fabric material with different particle sizes and orientations should have a porosity of at least 45% to 50%. A similar observation was made by (Cherry and Freeze, 1979) that the particles of geomaterials can contact one another when the porosity does not exceed 50 % and thus would provide an interactive of particles and form a load-bearing skeleton. Kim (2006) proposed the idea of DASR porosity being used for any variety of contiguous aggregate fractions that, when combined, will reduce the porosity value to less than 0.5. Therefore, the DASR porosity is a necessary tool that can be used to obtain any useful gradation envelopes of pavement layers' mixes. The initial equation was developed by (Kim, 2006) for calculating the porosity of an adjacent aggregate fraction of more than two ranges. In contrast, Denneman et al. developed the equation to determine the porosity of a single contiguous range of the aggregate fraction (Denneman, Verhaeghe and Sadzik, 2007).

2.4.3.1 Amount of interstitial components

EFT influences the samples' permeability in this study. The voids between the DASR aggregate are filled with a binder and IC. Excessive components of IC can lead to cracking. IC has to be controlled when reducing porosity using a parameter known as the DF (Greene, Chun and Choubane, 2014).

2.5 Compaction methods

Marshall compaction: Bruce Marshall developed 1939 this method. The method is used for the following a few principles :

- used for mixtures with a high amount of finely graded aggregate with a maximum aggregate size of 25 mm.
- The samples are compacted using compressive impact load using a hammer on both sides of the sample and for several blows.
- The method work based on targeted optimum values of air voids, binder content, strength, and durability of the mixture when using a mixed design

Roller compactor: It is a large compactor mainly used to compaction asphalt mixtures to simulate the compaction in the field. It is difficult to control the size of the void, and it is costly to operate.

Superpave Gyratory Compactor: It is an easy and portable device mainly used in the laboratory for asphalt mixture compaction. The gyratory compactor is widely used because of its efficiency and easy accessibility. This compactor work based on a few principles to achieve the desired compaction:

- The angle of gyration has a vital role in creating vertical and shear forces, which results in good compaction, and
- Vertical pressure of Superpave equivalent to 600 kPa using gyratory compaction basis recommended estimating field loading conditions.

2.6 Laboratory mechanical performance testing

2.6.1 Testing of rheological properties of a binder

Bitumen can be specified into penetration and viscosity graded specification as shown in Table 2-1, which measures their consistency. The specification is not considering stress modes or durability of the material.

Table 2-1: Penetration and Viscosity graded bitumen (Airey, 1997)

Penetration grades	Penetration @ 25°C (dmm)	Viscosity grade	Viscosity @ 60°C (Pa.s)
40/60	40 – 50	B24	170 – 300
50/70	60 -70	B12	105 – 165
80/100	8 -100	B8	55 -100
150/200	150 -200	B4	25 -50

Based on specification criteria field performance, specifications can be changed to empirical parameters, for example, penetration, ductility, and Fraass breaking point. It was complex to associate with pavement performance' specification criteria reliably. Depending on various areas of bitumen, response to temperature can be used to characterise bitumen using traditional empirical tests. The areas involve:

- Penetration refers to the semi-solid range.
- Fraass breaking point refers to the brittleness range.
- Softening point refers to the starting fluidity range point, and
- Viscosity is fluidity range.

Penetration grade bitumen is specified based on the consistency test of Penetration and softening point.

2.6.1.1 Penetration test

Penetration is a determination of uniformity of the bitumen, usually expressed as the vertical length in tenths of a millimetres in which the needle can penetrate the bitumen sample. As shown in Table 2-2, the penetration is conducted at a temperature of 25°C under a specific load and loading time. The longer Penetration length suggests that the bitumen is softer; thus, it can be regarded as an indirect measure of the bitumen viscosity at a temperature of 25°C.

2.6.1.2 Ring and Ball Softening Point test

The Ring and Ball Softening Point test is a conventional test used to measure the uniformity of bitumen by determining the equiviscous temperature at which bitumen is between solid and liquid behaviour. The softening point will be the same for different bitumen grades.

2.6.1.3 Viscosity tests.

The viscosity is additional data to show the significance of Penetration and Softening points resulting in a penetration-grade specification. Viscosity is a measure of the resistance to the flow of a liquid. It can also be defined as the applied stress and shear strain ratio. The rotational viscometer is commonly used as it is easiest and allows several bitumens ranges to different temperatures.

2.6.1.4 Dynamic Shear Rheometer (DSR)

DSR is mainly used for bitumen test samples' Dynamic Mechanical Analysis (DMA). A sinusoidal strain can be applied to a sample stress attained is observed as a function of frequency. The main purpose of DSR is to determine the linear viscoelastic parameters of bitumen binder through sinusoidal loading mode, and the stiffness and viscosity can be obtained at various temperatures.

2.6.1.5 Multi-stress creep recovery

In the original Superpave binder specifications, the parameter rutting factor ($G^*/\sin(\delta)$) measured at 10 rad/s is used to predict pavement rutting. The test was performed at the high-Performance Graded (PG) temperature and after short-term ageing by the standard

rolling thin film oven (RTFO) test (Soenen *et al.*, 2013). For pavement that is exposed to either high traffic volumes or low-speed traffic, bump grading can be included to help improve bitumen performance. High grading temperatures are adopted for rutting tests, possibly higher than the actual temperature occurring in the pavement. However, related literature pointed out that grade bumping is unsuitable for modified bitumens (Delgadillo, Nam and Bahia, 2006; D'Angelo, 2009). Delgadillo *et al.* showed that cyclic reversible loading is not able to separate energy dissipated in the permanent deformation and energy dissipated in the delayed elasticity (Delgadillo, Nam and Bahia, 2006). The study (Airey, 2002) indicated that the parameter $G^*/\sin(\delta)$ is appropriate and positively correlates with wheel-tracking tests. However, particularly for modified bitumen, this correlation is achieved if the repeated test of the parameter $G^*/\sin(\delta)$ is reduced significantly and is adjusted to the average loading times experienced in wheel-trafficking tests. An advanced testing method called MSCR can be used to anticipate the performance of both modified and unmodified bitumens. Applying a range of stress levels can identify excessively stress-sensitive bitumens in the non-linear domain by applying 1 s loading and 9 s recovery for 10 cycles, repeated at 2 various stress levels (0.1 and 3.2 kPa) continuously without any time break utilising the DSR. Currently, the studies incorporated the innovative parameter called the 'non-recoverable compliance' (J_{nr}). The compliance can be determined at each stress level by dividing the average non-recoverable strain by the applied stress.

2.6.2 Laboratory fatigue testing

Researchers have brought forward their research projects through several fatigue tests. Below, some general categories of the most used test methodologies over the past are presented (Tangella *et al.*, 1990).

2.6.2.1 Simple flexural

The stress or the strain is applied to the sinusoidal waveforms until the sample fails. So the accurate results can be determined by correlating the number of cycles to failure to the stress or strain level. A prismatic beam (or a trapezoidal beam) is usually subjected sinusoidally to a load under center-point or third-point configuration in simple flexural tests.

2.6.2.2 Wheel tracking tests

The correlation of stress and strain is subjected to the number of applied loads or cracking levels in the sample/slab. A wheel tracking machine is frequently used in the laboratory. A wheel loaded (with a pneumatic tire) traverses back and forth on the sample. The use of the wheel varies with rolling speed, especially in the laboratory, and most of the time leads to rutting more than significant fatigue. However, it is an excellent approach to predicting field conditions. The schematic of the wheel tracking apparatus is shown in Figure 2-12.

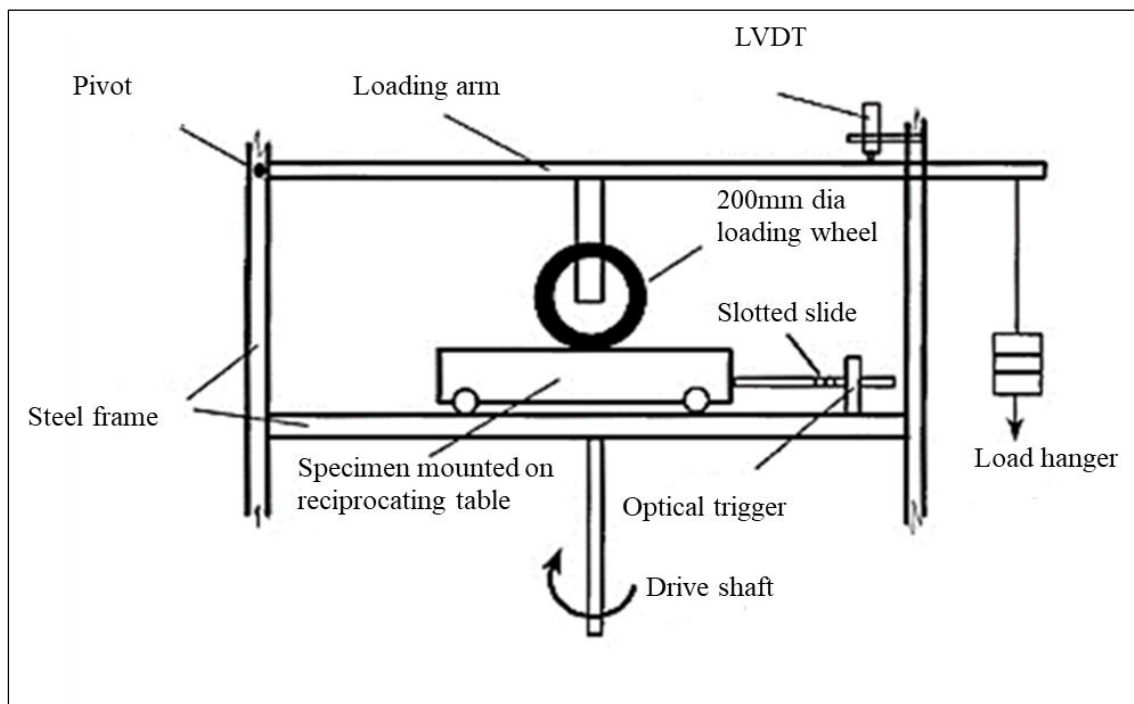


Figure 2-12: Schematic wheel tracking apparatus (Gibb, 1996)

Different wheel tracking tests have been developed to perform various duties, such as Georgia loaded wheel tester, APA, the Hamburg wheel tracking machine, the French wheel tracker, the Nottingham pavement testing facility, etc. The investigation is performed at large, moderate, or minor scales. Taherkhani considered the wheel tracking test a simulative field; studies have used it to authenticate their rutting prediction approaches (Taherkhani, 2006a; Hassan, 2016). The wheel tracking test is mainly used for permanent deformation.

2.6.3 Laboratory permanent deformation testing

The key laboratory tests are static uniaxial and triaxial test, cyclic uniaxial and triaxial test and wheel tracking test

2.6.3.1 Static uniaxial and triaxial test

The static uniaxial test is the most straightforward test used for assessing the deformation behaviour of asphalt mixtures as a viscoelastic material using cylindrical shape samples. In the past three decades, the Shell organisation developed it in Amsterdam for testing bituminous mixtures (Hills, 1973). The Journal of the Institutes of Petroleum proposed two ways to conduct the test: for example, tests can be either by (creep test) applying constant stress or constant strain rate in tension or compression. A friction reduction system is preferred between the sample and loading plates. The primary and most significant variation is the cyclic loading condition. At the same time, in a creep test, it is static. The pavement in the field is confined, while in the creep test, it is unconfined (uniaxial). Past studies have indicated that the cyclic loading of the sample produces more permanent deformation than static load (Gibb, 1996). The triaxial test was a good simulation of confined pavement fundamentals in the field.

2.6.3.2 Cyclic uniaxial and triaxial test

The cyclic uniaxial creep test or Repeated Load Axial Test (RLAT) was established to evaluate the performance of asphalt material under representative loading conditions. Repeated load is applied for a specific loading duration, and after every loading pulse, a rest period can also be instigated. The loading can be completed in various sinusoidal, square, triangular, and trapezoidal waveforms. Studies regarded the sinusoidal loading as the most simulative of field loading (Brown and Sparks, 1958; Loulizi *et al.*, 2002). It is necessary for loading time to correspond with the desired speed of the vehicle. Even if the load frequency on the sample is a crucial factor in the laboratory test, few researchers have evaluated the relationship between loading time to vehicle speed in the field (Al-qadi, Xie and Elseifi, 2008). A test was performed using various asphalt mixtures. He concluded that the cyclic uniaxial test gives more accurate permanent deformation behaviour than static creep (Gibb, 1996).

2.7 Microstructural analysis

2.7.1 Fabric tensor

Numerous researchers were interested in understanding packing logic and determining void distributions. Many models use the basis of continuum theories, but, in reality, aggregate skeletons are discrete mediums. Therefore, their internal structures can describe macroscopic behaviour significantly. Studying the aggregate packing mechanics is called fabric, which

refers to the microstructural properties of asphalt materials at the volumetric ratio that involves different aggregate size ranges. A few decades ago (Satake, 1982b) identified the fabric vectors as the easiest way to analyse the constitute layout of granular material by naming them aggregate orientation, voids, and aggregate contact fabric tensor. The microstructure of asphalt pavement is referred to as fabric, and its anisotropy is considered fabric tensors for addressing the aggregate orientation and quantifying the voids. Several constitutive models that used granular material fabric were:

- (i) the particle orientation fabric (s) referring to the orientation of the major axis of the particle (aggregate packing) (Zhang, Luo and Lytton, 2011; Gao and Zhao, 2015);
- (ii) contact normal fabric (t), meaning how the normal vectors of the contact planes are oriented (Fu and Dafalias, 2015); and
- (iii) the void fabric (v), which refers to the spatial distribution of voids (Fu and Dafalias, 2015; Theocharis, 2015).

Many studies used three various kinds of fabric individually. The three fabric types can be used for their possible correlations to enhance packing efficiency. At some point, the relationship between the void and normal contact fabric can be used to determine the packing degree of aggregate.

2.7.1.1 Void tensors of the microstructure

The two main various effects can quantify voids distribution of aggregate mixture. As already mentioned above, the pavement samples are described in x, y, z directions. Pavement layer response is regarded as anisotropic, meaning that the macro-scale response suggests the anisotropy of the aggregate and the contact alignments and the air void. Voids can be referred to as void cells. Void cells are described through the aggregate that makes closed loops and encloses the voids within those loops. A 2D makes it easy to recognise void cells that can be characterised through relative grains, which can also be used to extend to 3D (Theocharis, Vairaktaris and Dafalias, 2017). Due to compaction during an experiment, the aggregate shifts the positions to reduce, destroy, or create other void cells. To measure these kinds of voids requires a method that can measure all types of shapes. The void cell system can be used to describe a void fabric tensor. The void cell system is suitable for this type of tensor. To develop a void fabric tensor, the porosity is described as a directional measure based on the porosity connected directly to the void distribution. Its distribution can be characterised in the form of symmetric traceless tensors. The second-order terms are considered to be adequate to

determine the distribution of the porosity. Concerning the reality of the x, y, z coordinates of the samples, the directional distribution of the vector density can be determined by Eq 2.3 (Masanobu Oda, 1985; Ghedia and Sullivan, 2012; Theocharis, 2015).

$$E(\mathbf{n}_{vc}) = \overline{E^0}(1 + \mathbf{n}_{vc} \cdot \mathbf{a}_{vc} \cdot \mathbf{n}_{vc}) \quad 2-3$$

where $\mathbf{a}_{vc}$ is a non-dimensional second-order tensor, the “ vc ” is number of the void vectors and $\overline{E^0}$ is the average $E(\mathbf{n}_{vc})$. The fabric tensor of overall directions and the directional distribution of vector in discrete can be described by Eq. 2-4 (Ghedia and Sullivan, 2012; Theocharis, 2015).

$$G_{v_cell} = \frac{E_0}{N_{vc}} \sum_{k_{vc}}^{N_{vc}} V_{vc} \mathbf{n}_{vc} \otimes \mathbf{n}_{vc} l E(\mathbf{n}_{vc}) \quad 2-4$$

where; $\mathbf{n}_{vc}$ refers to the vectors joining the centre of the void cell and the contacts, k_{vc} refers to the numbering of the void vectors, N_{vc} is the total number of void vectors, and the volume V describes the area in two-dimensional or the volume in three-dimensional where the measurement of the fabric takes place l branch vector, E_0 is used for normalisation over the volume

2.7.1.2 Aggregate orientation and contact normal fabric

When aggregate skeleton subsets are combined, they make an aggregate mix. The matrix of the aggregate mix samples is described by the x, y, z coordinates of all packed aggregate. For suitable interlocking, neither spherical nor ellipsoidal aggregate can be used, but other shapes can be considered. The packing of the aggregate gradation can be assessed using the orientation of aggregate or the pattern of contacts among aggregate. To analyse the aggregate' orientations and their normal contacts in a set of the aggregate matrix, two-unit vectors ($\mathbf{n}$, $-\mathbf{n}$) are established on their main axis. The s and t denote the kth aggregate and aggregate contact normal fabric in the aggregate matrix set, respectively. Contact normal fabric is another way of quantifying solid-phase concerning how the aggregate interact with each other by using their interfaces. The weight of contact normal fabric directly influences the evolution of the void fabric tensor. The interaction is determined by measuring the aggregate contact along the plane, vertical to the contact point and the plane tangent to the aggregate in contact. That isn't easy to calculate using physical experiments or images. When referenced to these vectors, the single size aggregate has an equal fabric tensor. For any sample, the fabric tensor for aggregate orientation equals all the tensor product($\otimes$) of all

aggregate in a skeleton aggregate mixture. Based on the similar approach mentioned, the two-dimensional fabric tensor is used to determine the three-dimensional fabric in which the N_t The normal contact of the sample is in vectors (Oda and Nakayama, 1989). A 3-dimension (3D) spherical coordinates vector can be given by equation 2.5 (Shephard, Sander and Barocas, 2008; Theocharis, 2015). From what has been discussed above, it is clear that contact normal fabric directly influences the material's general response, especially the evolution of the void tensor (Bradford, 1976; Satake, 1982a; Oda, 1985).

$$F_{ij}^c = \frac{1}{N_t} \sum_{k_t \in V} \mathbf{n}_{t_i}^{k_t} \mathbf{n}_{t_j}^{k_t} (z^*) \quad 2-5$$

$$= \frac{1}{N_t} \begin{bmatrix} \sum_{k_a \in V} \sin^2 \theta_{k_t} \cos^2 \varphi_{k_t} & \sum_{k_a \in V} \sin^2 \theta_{k_t} \cos \varphi_{k_t} \sin \varphi_{k_t} & \sum_{k_a \in V} \sin \theta_{k_t} \cos \theta_{k_t} \cos \varphi_{k_t} \\ \sum_{k_a \in V} \sin^2 \theta_{k_t} \cos \varphi_{k_t} \sin \varphi_{k_t} & \sum_{k_a \in V} \sin^2 \theta_{k_t} \sin^2 \varphi_{k_t} & \sum_{k_a \in V} \sin \theta_{k_t} \cos \theta_{k_t} \sin \varphi_{k_t} \\ \sum_{k_a \in V} \sin \theta_{k_t} \cos \theta_{k_t} \cos \varphi_{k_t} & \sum_{k_a \in V} \sin \theta_{k_t} \cos \theta_{k_t} \sin \varphi_{k_t} & \sum_{k_a \in V} \cos^2 \theta_{k_t} \end{bmatrix}$$

where; N_t refer to the number of vectors, $\sum_{k_t \in V} \mathbf{n}_{t_i}^{k_t} \mathbf{n}_{t_j}^{k_t}$ (Satake, 1982a) are a summation of the product fabric tensor, and θ and φ are the spherical coordinates of the vector $\mathbf{n}_t$

2.7.2 X-ray computed tomography (X-ray CT)

Current investigations use various techniques to capture the microstructural properties. The three-dimensional (3D) methods are by X-ray, and the two-dimensional (2D) image processing method is based on a CCD by a digital camera (Shaheen, Al-Mayah and Tighe, 2016; Jiang *et al.*, 2017; Cai *et al.*, 2018; Xiao, Qiu, *et al.*, 2020). The methods and rules used in digital imaging analysis have been robust with technology novelties, and accomplishing the sectional images develops more reachable and correct (Coenen *et al.*, 2012; Busang and Maina, 2022).

In the new global technology of high-resolution images, the use of X-ray CT (Apeagyei, Grenfell and Airey, 2014; González *et al.*, 2018) and numerical simulation techniques, such as the DEM, rapidly increased (Samson *et al.*, 1999; Kuhn, 2003; Bell, Yu and Mucha, 2005; Liu *et al.*, 2020). Individual aggregate can be scanned in X-ray CT, and the

images can be processed in the MATLAB program to generate the STereoLithography (STL) file. These methods provide an alternative way of directly observing and quantitatively measuring aggregate packing properties such as particle contact and V content. However, the contact normal fabric is frequently measured in constitutive modelling, and it cannot be easily measured using X-ray tomography. The fabric requires identifying the contact points and the description of the contact tangent plane and the contact normal plane. This procedure seems easy to perform by numerical experiments, by taking into account the geometry of the sample, but an arduous task for physical experiments.

2.7.3 Discrete elementary method

In the past two decades, the DEM has been used to better understand the mechanical behaviour of pavement as a granular material. The method is used to simulate a granular material and its discrete nature; without using a constitutive model. Also, it can analyse granular samples at their microstructural level to assess the mechanical behaviour under several conditions. DEM is a quantitative tool that does not require image process analysis as used in the study by (Ghedia & Sullivan, 2012). DEM uses the positions and geometry of aggregate and uses a step-by-step approach for analyses (A. Theocharis, 2015). Numerous studies also used physical investigation and DEM simulation and noted changes in the topology of the void (Kutay, 2005; Kutay et al., 2007; Liu, 2015). Laboratory and DEM simulations results indicated the formation of a complex contact force network on pavement layers that transfers the applied stress on the material. The advancement of specially orientated power chains stresses has ramifications for the void shape. Studies by (Iwashita and Oda, 2000; Oda, 1998) performed the biaxial pressure tests, and the samples portrayed the development of stretched voids (Muthuswamy, 2009; Kuhn, 1999; Ma et al., 2020). This was due to aggregate moving apart and losing contact parallel to the pressure. As a result, the strong force chains created a parallel shear to the pressure direction. Iwashita and Oda's observation also suggested developing some elongated voids, though void geometry was not measured. That's clear evidence that aggregate packing has to be assessed with a method such as a scan line that can adapt to the chains stresses and changing shape and position of voids.

2.7.3.1 Scan line approach

The change in void topology within shear bands due to traffic loading shows scope for quantitative analysis of void shape within localisations, such as a scan line void based

approach. A scan line void-based approach is a DEM, the easiest way to quantify voids along the angle without physically using the sample. The method uses the fabric tensor vectors and the void fabric in a set of the aggregate matrix, two-unit vectors ($\mathbf{n}$, $-\mathbf{n}$) are developed on their main axis, and v refers to the kth void fabric. In 1985 Oda developed the method, and it was reworked by (Ghedia and Sullivan, 2012), who highlighted the need to identify inactive aggregate. Inactive refers to the aggregate, which is not in contact with any other aggregate, and that space is a result of a lack of contact of the aggregate in mixtures, which is called the wall effect. It usually happens to the aggregate infilled within the boundary of the larger aggregate. This effect can create a larger number of voids within a mixture, resulting in high porosity and increasing the chance of interconnected voids. Similarly, fine or medium aggregate particles pushing the larger aggregate apart can result in some aggregate being isolated; that effect also contributes to a larger fraction volume of voids and a high probability of interconnectedness of voids.

After determining the wall and loosening effect, mainly inactive aggregate, the whole sample is scanned by parallel lines along angle θ . The given angles θ are between -90° and 90° as shown in Figure 2-13. For each parallel line, it is easy to find the intersection points between the void and the aggregate (Theocharis, 2015). Those points are listed from smaller to larger coordinates, based on the angle θ of the line. Symbols denote those points α_t and α_{vs} refer to the difference between the highest and lowest principal values (for instance, fabric anisotropy) for the contact normal fabric and the scan line fabric, respectively. So, two adjacent points that do not belong to the same particle define a void vector. Individual void vector is characterised by $\mathbf{n}^\theta$ the unit vector along all scan line void vectors slanted at a particular angle θ . A novel scan line void fabric tensor was defined by (Oda and Nakayama, 1989) by applying a length of void vectors, a rework by (Ghedia and Sullivan, 2012).

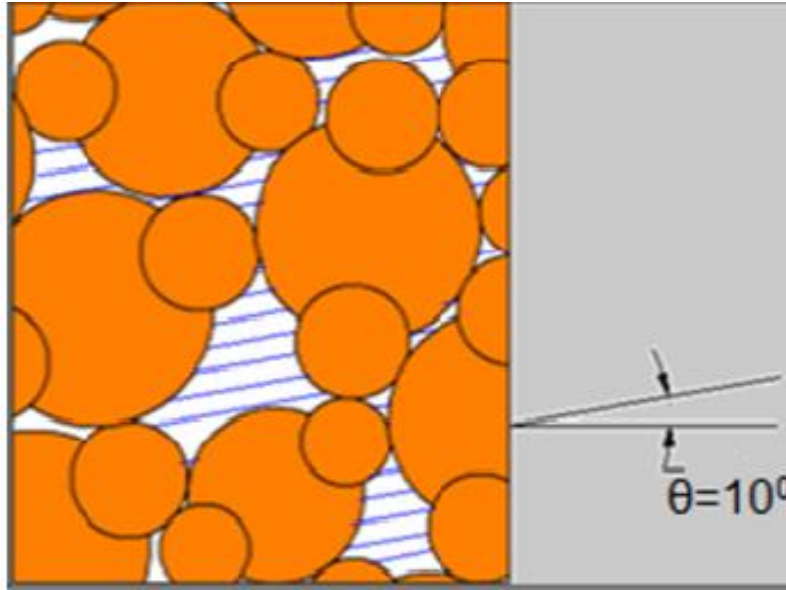


Figure 2-13: Illustration of wall and loosening effects and line scan void (Zheng *et al.*, 2015)

2.7.4 Hydraulic conductivity tensors

The hydraulic conductivity (K_{ij}) property depends more on the fraction volume of voids of the sample and how the void fabric tensor vectors are becoming more promising (Guo, 2012). The void size distribution is the main factor in studying fabric material fluid flow characteristics. The triaxial test is extensively used to examine the variation of permeability owing to fabric change due to axisymmetric stress conditions. Concerning the fluid-sample interaction with the focus based on the aggregate density, the permeability tensor of pavement layers can be calculated based on the fluid's macroscopic momentum balance equation. When classified, the contact normal and void fabric tensors describe the directional dependency of the tortuosity and hydraulic diameter, respectively. The globally used Carman-Kozeny equation (Gao *et al.*, 2012) assumes that the permeability-anisotropy factor is equivalent to the square of the void-channel tortuosity ratio. To measure the void size in and perpendicular to the flow direction, the aggregate mix's microstructure can be determined by the weight factor ($g^{\theta\varphi}$) and Areal Pore Size (APS) that describe the influence on permeability (Inglis and Pietruszczak, 2003). APS measure characterises void size in the plane perpendicular to any direction and can be obtained from an average of $g^{\theta\varphi}$. When a series of voids permit liquid flow, that should be taken as the effective voids volume (Bear, 1972). Hence, non-interconnected voids, dead-end voids and stagnant pockets are regarded as ineffective voids. This study explored the significance of APS in determining permeability by using the

permeability anisotropy ratio. As mentioned above, the permeability anisotropy ratio is a function of the fraction volumetric porosity and the medium's fabric. The permeability anisotropy ratio reduces when the porosity increases. Nevertheless, if the material anisotropy is weak, the reduction becomes insignificant. The permeability anisotropy ratio defined as the permeability in the bedding plane ($x - O - y$) to the permeability normal to the bedding plane (z-direction).

2.8 Clump

A clump is a rigid body made from a collection of spherical pebbles (a piece). The independently assigned clumps surface properties represent arbitrary shapes and are determined by using the positions of the pebbles and their radii. The clumps can obey the equations of motion by translating and rotating. Like balls, the clumps depend on the assigned mass properties; loading and velocity conditions exist. Mass properties are described using:

- The reference configuration and clump density obtainable using the positions and sizes of the pebbles in the reference configuration accounting for sphere overlap;
- (m, x, I) for the reference configuration. For this case, the mass properties are determined given direct specification; for example, the mass is separated from the pebble distributions, then pebbles are used to represent the surface, and
- Obtaining a closed surface and associated mass properties through clump density using automated computation (Blow and Binstock, 2004).

A closed geometry of line segments in 2D, triangular facets in 3D determines the pebble distribution and calculates the mass property. The *clump template create bubblepack* command is used to automatically create the pebbles to represent the surface to the desired fidelity. The user must define the clump templates. The three ways that can be used to insert clumps into the domain are replicating the clumps (*clump replicate*), generating non-overlapping groups of clumps (*clump generate*) and distributing overlapping clumps to match a specific size distribution (*clump distribute*).

Walls are created using *wall create* command, and facets are added individually using *wall addfacet* command. The facets must be set to a vertex in 2D, an edge in 3D. Wall configurations such as a box, plane, sphere, cylinder, cone, etc., are easily generated using *wall generate* command. In the case of complex shapes, a wall can be imported using the geometry generated in modelling software. *stl* or *.dxf* format of the geometry file.

2.9 Bitumen modification

Over the past decades, there has been aggregate attention to modifying asphalt mixtures to enhance their mechanical performance and increase the durability of pavements. Several investigations have used various modifiers to improve the quality of asphalt mixture (Oda, 2012; Cheng *et al.*, 2015). Among modifiers, various kinds of fibre, including steel, basalt, polypropylene and thermoplastics, have been utilised (Lou *et al.*, 2021; Yaro *et al.*, 2021). The effect of fibres on the mechanical performance of asphalt mixtures is of more benefits than of polymers such as Styrene-Butadiene Rubber (SBR), Styrene-Butadiene-Styrene (SBS) and Polyethylene (PE). Fibres can be used to prevent drain down in asphalt mixtures and improve mechanical properties such as viscoelasticity, rutting resistance, dynamic modulus, and reflective cracking (Mohammed *et al.*, 2020).

2.9.1 Use of fibre on bitumen modification

The recent decades have seen increasingly rapid advances in improving construction material with fibres (Wu *et al.*, 2014; Jahromi, 2015; Weise and Zeissler, 2016; Zachariah *et al.*, 2018). Various kinds of fibres have been used in asphalt binders as another way to reduce mechanical performance problems. A considerable amount of literature has been published on evaluating fibre modified bitumen mixtures (American concrete institute 1976; Chen and Lin, 2005; Mohammed, Parry and Grenfell, 2018). Fibre-modified asphalt mixtures have better strength, fatigue resistance, and ductility (Huang and White, 1996). Fibre modified bitumen mixtures have improved softening, penetration and viscosity (Wu *et al.*, 2014; Mohammed, Parry and Grenfell, 2018). Adding fibres makes a well-reinforced asphalt mortar because fibres' ability to function as a spatial network improves the absorption and adhesion of bitumen to aggregate (Tapkin, 2008; Wu *et al.*, 2014).

Several research results suggest positive outcomes when adding fibres to enhance the properties of bitumen mixtures, and a summary is given in Table 2-2. Although fibres have shown many desirable results, some studies have revealed that fibres, especially cellulose, can be costly due to high binder absorption. Various research used up to 2% cellulose fibres by weight of bitumen (McDaniel, 2015; Mohammed, Parry and Grenfell, 2018; Slebi-Acevedo *et al.*, 2019). However, (Slebi-Acevedo *et al.*, 2019) highlighted that it is critical to consider that an overabundance of fibres can make the mastic brittle. The functionality of the bitumen should be considered. Utilising a bitumen with high fibre content can prompt the mixing procedure for asphalt production. Wu *et al.*, (2014) added three kinds of fibres to bitumen to

measure its viscosity. The study concluded that 0.3% lignin by weight of bitumen provides the binder with the ideal fortification while blending more fibres could be uneconomic or make the bitumen increasingly brittle, which eventually would lead to asphalt failure.

Table 2-2: Main findings for reinforcing asphalt mixture using fibres (Slebi-Acevedo *et al.*, 2019)

Fibre type	Main Findings
Carbon	High strength and modulus Improves thermal stability Enhance thermal conductivity and reduce electrical resistivity of asphalt mixture Recovery influence in asphalt mixtures (Z. Wang <i>et al.</i> , 2016) Increases toughness and dynamic modulus (Khattak, Khattab and Rizvi, 2013) Improves fatigue Improves permanent deterioration (Jahromi and Khodaii, 2008)
Steel	Increases Marshall stability, rutting resistance, indirect tensile strength, and low-temperature cracking resistance (Wang <i>et al.</i> , 2016) Heals on its own (Sun <i>et al.</i> , 2017; González <i>et al.</i> , 2018)
Polyacrylonitrile	Improves Marshall strength, rutting stability (Chen <i>et al.</i> , 2009) Positive effect on plastic deformations (Weise and Zeissler, 2016) Improves rutting behaviour (Bijwe, 1997)
Glass	Increase strength and modulus (Bijwe, 1997) Increase in melting temperature (Bijwe, 1997) Lower elongation (McDaniel, 2015) High elastic recovery (McDaniel, 2015) Higher lingering pressure limit (Tanzadeh and Shahrezagamasaei, 2017; Morea and Zerbino, 2018) Rutting behaviour increases (Guo <i>et al.</i> , 2015) Increases tensile failure strain (Fakhri and Hosseini, 2017)]
Mineral	Enhances skid and abrasion resistance (Celauro and Praticò, 2018) Reduces crack and improves flexural strain at lower temperatures (Zhu <i>et al.</i> , 2007) Decreases chances for permanent failure (Xue and Qian, 2016)
Polyester	Promotes pothole, rutting, and fracture resistance (McDaniel, 2015) Improves the mix stability Increment rigidity limit

	Expands the crack vitality and durability Enhances toughness at high-temperature, expands the flexural endure low temperatures (Zhu <i>et al.</i> , 2007) Improves break spread opposition (Zhu <i>et al.</i> , 2007)
Cellulose	Reduce binder drain down in open and gap-graded asphalt mixtures (McDaniel, 2015). Obtained from various plant materials or recycled material like newsprints (Oda, 2012) Absorbs high content of binder, and that leads to a long durable mixture (Mohammed, Parry and Grenfell, 2018) Poor toughness and modulus (Bijwe, 1997; McDaniel, 2015) Poor tensile capacity (Bijwe, 1997; McDaniel, 2015) Absorption of a high amount of fibre is costly (McDaniel, 2015)

TK fibre's main constituents are lignin, hemicellulose and cellulose (Hendriks and Zeeman, 2009). Amongst those, cellulose's chemical and physical properties are associated with the arrangement of the cellulose molecules and have various proportions of crystallinity and amorphous structures (Diana, 2011). Hemicellulose is a common polysaccharide consisting of assorted pentose and hexose sugars (Pérez *et al.*, 2002). Lignin is a common amorphous heteropolymer composed of various phenylpropane units assembled with various linkage types (Rinaldi *et al.*, 2016). Generation of lignocellulosic wood waste from saw-mills/woodworks and other products has become a significant cause for concern as the trash is preordained for landfills that, in turn, becomes a fire hazard to society and the environment in Botswana (Motoc, Santiago and Pop, 2018; Arafat *et al.*, 2019; D. Wang *et al.*, 2019). Currently, small amounts of lignocellulosic waste are used and recycled as valuable bioproducts. Lignocellulosic materials have shown great potential as reinforcing fillers in the manufacturing of wood-plastic composites (Motoc, Santiago and Petru Pop, 2018; Setswalo *et al.*, 2019). It is readily available, low cost and renewable. Watkins *et al.* highlighted the existing chemical likenesses between cellulose, lignin and bitumen since they are hydrocarbon materials made primarily of carbon, hydrogen and oxygen (Watkins *et al.*, 2015). In this regard, lignocellulosic biomass is a potential modifier to enhance the performance of road construction materials. Also, applying lignocellulosic products as a modifier and partial substitute can reduce shortages of petroleum bitumen production (Wang *et al.*, 2019).

Some studies towards bitumen modification by lignocellulosic materials have shown promising results. Arafat *et al.* used various lignin fibres to modify the asphalt mixture and observed improved rutting resistance without losing resistance to moisture-induced damage (Arafat *et al.*, 2019). (McCready and Williams, (2008) indicated that lignin fibres enhanced

the temperature sensitivity of bitumen . A study by Pan discovered that the addition of lignin fibre reduces the rate of ageing of bitumen (Pan, 2012). In a study by (Batista *et al.*, 2018), the addition of lignin to the bitumen showed better performance in rutting and cracking resistance. The inclusion of lignin also led to better thermal stability. Other reports on the application of cellulose to modify bitumen have shown the enhancement of the mechanical performance of mixtures, such as rutting and fatigue cracking resistance (Abiola *et al.*, 2014).

2.9.2 Use of fibre to improve performance under action of salts

In the study by (Yang, Zhang and Shi, 2018), Yang *et al.* pointed out that a small amount of nanoclay called polysiloxane-modified montmorillonite improved the stripping resistance, reduced moisture susceptibility, and minimised the damage of asphalt mixtures to de-icers without chloride (Yang, Zhang and Shi, 2018). The results from a study by Wei *et al.* suggested that an asphalt mixture modified with nanoclay and carbon microfibres improved the moisture susceptibility and performance after the de-icing solution's corrosion (Wei *et al.*, 2011). The material was produced using fine fibres basalt extracted from plagioclase and pyroxene and was tested using the bending test. Olivine improved the low-temperature properties of low-temperature properties. Shi *et al.* investigated the impact of nanoclay in reducing the deterioration of asphalt mixture to non-chloride deicers (Shi *et al.*, 2012). Results indicated that when soaked in the 31% calcium chloride (CaCl_2)-based deicer, the fracture energy of unmodified hot mix asphalt (HMA) averaged at 34.3 J/m^2 , while a fracture energy up to 42.4 J/m^2 (a 24% increase), was achieved by adding 2% nanoclay and 0.7% carbon microfiber modified bitumen. Iong *et al.* investigated the effect of a freeze-thaw cycle, including salt concentration, on asphalt-aggregate interfacial bonds (Iong *et al.*, 2011). The results showed that the asphalt-aggregate mixture slowly lost adhesion due to increased freeze-thaw cycles and salt concentrations.

2.10 Discussion

It is essential to optimise the microstructural properties to design the mix and improve mechanical performance. Several factors were shown to significantly affect the microstructural properties and decrease the resistance to the mechanical performance of the asphalt pavement. Therefore, optimising microstructural properties needs a good understanding of the most important contributing factors.

The review concluded that microstructural properties influence the mechanical performance of asphalt mixtures. Microstructural properties affect aggregate grading, packing, compaction and energy method, and the quality of binders. Packing depends on aggregate gradation and physical properties such as texture, morphology and shape. Physical properties and strength depend on the rock origin and chemical composition. Measurements of microstructure are called fabrics. The anisotropy of microstructure can be measured using fabric tensors. Fabric tensors can be captured using as scan line method. Other methods useful for capturing microstructural properties are the three-dimensional (3D) method based on X-ray and the two-dimensional (2D) image processing method based on a CCD by a digital camera. The internal structure of the aggregate skeleton based on contact correlations can be evaluated by the length of the contact line) and normal contact fabric tensor (based on vectors). MATLAB can capture the images of the actual aggregate create STL files that can be exported to PFC3D to create realistic aggregate shapes called clumps. Virtual samples can be created using PFC3D, and triaxial test can be simulated to appreciate the anisotropy. The quality and content of a binder have a significant influence on the mechanical performance of asphalt mixtures. Fibres like hemicellulose can be used to enhance the rheological properties of a binder.

CHAPTER 3: METHODOLOGY

3 NUMERICAL MODELLING OF ANISOTROPY OF MICROSTRUCTURAL PROPERTIES ASPHALT MIXTURE THE GRADATION

An excellent quality pavement is essential for sustainable development. Such service provides such pavements provide a smooth ride and high resistance to thermal cracking, withstand high traffic volumes, and effectively bear and transfer the load to the underlying (Mohammed et al., 2020). Horak *et al.* (2017) advised that the aggregate gradation must be designed to offer a strong aggregate microstructure capable of withstanding repeated load applications and high resistance to rutting or fatigue cracking. Studies indicated that gradation methods that can improve the aggregate packing efficiency incorporate all influencing factors, such as aggregate physical properties (such as aggregate size, orientation, morphology, texture, shape) and layer thickness (Rajan and Singh, 2017; Hassan *et al.*, 2021). The shortfall of these methods is that they focus on specific aspects and are aided by some laboratory experiments. This research focuses on incorporating all factors to improve aggregate packing efficiency. In this study, the use of fabric tensors using DEM and the scan line approach is acknowledged as appropriate for developing the aggregate microstructure and characterising their anisotropy. The advantage of DEM aggregate gradation packing is the ability to simulate microstructure by creating clumps using the coarse aggregate images and controlling the DF. This method can incorporate aggregate texture and shapes, maintaining fraction densities. The triaxial test was adopted, and the void scan line method was applied to measure the air voids' size, shape, and orientation. All those mentioned above are achievable using MATLAB coupled with PFC3D commercial software.

3.1 Objective(s) and scope

This chapter aims to achieve the following, and the flow of the study is presented in Figure 3-1:

- To create virtual aggregate gradation using clumps to simulate the realistic particles shape and triaxial test for compaction.
- To analyse the virtual microstructure using DEM and analysis it to obtain features such as inter-aggregate contact and voids in the x, y, z – directions using the statistical distribution vectors by applying the void scan line. The air voids' size, shape, and

orientation were measured based on second-order fabric tensors. The correlation between the contact normal fabric tensor and void fabric tensor was determined

- The void fabric tensors were used to calculate the porosity of the virtual microstructure. Also, the porosity binary mixtures in a microstructure according to the Bailey method were determined and, most importantly, DASR, and
- Determine the aggregate gradation which will be used for laboratory assessments.

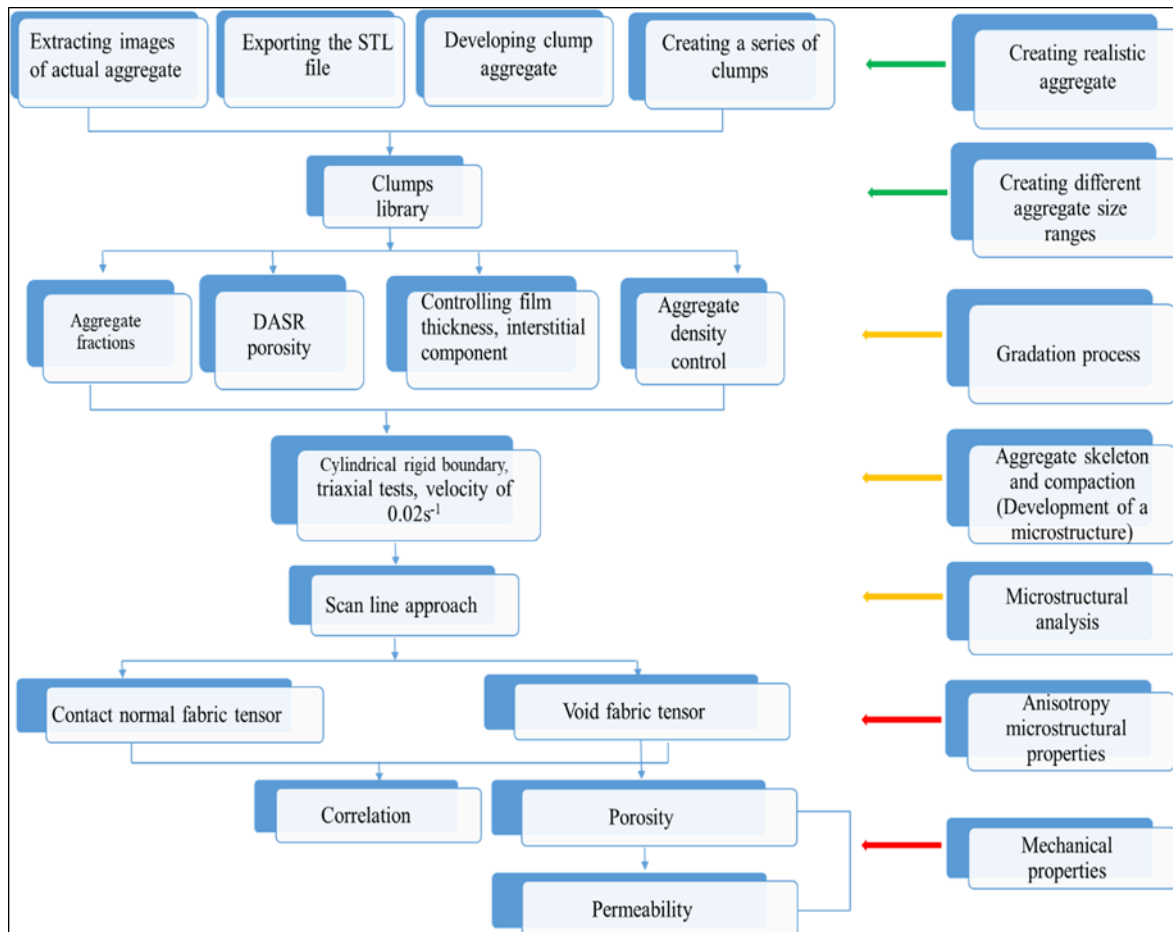


Figure 3-1: Chapter flow chart

3.1.1 Creating the realistic aggregate particles shapes

Extracting images of actual aggregate

There are two main reasons for characterising mineral aggregate morphology to conduct discrete element modelling.

- The aggregate-based material volume or mass consists of mineral aggregate particles. So, aggregate morphological properties form a crucial basis for building the digital sample of an aggregate-based mixture, which is essential to discrete element modelling.

- The aggregate morphological characteristics (shape, texture, angularity) are virtual for interlocking and mechanical behaviours of aggregate particles in a stone matrix mixture.

The user-defined model is adopted and conducted by computer programming by governing a few user-defined parameters. This model simulated the actual aggregate in polygons, polyhedrons, ellipsoids, cubes, and other regular shapes to develop a realistic, shape-based mixture. Over 200 individual aggregates were scanned, and two-dimensional images were captured for each aggregate particle. The steps for creating actual images were as follows:

As illustrated in Figures. 3-2a and 3-2b, all X-ray CT images of the aggregate size range for Granite (1), Granite (2) and limestone (3) based on the Bailey methods, two different NMAS. The total volume of design samples was processed through a MATLAB program to acquire coordinates of aggregate surfaces. This step involves:

- binarisation using the image greyscale as representative of aggregate (Kutay, 2005; Elnasri, 2015; Liu *et al.*, 2017; Gong *et al.*, 2018);
- building matrix of x,y - coordinates and utilising the height value provided by the scanning as the z - coordinate to represent the actual data replicating properties of a particular edge of an image which is a cross-section of the aggregate (Liu *et al.*, 2017).

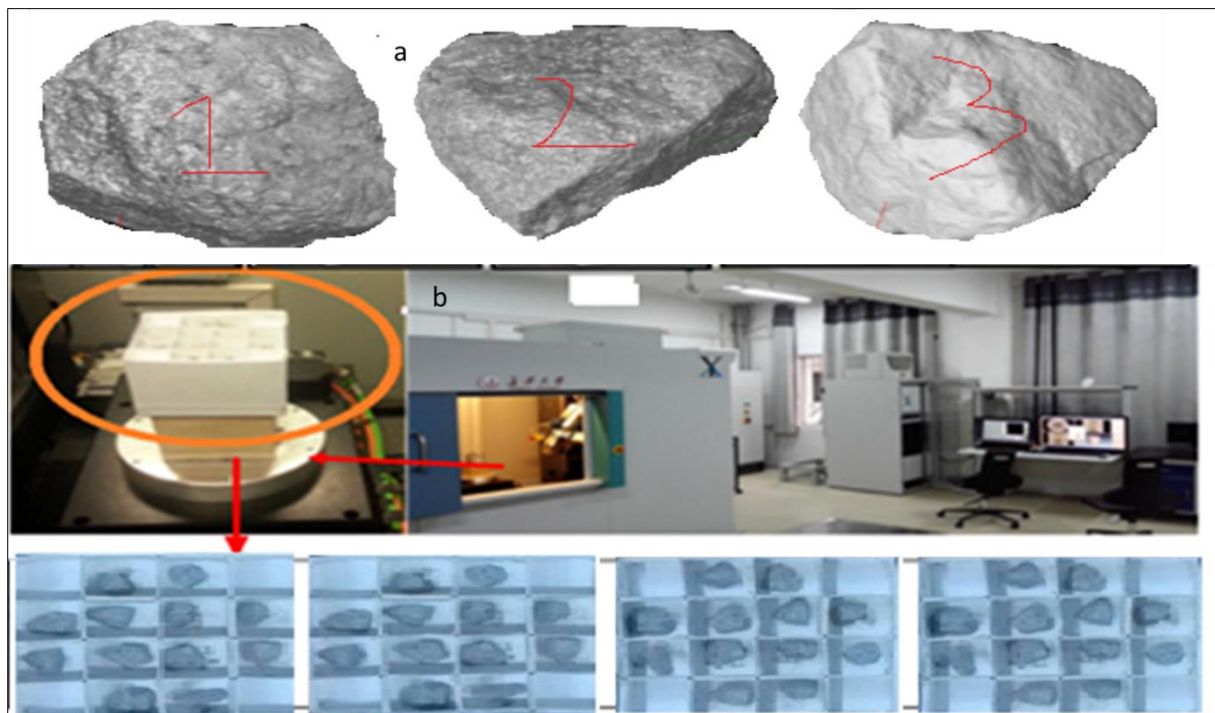


Figure 3-2: X-ray CT images (a) actual aggregate (b) scanner

Exporting the STL file:

Assemble the coordinates matrixes of all aggregate images, stack them to make a big matrix, and develop the resultant STL file as shown in Figure 3-3. (Theocharis, 2015; Liu *et al.*, 2017).

The STL files are exported by converting the quadrangles into triangles in STL file format. The STL files are the critical inputs of the PFC command used for developing clump logic templates of aggregate particles. A clump logic template enables the generation of the artificial aggregate of random shape, as illustrated in Figure 3- 4 (Liu, 2015; Gyurkó and Nemes, 2018; Liu *et al.*, 2020).

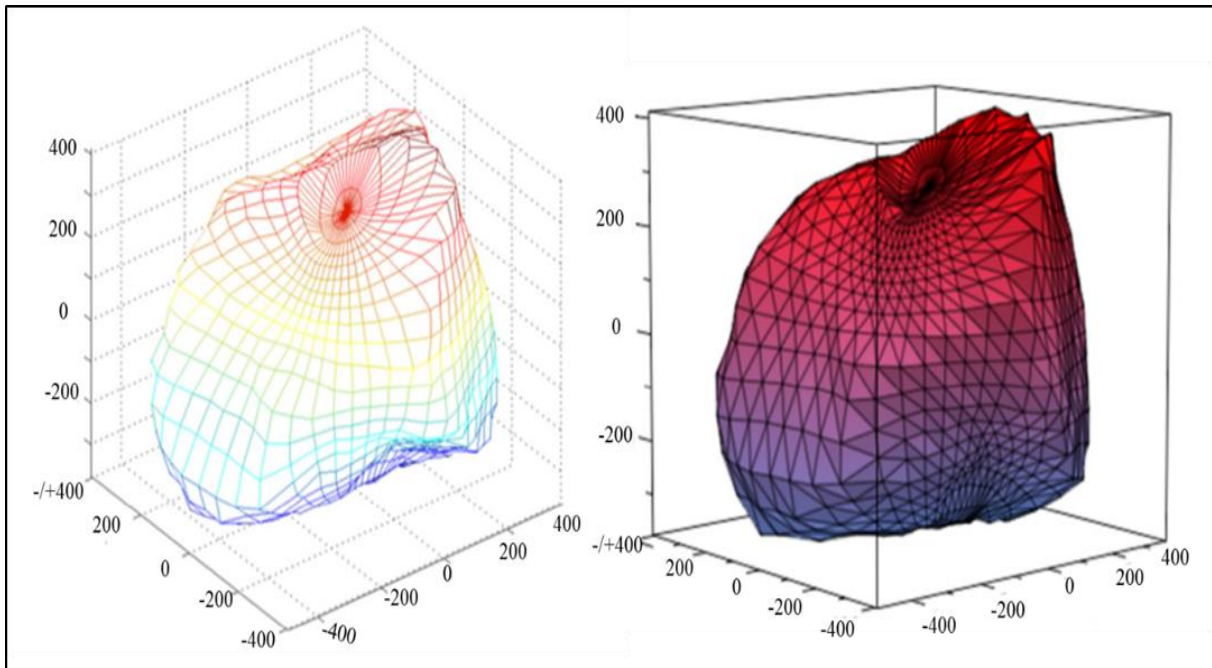


Figure 3-3: Quadrangle and STL model

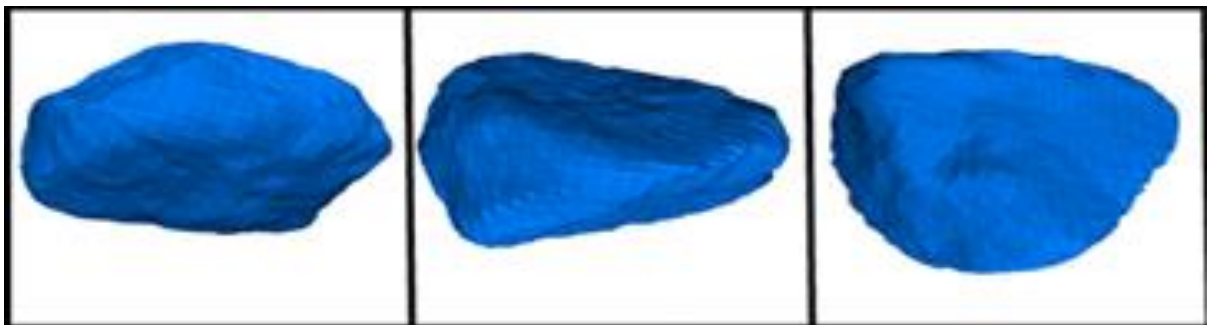


Figure 3-4: STL files

Developing clump aggregate:

The keyword geometry and pebbles are automatically filled into the geometries to create clump templates through the keywords bubblepack and surfcalculate, as shown in Figure 3-5. Many researchers have discussed the spheres filling methodology (Liu *et al.*, 2009; Adhikari and You, 2010).

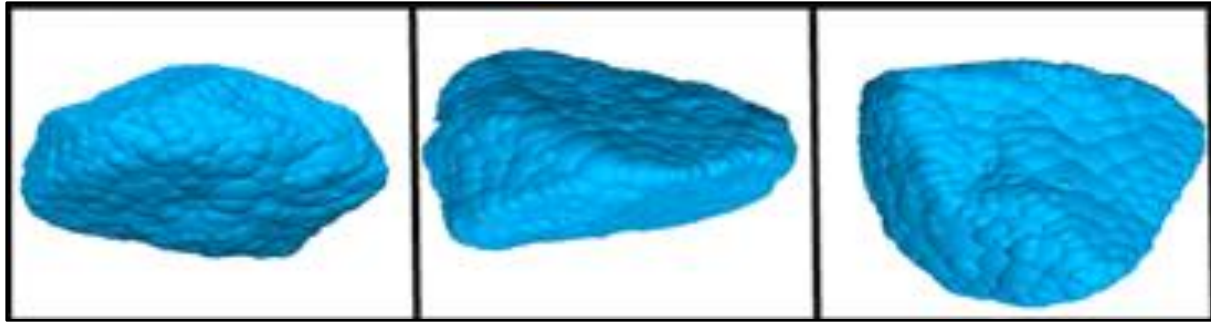


Figure 3-5: Clumps simulating realistic shapes

Creating a series of aggregate size ranges:

The clump templates signify mineral aggregate size ranges morphological features. Therefore, the corresponding clump templates can generate a representative aggregate-mixture. Figure 3-6 shows a hub of 15 clump aggregate was generated then exported to the 15 files named *shape_n.clp*. The series number of an aggregate template is denoted by 'n'.

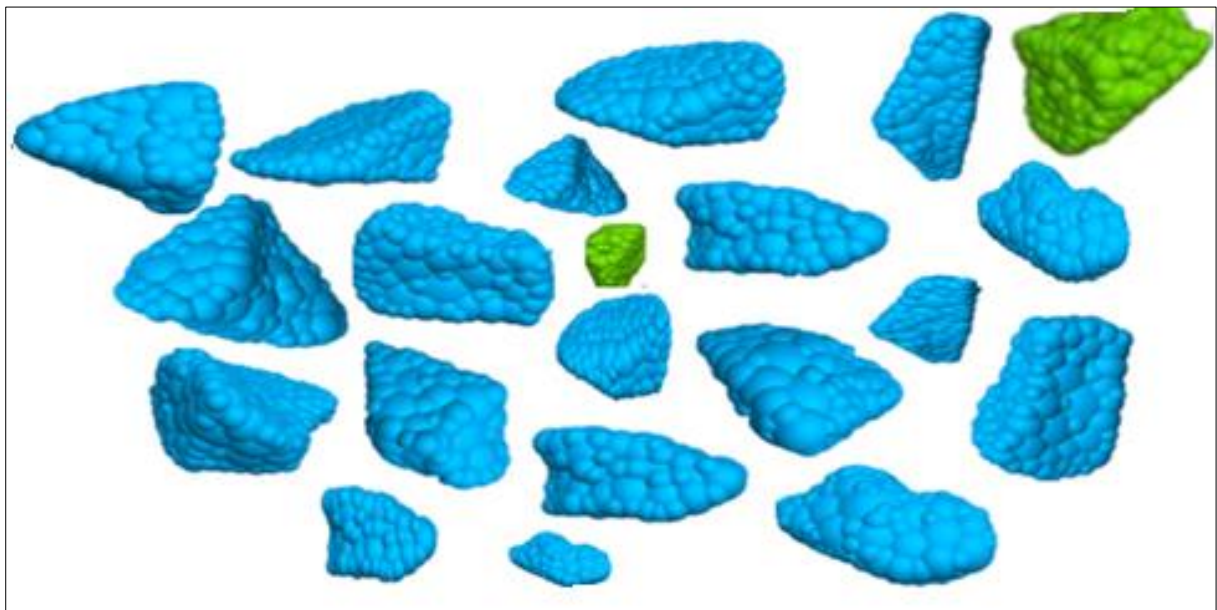


Figure 3-6: Clumps library

3.1.2 Aggregate gradation

Aggregate fraction

Fractions of aggregate size ranges for a mix are called aggregate skeleton subsets and voids for these aggregate packing subsets, and their densities can be determined separately. The aggregate packing subsets can be classified into coarse, medium and fine aggregate. The aggregate skeleton for each subset is estimated by area fraction, as shown in Eq 3-1 (Lee and Hogan, 2021).

$$\rho(z^*) = \lim_{\Delta z^* \rightarrow 0} \frac{\sum_{i=1}^N V_i(z^* \rightarrow z^* + \Delta z^*)}{A_{tot}^* \Delta z^*} = \frac{\sum_{i=1}^N A_i(z^*)}{A_{tot}^*} \quad 3-1$$

where N is the total number of particles of the mix, V_i is the volume of subset i of a given z^* , A_{tot}^* is the total area of the mix, A_i is the cross-sectional area of subset i , z^* is the height of the subset, Δz^* refers to the small increment of dimensionless height z^*

DASR control

The DASR porosity concept was incorporated to regulate the porosity of a range of adjacent aggregate fractions in series that do not overlap. Roquier, (2016) advised that any fabric material with different particle sizes and orientations should have a porosity of at least 45% to 50%. A similar observation was made by (Cherry and Freeze, 1979) that the particles of geomaterials can contact one another when the porosity does not exceed 50 % and thus would provide an interactive of particles and form a load-bearing skeleton. Using FISH code (Denneman, Verhaeghe and Sadzik, 2007) Eq. 3-2 (Kim, 2006) was applied to determine the porosity of a single contiguous range of the aggregate fractions.

$$\eta(4.75 - 2.36) = \frac{\left[\left(\frac{PP2.36}{100} \right) (V_{TM} - VMA) + VMA \right]}{\left[\left(\frac{PP4.75}{100} \right) (V_{TM} - VMA) + VMA \right]} \quad 3-2$$

where, V_{TM} refers to the total volume of a mix, VMA voids in mineral aggregate, $\eta(4.75-2.36)$ means porosity of a typical fraction passing 4.75mm sieve and retained on 2.36mm sieve, $PP2.36$ means % age particles passing 2.36mm sieve, $PP4.75$ means %age particles passing 4.75mm sieve.

3.1.3 Virtual packing and sample testing

The keywords horizontal, height and slope, were used to control aggregate orientations; A cylindrical rigid boundary was created, and triaxial tests were simulated using the command WALL (Zhan, Nan and Jixiong, 2013; Theocharis, 2015; Liu *et al.*, 2017; Gong *et al.*, 2018). The properties of the mixture are in Table 3-1. The aggregate matrix for the density of asphalt mixture was set as 2650 g/cm³, and the effective modulus and friction coefficient were 50 GPa and 0.4, respectively (Zhan, Nan and Jixiong, 2013; Liu *et al.*, 2020). Simulation properties involve the friction coefficient μ normal contact stiffness k_n , shear contact stiffness k_s , parallel bond normal and shear strength pb_nstren and pb_sstren , parallel bond normal and shear stiffness pb_kn and pb_ks (Zhan, Nan and Jixiong, 2013).

Loading was made under quasi-static conditions, and velocity was imposed to walls in a way that the stresses eventually reach the preferred state, at tolerance 10^{-5} with a maximum velocity of 0.02s^{-1} . Figure 3-7 is an example of a virtual sample (Peña *et al.*, 2008).

Table 3-1: Main micro-properties

Name of the properties	Value of the aggregate skeleton
ℓ	0.5
k_n	500
k_s	600
pb_nstren	50
pb_sstren	50
pb_kn	12
pb_ks	12

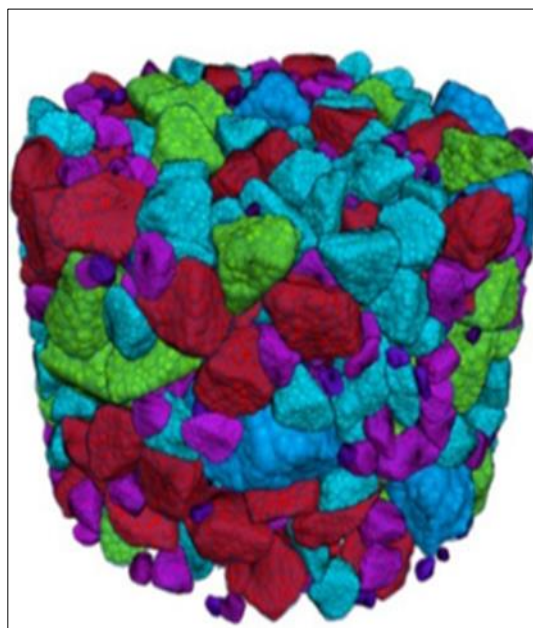


Figure 3-7: Virtual samples

Controlling sample thickness and interstitial components

The asphalt mixture's creep rate and adequate fracture energy were kept to improve cracking performance (Zhang, Roque and Birgisson, 2001). FAR was controlled to minimise the creep rate. Suitable DF and Effective film thickness (EFT) can increase fracture energy (Chun *et al.*, 2012). The fine aggregate represents the fineness of the IC ratio (FAR), which is the ratio of the coarse portion of the fine aggregate (CFA) and the fine amount of the fine aggregate (FFA). The CFA is distinct as the largest particle size of the IC, while the FFA is the remaining finer portion of the IC. EFT influences the samples' permeability, and in this

study, it was obtained using Eq 3-3. The voids between the DASR aggregate are filled with a binder and IC. Excessive IC can lead to cracking. Therefore, IC has to be controlled when reducing porosity using a parameter known as the DF. The DF can be obtained from Eq. 3-4 (Greene, Chun and Choubane, 2014).

$$EFT = \frac{V_{be}}{SA \cdot W_T \cdot PF_{AGG} \cdot G_b} = \left[\frac{P_b - \left(\frac{Abs}{100} \right) \cdot P_{AGG}}{SA \cdot PF_{AGG} \cdot G_b} \right] \times 1000 \quad 3-3$$

$$DF = \frac{\text{volume of potentially disruptive IC particles}}{\text{volume of DASR voids}} \quad 3-4$$

where

V_{be} = effective volume of asphalt binder, W_T = total weight of the mixture, P_b = percentage of the amount of bitumen or water content by mass of the total of the mixture, Abs = absorption, P_{AGG} = aggregate percentage by mass of total mixture, and G_b = specific gravity of bitumen binder, SA is the surface area of fine aggregate, and PF_{AGG} percentage of fine aggregate by mass of total mixtures.

Density control

It is important to control the density of a mixture to avoid premature permanent deformation. In this study, the density coefficient was applied to regulate the variation between the simulation and the laboratory experience: binary mix is made of two aggregate size ranges: course range i and fine range j . The volumetric fractions of course range i and fine range j are r_i and r_j , respectively (where, $r_i + r_j = 1$), and ϕ_i and ϕ_j refer to the packing densities of course range i and fine range j , respectively. The packing density of the binary aggregate skeleton mixture when size range i is predominant (indicated by ϕ_{i*}) the packing density of the binary aggregate skeleton mix when size range j is dominant (denoted by ϕ_{j*}) are given by Eqs.3-5, to 3-7, respectively (Kwan, Wong and Fung, 2015). To obtain the final packing density of the binary mix of aggregate can be simplified to a $\min(\phi_{i*}, \phi_{j*})$:

$$\frac{1}{\phi_{i*}} = \left(\frac{r_i}{\phi_i} + \frac{r_j}{\phi_j} \right) - (1 - b_{ij})(1 - \phi_j) \cdot \frac{r_j}{\phi_j} \cdot [1 - c_{ij}(2.6^{r_j} - 1)] \quad 3-5$$

$$\frac{1}{\phi_j^*} = \left(\frac{r_i}{\phi_i} + \frac{r_j}{\phi_j} \right) - (1 - a_{ij})(1 - \phi_j) \cdot \frac{r_i}{\phi_i} \cdot [1 - c_{ij}(3.8^{r_j} - 1)] \quad 3-6$$

$$\phi = \min \left(\phi_i^* = \frac{r_i}{1 - \left(1 - \frac{r_i}{r_j} b_{ij} \right) r_2}; \phi_j^* = \frac{r_j}{1 - \left(1 - r_j + a_{ij} r_j \left(1 - \frac{1}{r_i} \right) \right) r_1} \right) \quad 3-7$$

where a_{ij} is the loosening effect coefficient b_{ij} is the wall effect coefficient and c_{ij} is the wedging effect coefficient and are denoted as functions of the size range ratio.

3.2 Microstructure analysis by fabric by scan line approach

3.2.1 Normal contact and scan line void fabric tensors

Inactive (wall effect) aggregate not in contact with any other aggregate were removed. It normally happens to the aggregate infilled within the boundary of the larger aggregate. This effect can create a larger number of voids within a mixture, resulting in high porosity and increasing the chance of interconnected voids. Similarly, fine or medium aggregate particles pushing the larger aggregate apart can result in some aggregate being isolated; that loosening effect also contributes to a larger fraction volume of voids and a high probability of interconnectedness of voids.

After determining the area of the wall and the loosening effect, mainly inactive aggregate, the whole sample was scanned by parallel lines along angle θ , at 1% strain increment using the 3D scan line approach by applying Eq. 3-8. The given angles θ are between -90° and 90° . For each parallel line, it is easy to find the intersection points between the void and the aggregate (Theocharis, 2015). The non-diagonal terms were at zero or very close to zero, and obtained values based on the x and y coordinates are the main values. Those points are denoted by symbols α_t and α_{vs} refer to the difference between the highest and lowest principal values (for instance, fabric anisotropy) for the contact normal fabric and the scan line fabric, respectively. So, two adjacent points that do not belong to the same particle define a void vector. Individual void vector is characterised by $\mathbf{n}^\theta$ the unit vector along all scan line void vectors slanted at a particular angle θ . Figure 3-8 is an example of a scan line method.

$$G_v = \frac{1}{\sum_{\theta\varphi=-90^\circ}^{\theta\varphi=90^\circ} \left(\sum_{\varphi=0}^{N^\theta} l_i^{\theta\varphi} \right)} \sum_{\theta\varphi=-90^\circ}^{\theta\varphi=90^\circ} \left(\sum_{i=1}^{N^{\theta\varphi}} l_i^{\theta\varphi} \right) (\mathbf{n}^{\theta\varphi} \otimes \mathbf{n}^{\theta\varphi}) \quad 3-8$$

where i_{th} is a v vector with respect to θ , $v_i^\theta = l_i^\theta \mathbf{n}^\theta$ where the $l_i^{\theta\varphi}$ refers to the length and $\mathbf{n}^{\theta\varphi}$ the unit vector of the i_{th} v scan line. Since the i_{th} $\mathbb{V}$ tensor can be measured as an area, N^θ refers to the sum of scan line segment inclination angle $\theta\varphi$, then the $g_i^{\theta\varphi} = l_i^{\theta\varphi} \mathbf{n}^{\theta\varphi} \otimes \mathbf{n}^{\theta\varphi}$ where the sum of the lengths with inclination to angle θ represents the weight factor $g^{\theta\varphi}$, and φ, θ is the direction of the unit vector in 3D.

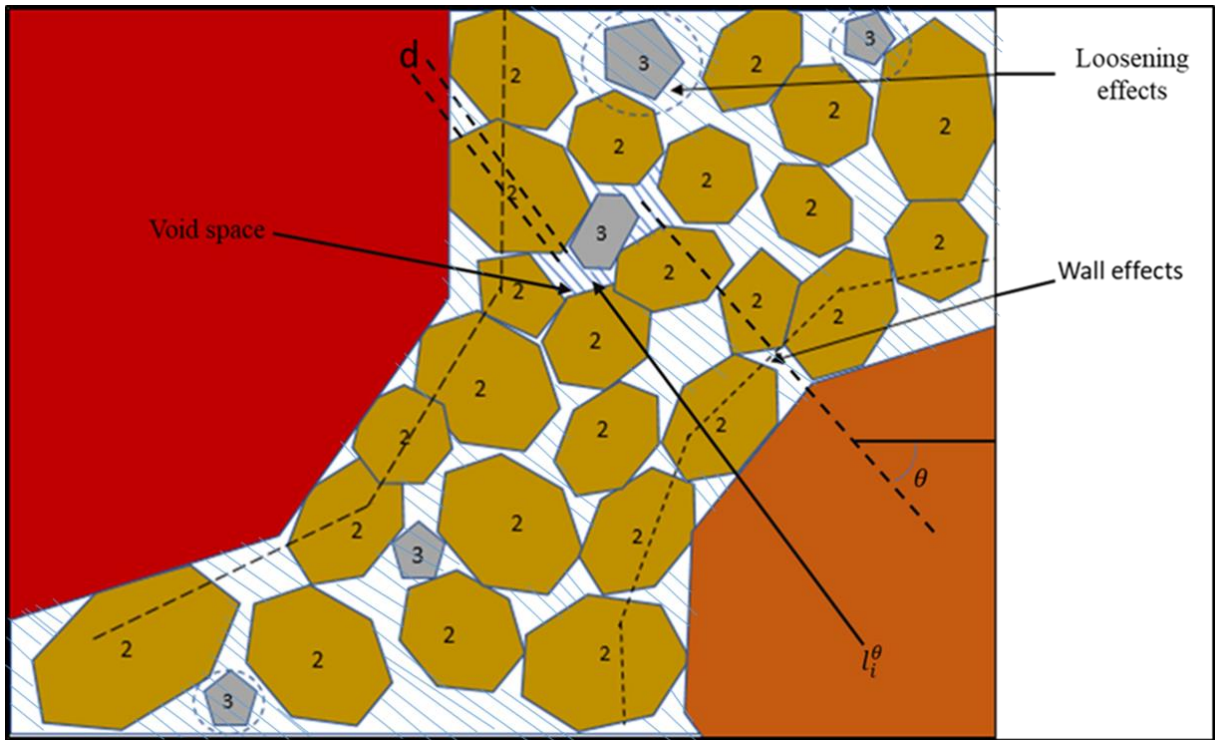


Figure 3-8: Scan line approach

3.3 Hydraulic conductivity tensors

Permeability is a crucial mechanical property of asphalt mixture. The void fabric tensors were used to determine permeability anisotropy. The permeability anisotropy ratio defined as the permeability in the bedding plane ($x - O - y$) to the permeability normal to the bedding plane (z -direction) can be calculated as Eq. 3-9. (Liu, 2015)

$$K_{ij} = \frac{3\eta \bar{\Delta}_V^2}{C_v} [(10 + 3\eta)\delta_{im} + 2\eta g^{\theta\varphi}]^{-1} g^{\theta\varphi} F_{lk}^{AVS} (2g^\theta + 3\delta_{kj}) \quad 3-9$$

where F_{lk}^{AVS} is the fabric of APS and δ_{im} are the identity tensors.

3.4 Preliminary results and discussions

In this chapter, realistic aggregate shapes were successfully created. The X-ray CT images aggregate were analysed using MATLAB, and STL files were developed. STL files were exported to PFC3D, and the high details clumps aggregates were developed, and different sizes were created based on Bailey method descriptions clumps. Gradations were created by controlling indices such as different aggregate binary fractions, the density of binary aggregate, DASR porosity and IC. The size range distribution, packing density, stress state, and inter-particle friction angle to develop a natural aggregate skeleton were simulated PFC3D.

3.4.1 Anisotropy microstructural properties

Figure 3- 9 present axial strain variation from 1% to 16%, and for minor strain from 0 to 0.4%. Also, when the samples reach a critical state, the values of a_t and a_{vs} are smaller at the largest strain level. When the load increases, both values of fabric measurements increase, and when reaching critical state conditions a_t and a_{vs} reach almost constant values. Figure 3-10 shows the development of fabric variances a_t and a_{vs} under different vertical axial strain ε_{axial} obtained through DEM analysis based scan line approach. It can be seen that the evolution of fabric increased with increased vertical axial strain. This is an indication that under that perception, the anisotropy of the void scan line seems to be appeared to be small, though its trend is clear, and a_t shows a significant increase with the increase of the compaction load and of a_{vs} which is associated with the increase of contact normal fabric. There is a clear indication that the two parameters have a correlation; for 72 points, the correlation coefficient indicates $r^2 = 0.709$. The linear regression is set to pass the origin (0,0) and indicate $a_{vs} = 0.0723 a_t$.

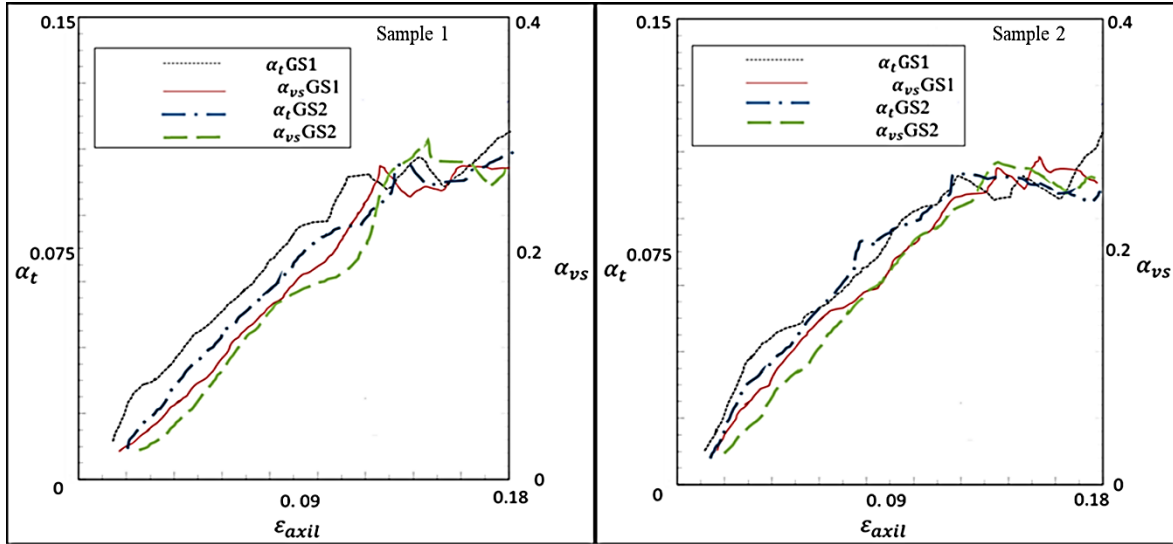


Figure 3-9: Development of fabric variances α_t and α_{vs} under vertical axial strain

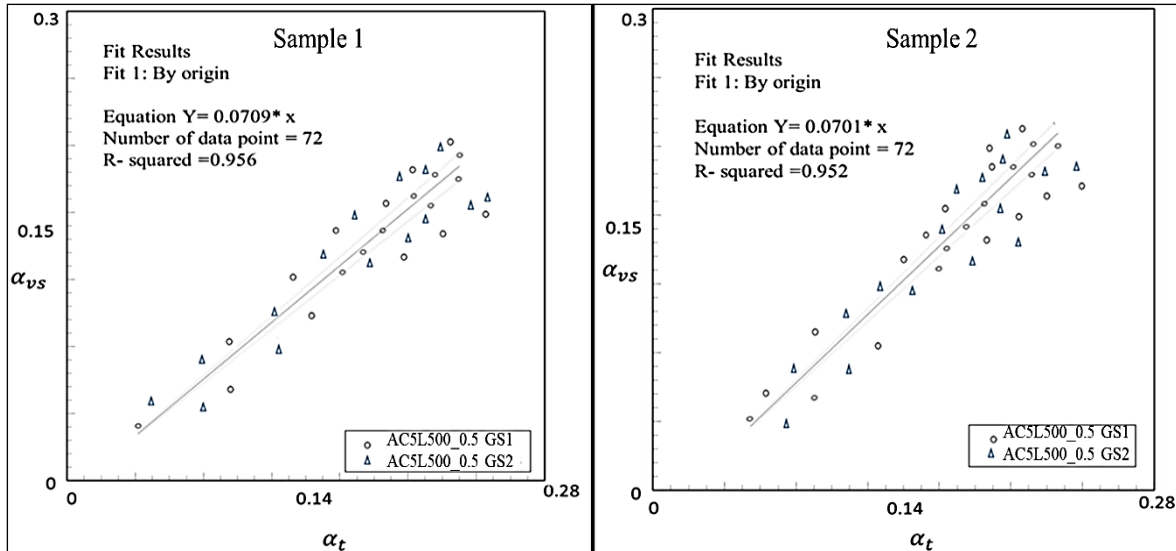


Figure 3-10a and b: Relationship between α_t and α_{vs} for all samples, 5L500_0.5. The solid line relates to a linear regression through the origin, and the two grey lines characterise a 95% confidence level

3.4.2 Porosity

3.4.2.1 DEM Binary aggregate fraction porosity

Tables 3-2 to 3-3 provide the interior relationship between independent variables of all binary samples, and the dependent variable of samples in terms of porosity is obtained using the scan line void method. It was observed that combinations with a very less oversized and pluggers had high porosity, as it can be seen that from 0.01 oversized, 0.4 NMAS and 0.35 pluggers and 0.05 DASR had the highest dependent Y porosity while 0.01 oversized, 0.3 NMAS, 0.16 pluggers and 0.33 DASR had the lowest dependent Y porosity. Another

observation was that 0.04 oversized, 0.19 NMAS and 0.23 pluggers and 0.34 DASR had moderate dependent Y porosity.

Table 3-2: Recorded porosity for various binary mixes for GS 1

Sample no	Independent variable X-weight of material within a fraction (grading scope 1) (40mm)						Dependent variable Y-porosity
	16mm-19mm	13.2mm - 16mm	9.5mm - 13.2mm	4.75mm-9.5mm	2.36-4.75	1.18mm - 4.78	
1	0.03	0.05	0.44	0.25	0.23	0	0.4133
2	0.01	0.06	0.18	0.124	0.4	0	0.4013
3	0.06	0.06	0.34	0.43	0.39	0.02	0.3834
4	0.05	0.04	0.23	0.34	0.023	0.16	0.3993
5	0.07	0.07	0.17	0.51	0.036	0.01	0.364
6	0.08	0.16	0.08	0.15	0.48	0.28	0.3365
7	0.02	0.11	0.22	0.11	0.45	0.44	0.3372
8	0.06	0.27	0.23	0.36	0.46	0.27	0.3379
9	0.07	0.15	0.15	0.02	0.53	0.33	0.3342
10	0.03	0.08	0.09	0.08	0.49	0.53	0.3364
11	0.02	0.06	0.38	0.171	0.2313	0.5	0.41
12	0.07	0.02	0.17	0.45	0.3988	0.01	0.4039
13	0.05	0.09	0.389	0.369	0.3887	0.06	0.39672
14	0.08	0.1	0.141	0.467	0.04	0.03	0.4019
15	0.01	0.11	0.121	0.198	0.0392	0.05	0.3858
16	0.06	0.21	0.042	0.11	0.4588	0.02	0.3579
17	0.06	0.13	0.2001	0.1202	0.4386	0.29	0.3689
18	0.02	0.08	0.2101	0.031	0.27988	0.15	0.3392
19	0.03	0.22	0.131	0.012	0.4488	0.38	0.34433
20	0.04	0.14	0.079	0.032	0.5088	0.04	0.3676
21	0.08	0.08	0.28	0.172	0.2326	0.48	0.3384
22	0.01	0.05	0.18	0.358	0.3976	0.02	0.398
23	0.06	0.06	0.388	0.268	0.4874	0.12	0.3754
24	0.02	0.02	0.142	0.464	0.055	0.01	0.39872
25	0.03	0.09	0.122	0.306	0.0394	0.18	0.4029
26	0.02	0.19	0.044	0.14	0.4376	0.03	0.3978
27	0.05	0.1	0.2002	0.1204	0.2372	0.27	0.3399
28	0.08	0.21	0.2102	0.032	0.17976	0.48	0.3509
29	0.05	0.13	0.132	0.014	0.4976	0.36	0.3812
30	0.06	0.08	0.078	0.034	0.5076	0.42	0.33633

It was also observed that porosity was the highest for GS 2 when DASR was 0 and 0.36 pluggers and 0.16 NMAS and 0.01 oversized. That indicates that the fractions' ratio had a major influence on the porosity and is also associated with high DASR. GS 2 showed the lowest porosity at 2.2%, 28%, 14%, 1%, and 54% of oversized NMAS, pluggers, interceptor, and DASR. The results are consistent with the results of (Liu *et al.*, 2020); they recorded the

dependent Y fraction for X aggregate fractions and obtained the lowest porosity 2%, 27%, 14.1%, 1.2%, and 55% of oversized, NMAS, pluggers, interceptors, and DASR, respectively. Also, (Kim, 2006) used individual fractions and combinations of aggregate size ranges. The results showed the lowest porosity with combinations that involved a high amount of the fraction 4.75mm-2.36mm.

Table 3-3: Recorded porosity for various binary mixes for GS 2

	Independent variable X-weight of material within a fraction (Grading scope 2) (20mm)					Dependent variable Y-porosity
	13.2mm - 16.0mm	9.5mm -13.2	4.75-9.5	2.36-4.75	1.18mm -4.78	
1	0.07	0.31	0.18	0.34	0	0.3412
2	0.06	0.26	0.16	0.26	0	0.3423
3	0.05	0.25	0.34	0.11	0	0.3729
4	0.06	0.23	0.12	0.34	0.19	0.3456
5	0.08	0.3	0.41	0.07	0.11	0.3747
6	0.02	0.14	0.37	0.08	0.18	0.3858
7	0.04	0.29	0.26	0.37	0.36	0.3516
8	0.03	0.13	0.2	0.22	0.3	0.3571
9	0.01	0.21	0.24	0.09	0.44	0.3616
10	0.03	0.25	0.29	0.12	0.55	0.3584
11	0.05	0.311	0.158	0.34	0.5	0.3427
12	0.06	0.262	0.119	0.27	0.01	0.3405
13	0.05	0.283	0.429	0.08	0.06	0.375
14	0.06	0.24	0.121	0.36	0.03	0.3463
15	0.06	0.329	0.4	0.06	0.05	0.3792
16	0.02	0.0412	0.349	0.07	0.02	0.3775
17	0.05	0.187	0.231	0.36	0.29	0.3508
18	0.02	0.1489	0.211	0.17	0.15	0.3562
19	0.05	0.201	0.232	0.07	0.38	0.3562
20	0.03	0.149	0.281	0.11	0.24	0.3717
21	0.04	0.322	0.156	0.35	0.48	0.37169
22	0.08	0.274	0.118	0.27	0.02	0.35434
23	0.04	0.296	0.428	0.10	0.12	0.376
24	0.06	0.27	0.122	0.35	0.01	0.3462
25	0.05	0.328	0.39	0.06	0.18	0.3782
26	0.03	0.0424	0.348	0.09	0.03	0.3776
27	0.06	0.184	0.232	0.34	0.27	0.3505
28	0.03	0.1478	0.212	0.16	0.33	0.3488
29	0.06	0.202	0.234	0.07	0.36	0.3563
30	0.04	0.148	0.282	0.11	0.41	0.3719

3.4.2.2 DARS porosity

Table 3-4 presents the DARS porosity and IC parameters for gradation for scope GS1 and GS2 mixes. All the gradation scopes depicted good DARS porosity. Another important observation was that when DARS porosity is high, the DF become high. Most of the samples have shown good porosity and relatively lower DF. Most importantly, it was observed that when the value of DFT increases, the value of FAR also increases. DARS porosity is also influenced by *VMA* (Consolmagno, Britt and Macke, 2008). So, good DARS porosity was due to less *VMA* of granite and limestone rock source used for all scopes. (Consolmagno, Britt and Macke, 2008).

Table 3-4: DARS–IC Parameters for AC gradation

AC GS1					
Sample no	DARS		IC		
	DARS (mm)	DARS porosity (%)	DF	EFT (microns)	FAR (CFA/FFA)
1	4.75 - 2.36	41.9	0.62	52.8	0.47
2	4.75 - 2.36	40.8	0.6	53	0.49
3	4.75 - 1.18	44.8	0.64	36	0.41
4	4.75 - 1.18	43.9	0.65	27	0.254
AC GS2					
Sample no	DARS		IC		
	DARS (mm)	DARS porosity (%)	DF	EFT (microns)	FAR (CFA/FFA)
1	4.75 - 2.36	45.4	0.66	32	0.36
2	4.75 - 2.36	39.9	0.54	28.6	0.44
3	4.75 - 1.18	46.8	0.67	30.2	0.3
4	4.75 - 1.18	47.6	0.69	37.4	0.24

3.4.2.3 Estimated directional porosity in different depths

Figures 3 -11 and 3-12 show different porosity depths for all samples scopes estimated using Eq.12. It can be observed that the estimated porosities are high at the mid-depths than at the bottom and top of samples. This could be that aggregate particles are closely packed in the middle than at the top and bottom; the aggregate and the boundary may not be in contact with the edges. A similar observation was noted by Kutay, who recorded the lowest permeability in the middle for all samples at different compactions (Kutay, Aydilek and Masad, 2007).

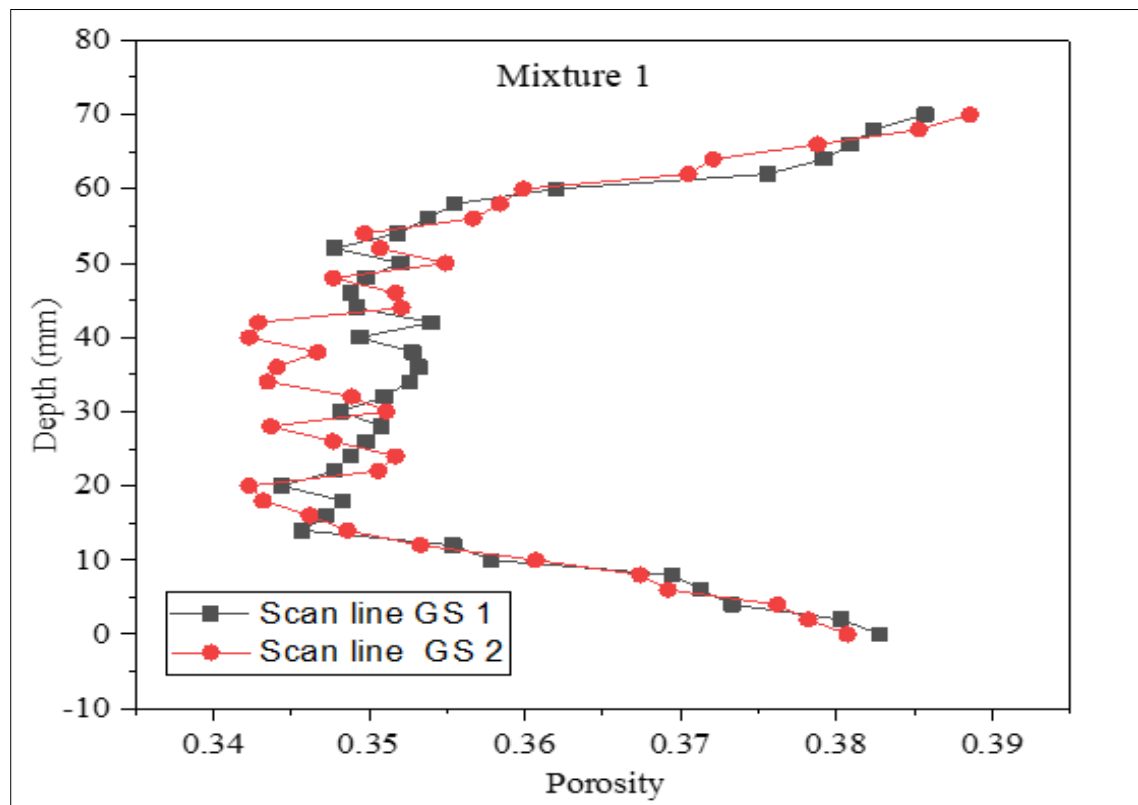


Figure 3-11: Porosity at different depths for mixture 1

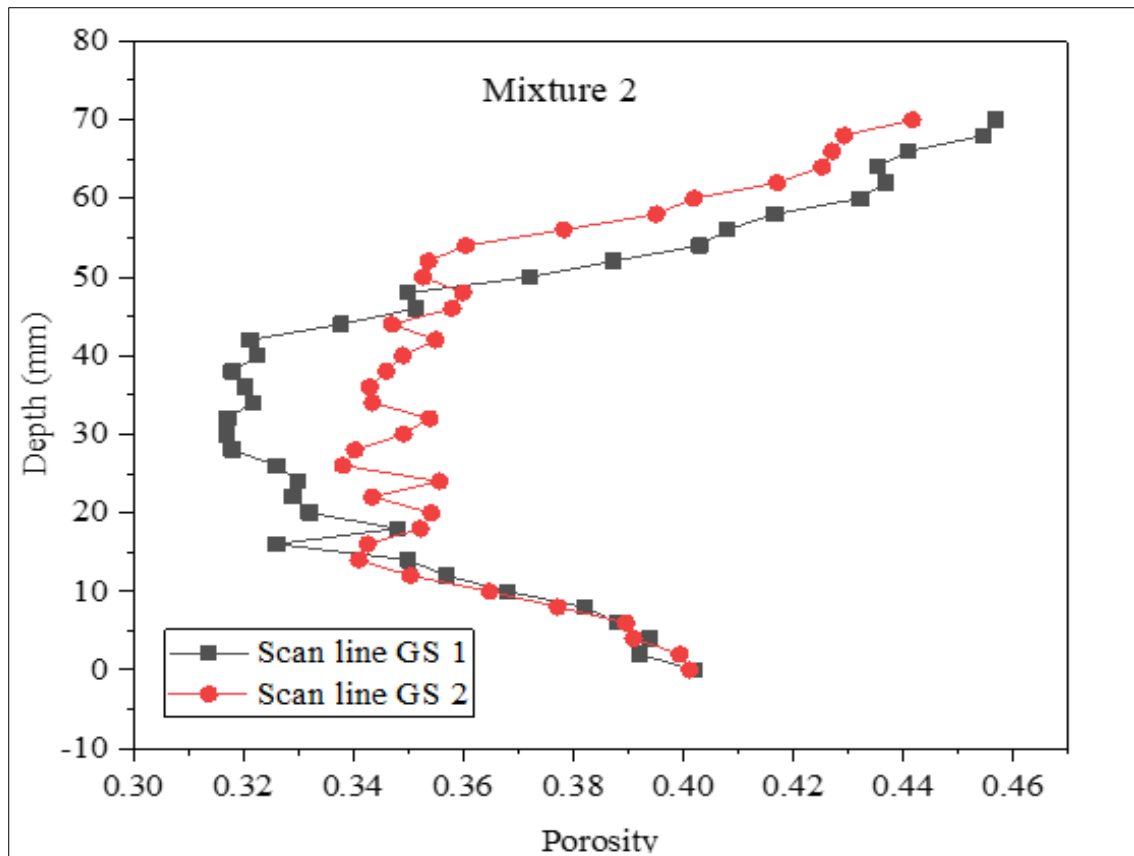


Figure 3-12: Porosity at different depths for mixture 2

3.4.2.4 Gradation

From the optimum porosity, density and IC, all fraction sieve passing and shapes percentages were determined for aggregate gradation as given in Chapter 4 in Table 4-1 and 4-2, and shapes in Table 4-3, respectively.

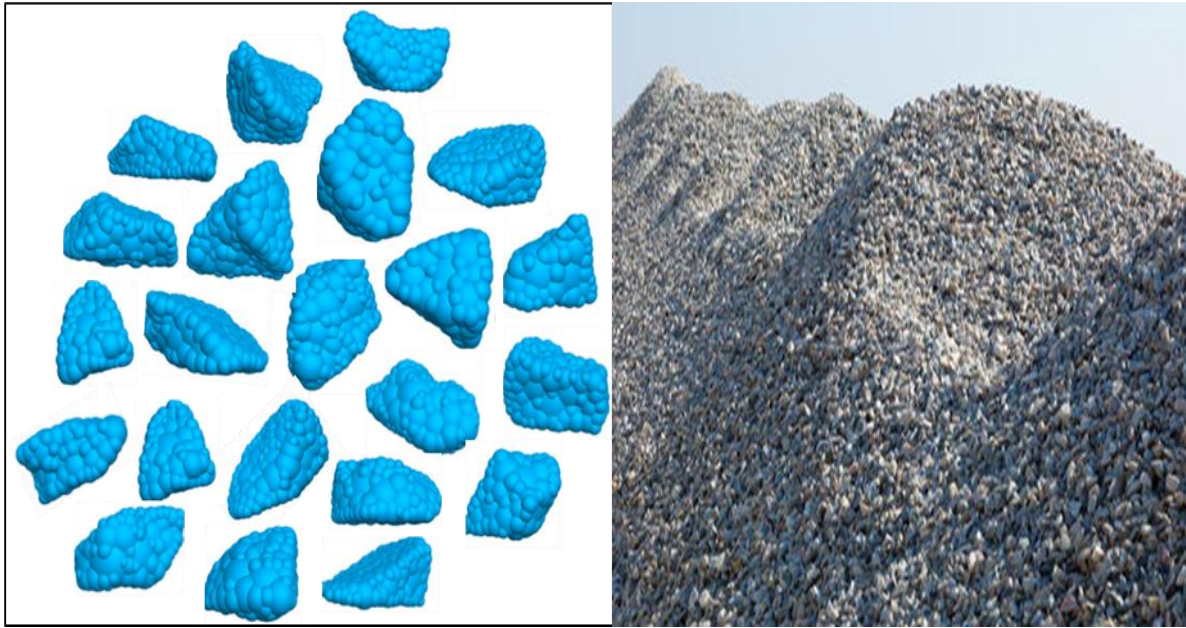


Figure 3-13: Gradations

3.5 Discussion

This chapter began by capturing the actual aggregate images using X-ray CT, followed by STL files using MATLAB. The STL lab was exported to PFC3D commercial software to create library natural aggregate shapes called clumps using Fish code. Gradation was generated by incorporating all factors influencing using DEM utilising PFC3D software. Wall code was used to simulate the aggregate microstructure. Anisotropy of microstructure was analysed using the scan line approach. The results from the scan line method were used to determine the porosity and permeability. Finally, the gradation scopes were generated and are given in Chapter 4.

CHAPTER 4: MATERIALS AND DATA

4 MATERIALS AND CHARACTERISATION

This chapter consists of three sections. The first section introduces and characterises the aggregate used in the study. The gradations obtained in Chapter 3 are presented in this section. The second section introduces and characterises bitumen grades. The third section introduces and characterises TK fibre. Finally, the Na_2CO_3 is introduced and characterised in the last sections.

4.1 Aggregate (rock mineral in Botswana)

Most aggregates in Botswana are granite or limestone, and these are used as the traditional materials to produce asphalt mixtures. The mineral composition that makes up aggregate is based on its hydrophilic or hydrophobic properties, and its relationship with bitumen is vital in moisture damage. High-carbonate aggregate (hydrophobic or basic), like limestone, is easier to coat. These aggregates create a great bonding with the bitumen compared to aggregate with a high percentage of silica, i.e. granite (acidic or hydrophilic aggregate), which is the main reason for the acidity of the bitumen (Behbahani, 2020).

Granite aggregates are the acidic igneous rock in mineral composition was characterised by: quartz (>50 %); plagioclase; feldspars; mica. Chemical composition of granite: SiO_2 ; K_2O ; Al_2O_3 ; Fe_2O_3 ; TiO_2 ; FeO (Yu, 1955). Granite is classically an acidic aggregate, with large texture depth surface microstructure, more texture, and high resistance to wear. Granite also has many physical properties, such as resistance to polishing, which is superior to limestone (Yi-qiu, Li and Zhou, 2010). The interaction of granite and bitumen is a significant factor in developing the microstructure of asphalt mixtures. The granite aggregate, whose relatively small mineral particles have a higher adhesion. When the mineral particles of the granite are relatively large, with certain minerals glossy crystal faces, it has poor adhesiveness with bitumen (Hu, 2011). Dense marble-like limestone comprises either calcite or dolomite, while dolomite is the most common. The chemical formula of limestone includes the following compounds: CaCO_3 ; MgCO_3 (Yu, 1955). The interaction of these compounds has a favourable impact on the adhesion of bitumen to the mineral surface (Yefremov, 2020). The selection of aggregate was based on three principles: (i) most rock-forming minerals must be of silicate or carbonate origin; (iii) the deposits of the selected rocks must be in large quantities. In Botswana, the quarries that complied were located more than 500 km apart.

Table 4-1 and Table 4-2 show the gradations of local aggregate: (I) Granite (GD 1) supplied by a Belabela quarry in Mokolodi, the southern part of Botswana; (II) Granite (GD 2) supplied by a quarry in Sekoma, a desert area in Botswana and Limestone (GD 3) supplied by a quarry in Chobe district, the northern part of Botswana. Aggregate gradation involves various parameters that influence the asphalt mixtures. The designated parameters were; NMAS, and Based on the Bailey method fractions description, two gradations of shape and sizes, namely, gradation scope 1 (GS 1) and gradation scope 2 (GS 2) for asphalt mixtures. Lastly, the particle size distributions for the control of the shape are given in Table 4-3. The mineral composition and oxide constituents of GD 1, GD 2 and GD 3 were obtained from the mineral fillers (75µm) using X-Ray Spectrometer Model Rigaku RIX 3000 as given in Table 4-4, and the strength properties, bulk specific gravity, and apparent relative gravity are in Table 4-5.

Table 4-1: Gradation scope 1 of 3 types of aggregate.

Sieve/ mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Gradations	Passing rate /%									
GD 1	100	59	34	27	23	19.7	14.5	11.3	9.7	6.2
GD 2	100	70.3	48.3	28.1	22	19.3	14.2	11.5	9.8	6.2
GD 3	100	74.6	57.2	41.6	24	18.2	13.4	10.7	9.4	6.2

Table 4-2: Gradation scope 2 of 3 types of aggregate.

Sieve/ mm	19	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Gradations	Passing rate /%									
GD 1	100	69	37	26	25	19.7	14.5	11.2	9.6	6.2
GD 2	100	72.3	51.3	27.8	23	19.3	14.2	11.5	9.7	6.2
GD 3	100	75.1	58.3	42.3	22	18.2	13.4	10.5	9.5	6.2

Table 4 -4-3: Particle size distribution for the control of the shape

Fractions	Maximum and minimum allowable percentage weight of material within a fraction	
	Grading scope 1 (max size 40mm)	Grading scope 2 (max size 20mm)
19mm - 4.75mm	29 – 49	
9.5mm - 2.36mm	13 – 35	21 – 47
4.75mm - 1.18	6 – 26	9 – 35
2.36mm - 600µm	5 – 21	6 – 26
1.18mm - 300µm	4 – 18	4 – 22
600µm - 150µm	2 – 13	2 – 16

Table 4-4: Chemical composition of aggregate

Oxides	GD 1	GD 2	GD 3
SiO ₂	70	67	5.38
Al ₂ O ₃	16	15.3	9.72
K ₂ O	6.1	7.4	3.2
Fe ₂ O ₃	2.3	2.9	0.12
CaO	2.2	2.6	59.1
Na ₂ O	1.9	2.3	5.4
MgO	0.88	0.91	0.13
TiO ₂	0.3	0.32	14.2
P ₂ O ₅	0.18	0.24	0.87
MnO	0.18	0.23	0.09
SO ₃	0.12	0.16	0.21
Rb ₂ O	0.058	0.09	0.08
BaO	0.049	0.05	

Table 4-5: Aggregate particles properties

GD 1											
Coarse aggregate					Fine aggregate.						Standards
Sieve size/mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
Bulk specific gravity /(g/cm3)	2.689	0.693	0.691	0.7							T0304
Apparent relative gravity /(g/cm3)					2.76	2.67	2.684	2.755	2.742	2.733	T0304
Crushing Value (CV)					19.2						T0316
Los-Angeles Abrasion (LAA)					16.11						T0317
Water Absorption (WA)					1.49						T0304
Flakiness Index (FI)					10						0T312
Roundness Index (RI)					0.73						
GD 2											
Coarse aggregate					Fine aggregate.						
Sieve size/mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
Bulk specific gravity /(g/cm3)	2.65	0.682	0.688	0.701							T0304
Apparent relative gravity /(g/cm3)					2.66	2.65	2.654	2.705	2.731	2.712	T0304
Crushing Value (CV)					18.78						T0316
Los-Angeles Abrasion (LAA)					17.02						T0317
Water Absorption (WA)					1.62						T0304
Flakiness Index (FI)					14.2						0T312
Roundness Index (RI)					0.61						
GD 3											
Coarse aggregate					Fine aggregate.						
Sieve size/mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
Bulk specific gravity /(g/cm3)	2.61	0.674	0.676	0.681							T0304
Apparent relative gravity /(g/cm3)					2.62	2.63	2.65	2.685	2.703	2.686	T0304
Crushing Value (CV)					18.66						T0316
Los-Angeles Abrasion (LAA)					16.72						T0317
Water Absorption (WA)					1.51						T0304
Flakiness Index (FI)					14.15						T0312
Roundness Index (RI)					0.58						

4.2 Bitumen

The study used bitumen bought from Tosas Botswana, and the properties are given in Table 4-6 and Table 4-7. The properties of asphalt were assessed per the relevant requirements of the Test Procedure for Highway Engineering Asphalt and Asphalt Mixtures (JTJ 052-2000) [51].

Table 4-6 : Bitumen properties

Property	Specification	Test value
Penetration (25 °C), 0.01 mm	40/60	55.1
Softening point (ring and ball method)/°C	70 Min.	59.1
Ductility (5 °C), cm	≥100	>100
Brookfield Viscosity (135 °C), Pa.s	3.0 Max.	2.373
Flash Point (COC), °	260 Min.	298
RTFOT (163 °C, 85min), Quality /%, no	≥±0.8	
Residual penetration ratio (25 °C) /%	≥61	59.3
Residual ductility (10 °C)/ cm	≥04	7
Residual ductility (15 °C)/ cm	≥15	32.1
Density (15 °C)g/cm ³	Measured	1.057

Table 4-7: Bitumen properties

Property	Specification	Test value
Penetration (25 °C), 0.01 mm	50/70	65.1
Softening point (ring and ball method)/°C	70 Min.	59.1
Ductility (5 °C), cm	≥100	>100
Brookfield Viscosity (135 °C), Pa.s	3.0 Max.	2.373
Flash Point (COC), °	260 Min.	298
RTFOT (163 °C, 85min), Quality /%, no	≥±0.8	
Residual penetration ratio (25 °C) /%	≥61	59.3
Residual ductility (10 °C)/ cm	≥04	7
Residual ductility (15 °C)/ cm	≥15	32.1
Density (15 °C)g/cm ³	Measured	1.057

4.3 Teak fibre

TK fibres were collected from a local company, Tack Cooney, which manufactures furniture. Teak (TK) is a lignocellulosic hardwood commonly found in Botswana. It has various names: in Botswana is called *Mowana*, in South Africa, it is known as *Moroots*, and it is mainly used for furniture, building construction, and medicine (Stahle *et al.*, 1999; Shackleton, 2002). TK fibres are white with a specific gravity of 2.257, as shown in Table 4 - 8, and contain high cellulose and hemicellulose, as shown in Figure 4-9. Several studies have shown cellulose fibre to be compatible with bitumen and that it can improve its properties such as penetration point, softening point and viscosity. Therefore, they can enhance the deformation resistance of asphalt mixtures (Candy, 2002; Mohammed, Parry and Grenfell, 2018). Table 4 -9 shows that TK fibres were placed at 160 °C for 1h30 to test decomposition and reduce water content. TK fibres managed to resist decay at high temperatures. Similarly, Setswalo *et al.* (Setswalo *et al.*, 2019) performed a decomposition test of cellulose and hemicellulose at high temperatures. The results showed that they started decomposing at temperatures between 290 to 300 °C. The results are also consistent with a study by Motoc *et al.*, who conducted cellulose and lignin degradation and found that their degradation temperatures were 300 and 400 °C, respectively (Motoc, Santiago and Pop, 2018). This implies that they will withstand bitumen or asphalt mixing temperatures. Mohammed, Parry and Grenfell, (2018) reinforced bitumen with cellulose fibre and found a significant reduction in the phase angle at all ranges of frequencies. The reduction of phase angle indicates improved bitumen elasticity.

Similarly, (Chen and Lin, 2005) evaluated the effects of rock, wool, cellulose, and polyester fibre on the mechanical properties of the asphalt mixture (Thanh, Pei and Hai, 2011; Wang *et al.*, 2016). The results showed that all fibres had a good adhesion with bitumen and enhanced the strength of the bitumen-fibre mastics. Lignin fibre significantly improved the low-temperature properties of the asphalt mixture (Luo *et al.*, 2019). Lignin fibre can entangle itself between the aggregate, increasing bitumen sample thickness (Thanh, Pei and Hai, 2011).

4.3.1 Thermogravimetric analysis

The thermal stability, moisture, ash and volatile contents of TK fibres were determined using the leco TGA701. Thermogravimetric analyser coupled with Differential Scanning Calorimetry (DSC). A nitrogen atmosphere, the heating rate of 10 °C/min and a temperature

of 25 to 700 °C were kept constant for all experiments. The thermographic graph is shown in Figure 4-1.

To assess the crystallinity of TK fibre, the Bruker D8 advance X-ray diffractometer, with a generator operated at 40kV and 40mA was used. The specimens were scanned in the 2θ range of 5 - 55°. The study obtained crystallinity index (CrI) based on Segal empirical method by Segal et al. using Eq.4- 1(Segal *et al.*, 1959) and The crystallinity index ranged from 30 to 37, as given in Table 4-10.

$$CrI = \left[\frac{I_{002} - I_{am}}{I_{002}} \right] \times 100 \quad 4-1$$

Where:

I_{002} refers to crystallographic counter reading, and

I_{am} refers to amorphous phase counter reading at 2θ in the specimen

Table 4-8: Properties of TK fibres

TK Fibres	Specific density (g/cm ³)	Length (cm)	Width (μm)	Colour
TK 1	2.557	13	12	Cream white
TK 2	2.557	6	12	Cream white

Table 4-9: TK fibre parameters

% Parameter	Raw	Thermalised (160 °C)
α-Cellulose	48.43	50.41
Hemicellulose	28.24	26.21

Table 4-10: The crystallinity index of TK fibre

E	100 – 200	200 – 300	300 – 425	425 -710
Crystallinity Index (%)	31.15	37.11	37.11	30.34

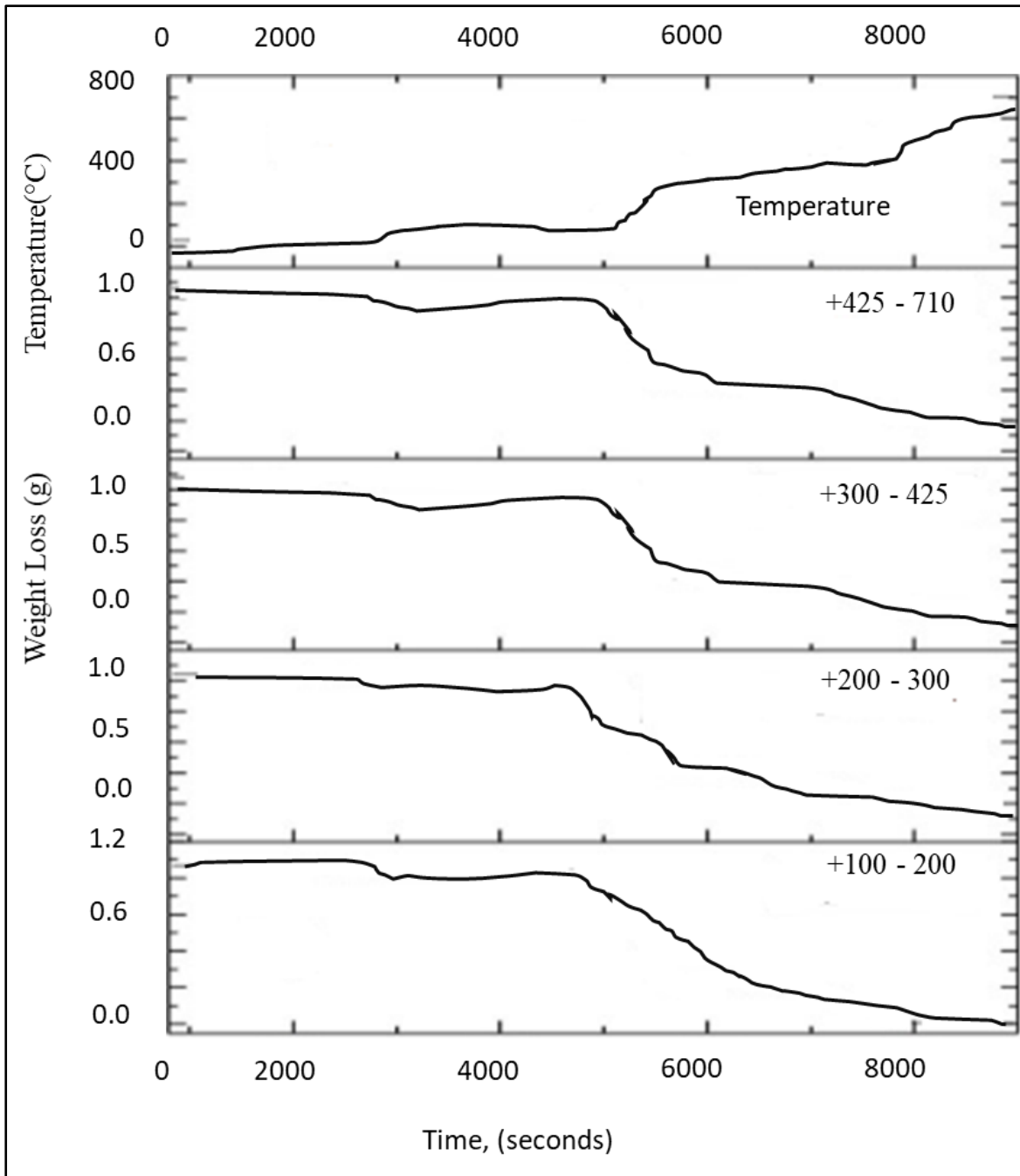


Figure 4-1: Thermograms of TK fibre at various particle sizes

From Figure 4-2, it can be seen that TK fibres has a rough texture. The shrinkage of radial: 1.9%, tangential: 3%, volumetric: 5.7%, T/R Ratio and elastic modulus of 8.8 GPa as shown in Table 4-11.

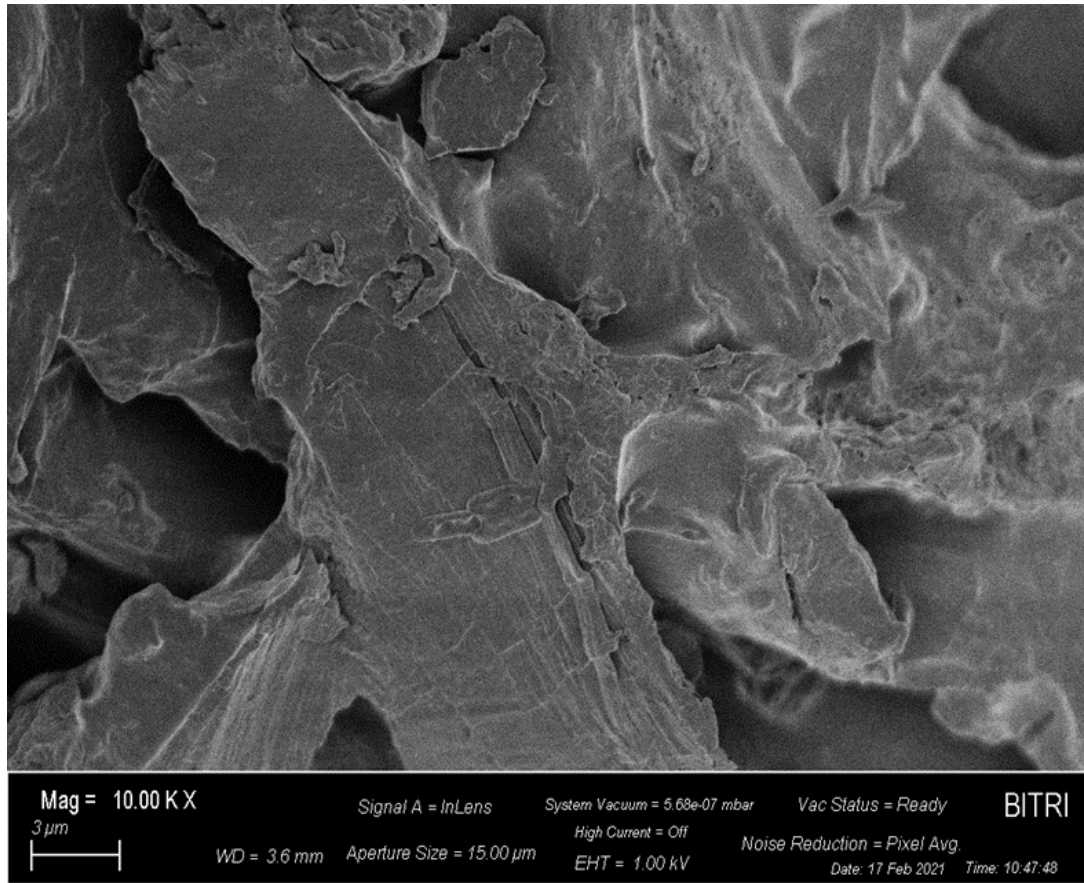


Figure 4-2: TK fibre SEM

Table 4-11: Mechanical properties of TK fibre

Scientific Name	Pterocarpus angolensis
Average Dried Weight	600 kg/m ³
Janka Hardness	6,000 N
Modulus of Rupture	99 MPa
Elastic Modulus	8.8 Gpa
Crushing Strength	55.9 MPa
Shrinkage	Radial: 1.9%, Tangential: 3%, Volumetric: 5.7%, T/R Ratio
Common uses	Asphalt modification

4.4 Daily environmental

A parametric study was performed to evaluate gradation effects on the asphalt mixture's thermal conductivity and heat capacity. Daily environmental information was collected from Botswana Environment Statistics Climate Digest in this study, forming two

sets of data: cold environment representing winter and hot environment representing summer (Government of Botswana, 2019). Other data used involved the material properties such as the absorptivity ($\alpha = 1 - \beta$); the emissivity (e) of the top layer; the thermal conductivity (k); and the volumetric heat capacity (c) of asphalt mixture. For all materials, the absorptivity ($\alpha = 0.9$); the emissivity (0.85) (Shi *et al.*, 2017).

4.5 Discussion

This chapter selected and characterised all materials, including aggregate, bitumen and the TK fibre. The aggregates selected were G1, G2 and G3. G1 had more crushing value and strength and had the highest amount of SiO_2 , K_2O , Al_2O_3 ; followed by G2, and a minor being G3. G1 has the roughest texture and the highest angularity, followed by G2 and G3. TK fibres are selected to recycle waste materials. They presented properties such as length, adhesion, absorption, and swelling. Two selected pen grades are 40/60 and 50/70, and they are suitable grades for the local condition. Due to dynamic traffic volumes and climates, the bitumen grade are modified using Tk fibres, and the methodology is provided in Chapter 5 and interpretation and discussion of the effect of modification will be provided in Chapter 6

CHAPTER 5: LABORATORY TESTING

5 EXPERIMENTAL PROCEDURES

The tests methodologies of the experimental works were carried out by conducting experiments in the laboratory using material presented in chapter 4. The laboratory equipment is presented and described in this chapter. The sample preparation, tests procedures and number of replicates are undertaken, including a series of planned tests executed as outlined in each section. They are three sections in this chapter. The first section focuses on comparing modelled and laboratory permeability. The second sections discuss the methodologies and procedure used to assess the rheological properties of TK fibre modified bitumen mastic. The last section uses the gradation obtained from the modelling, TK fibre modified bitumen mastic from section 5.2 of this chapter to evaluate the influence of chemical composition on physical properties of aggregate, microstructural properties and mechanical performance.

5.1 Comparison of modelled and laboratory permeability

The section compares the estimated porosity at different depths using Eq 3-12 in Chapter 3 and the laboratory porosity.

Two laboratory samples per scope were prepared to evaluate the magnitude of permeability simulating, as illustrated in Figure 5-1. (ii) degree of compaction (total of gyrations in the gyratory compactor); and

Samples were prepared involving various parameters that influence the microstructure of the asphalt mixture. The permeability of all samples was measured using Bubble Tube Constant Head Permeameters (BTCHP). The schematic of the BTCHP is shown in Figure 5-2c. The BTCHP can accommodate high flow related to testing high permeable granular material. It was designed to eliminate valves, fitting and small circumferences tubings that result in head losses interfering with the investigation measurements and accommodating very low hydraulic gradients.

Most importantly, the sidewall leakages are reduced by membrane Figures 5-2a, 5-2b. and 5-3c is illustrating bubble tube constant head permeameter

The pressure gradients that ranged from 9.97×10^{-7} to $1 \times 10^{-3} \text{ g/mm}^2 \cdot \text{sec}^2$ were set between the inlet and outlet of all samples. The results will be compared to the estimated permeabilities in Chapter 3.

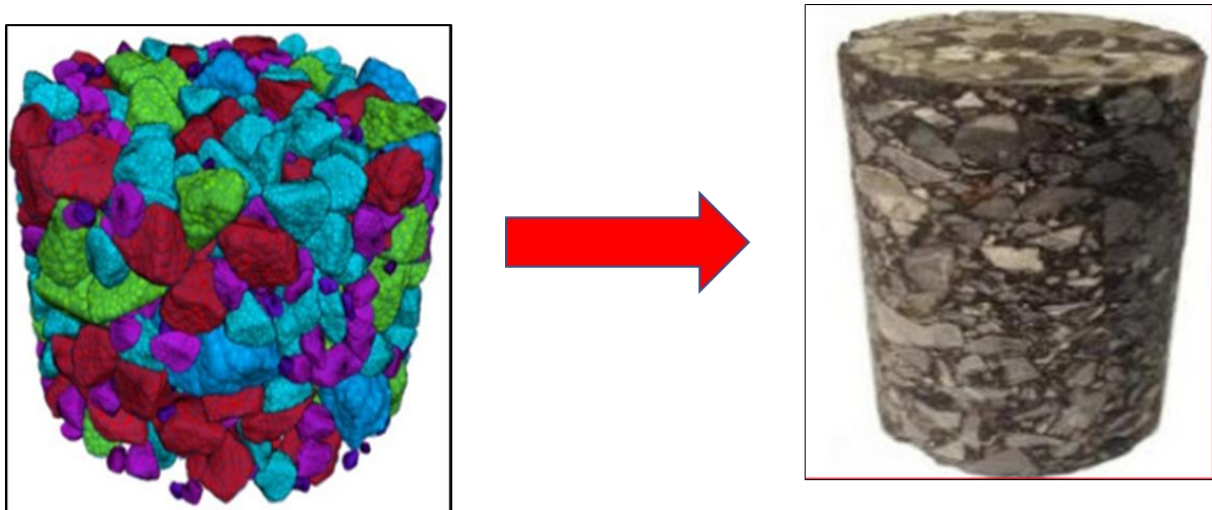


Figure 5-1: Prepared laboratory samples using a modelled gradation

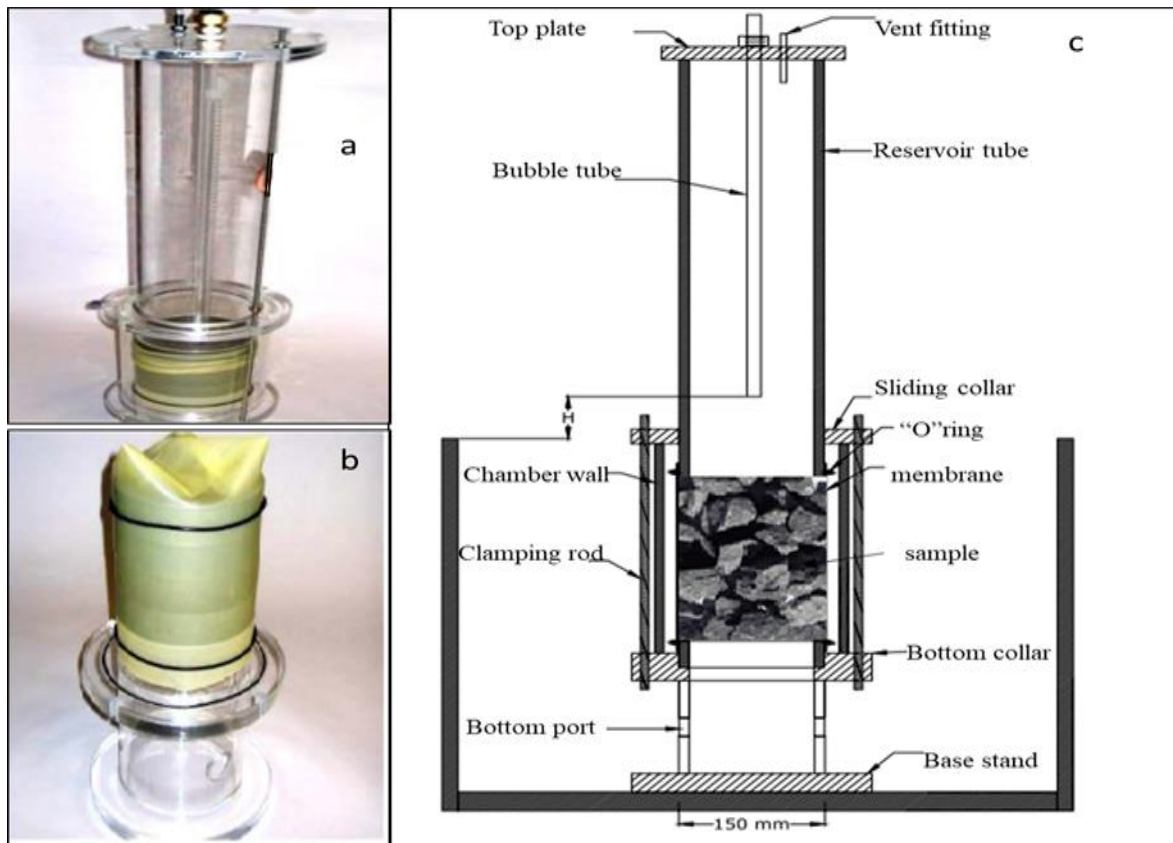


Figure 5-2 and 5-2b: A picture of upper and lower portions of the bubble tube constant head permeameter, and 5-2c: Bubble tube constant head permeameter

5.2 Bitumen modification using TK fibres

A literature review concluded that bitumen binders significantly influence fatigue and permanent deformation. Several studies have shown that fibre modified bitumen mastic present improved rutting factor, penetration point, thermal conductivity and a high percentage of the creep recovery (Nazki, Chopra and Chandrappa, 2020; Bellatrache *et al.*, 2020;

Mohammed *et al.*, 2020). The section aimed to improve the rheological properties of bitumen using TK fibre. Figure 5-3 demonstrates the flow charts of this section.

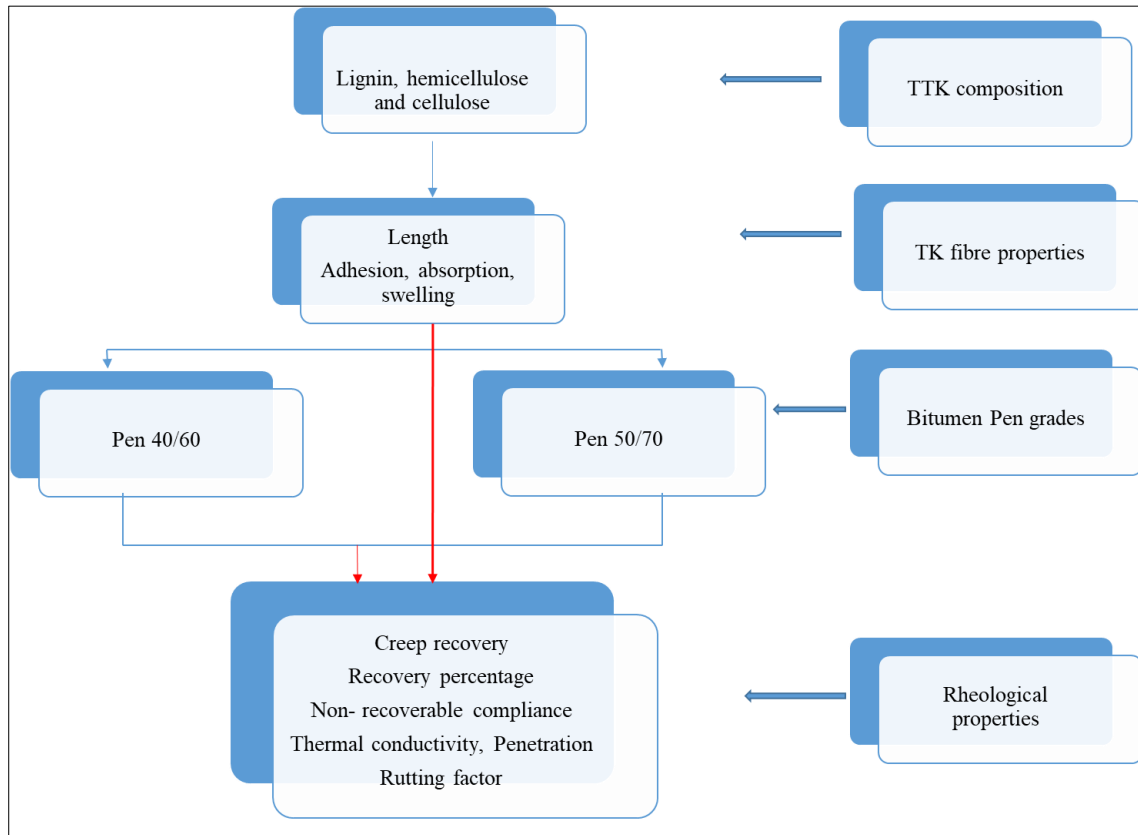


Figure 5-3: Flow chart of the section

TK fibre was collected from a local company, Tacy Cooney, manufacturing furniture. TK fibre was divided into two lengths (13mm and 6mm), all with a diameter of 12 microns, before drying in an oven at 60 °C for 24 hours to reduce the amount of moisture. This study designated 13mm long TK fibres as TK 1 and 6mm long as TK 2. Then 0.50 kg specimens of 40/60 pen and 50/70 pen bitumen were placed in an oven for 1hr at 160 °C. These grades were selected because they are the most commonly used in Botswanan pavements based on the climatic conditions in the country. The TK fibres at 0.5%, 1.0%, 1.5% and 2.0% by weight of the bitumen were added and mixed to form the TK fibre-modified bitumens. These TK contents were selected as they are realistic because a high amount of fibre can cause high absorption of bitumen (Mohammed, Parry and Grenfell, 2018). Also, some studies have shown brittleness of the bitumen caused by a high amount of fibre (Bijwe, 1997; McDaniel, 2015). All fibre contents were mixed with bitumen using a paddle mixer, a Ross LDM-130 12852 at a low speed (140 ± 5 rpm). The study followed a procedure used by (Sobolev *et al.*, 2014). Mixing was carried out for 90 seconds, and then the mixtures were reheated for 10 min at 160 °C. The

procedure was repeated four times to complete 6 minutes of mixing for each sample. Each mixture was then mixed for an additional 90 seconds after four repetitions, reheated for 10 min at 160 °C, and remixed for an additional 30 seconds. All the materials were mixed again for 8 min. Table 5-1 summarises the experimental programme.

Table 5-1: Experimental programme

Materials	Variables	Methods	Replicates
Bitumen	Fibre	Penetration test	3
Pen 40/60	content	Rutting factor	3
Pen 50/70	0.5%, 1%, 1.5%, 2%	Thermal conductivity	3
Fibre	Fibre names TK 1, TK 2	Multiple stress creep recovery test	3

The penetration test was performed to assess TK fibre's influence on the rutting resistance properties of the modified bitumen. For thermal equilibration, all the specimens were left at room temperature for 1 hour and then in a water bath for 1 hour. The penetration of all the samples was measured using a Setamatic Penetrometer. Bitumen hardness was measured by the penetration test ('European Committee and British Standard, 1426: Bitumen and bituminous binders—determination of needle penetration, British Standards., 2007).). Penetration was determined by measuring the depth in 0.1 mm increments that a standard needle has penetrated vertically into the specimen at 25 °C subjected to a weight of 100g for 5 seconds. The penetration tests were repeated three times, and the average was calculated. The softening point (ring and ball) tests were performed using standard test conditions (EN 1427, 2015). Water was used as the medium to measure the softening point up to 80 °C. The thermometer measured the softening point temperature when the steel ball in the bitumen touched the bottom plate 25 mm below the ring. The mean temperature for two readings was calculated to the nearest 0.2 °C.

In this study, a rotational viscometer, LVDV-II+ PRD Model, was used to determine the viscosity of the additive modified bitumen mastics (13302:2018, 2018). The dried samples were aged using RTFO at a temperature of 163 °C for 85 mins to simulate short-term ageing. Then to simulate the long-term, the dried samples were aged by using a pressure ageing vessel (PAV) at 90 °C and 2.1 MPa for 20 hours.

A Bohlin Gemini 200 Dynamic Shear Rheometer (DSR), as shown in Figure 5-4, with a torque range between 0.5 ($\mu\text{N}\cdot\text{m}$) and 200 ($\text{mN}\cdot\text{m}$) and a sensor on the shaft to detect the movement of the plates, was used to evaluate the rheological properties of bitumens.

The following parameters were used in the rheological testing (Airey, 1997):

- (I) Frequencies ranging from 0.1 to 10.0 (Hz), 1% strain control and,
- (II) Temperatures between 30 and 70 °C (at 5 °C increments).



Figure 5-4: Dynamic shear rheometer

To measure the thermal conductivity, bitumen samples were prepared to a size of 60 mm thickness by 300 × 300 mm. Figure 5-5 present a picture of A Hilton Heat Transfer Unit H112N was used to measure the thermal conductivity, and the procedure is given in ISO 8301 (ISO 8301, 1991).



Figure 5-5: A Hilton heat transfer

5.2.1 Case study

Asphalt pavements roads are exposed to heat from the sun's radiation in semi-arid areas. This heat is conducted through the lower layers to the underlying moisture containing salts. As a result, salt-containing moisture evaporates through the pores of the lower layers of the pavement to the asphalt layer. Samples were soaked in different salt solutions for different duration periods to simulate all possible conditions in semi-arid areas. Trona was selected as the salt to simulate semi-arid conditions. Botswana has one of the largest salt pans globally, the Makgadikgadi Pan system. These pans extend through the Kalahari Desert southeast of the Okavango Delta in the northern part and are one of the largest producers of Trona in the world (Nash and McLaren, 2003; Dill *et al.*, 2014; Nield *et al.*, 2016). The solutions applied were 0.3%, 1%, 3%, and 5% and the exposure durations were, 7 days (d7) and 28 days (d28). All the specimens were placed above salt solutions at 25 °C. Several case studies in Botswana on damaged roads have recorded between 0.1 to 3% on the surface of damaged roads (M. E Woodbridge, Obika, 1994; Woodbridge and Obika, 1994; Ministry of Works, Transport & Communications Botswana, 2001). Other researchers indicated salt content between 0.1 and 5% in the subgrade material and the near surrounding (Woodbridge and Obika, 1994; Ministry of Works, Transport & Communications Botswana, 2001).

5.2.2 Multiples stress creep recovery

The MSCR test was conducted to determine the creep and recovery behaviour of the base, and TK modified bitumens. The 1.0 s creep loading and 9.0 s recovery period were applied in this test at eight stress levels, ranging from 0.1 kPa to 3.2 kPa for 10 cycles each, as provided in Table 5-2. The temperature of 65 °C, which was used, represented the peak temperature of the pavement surface during the summer season in Botswana. The percentage recovery (%) and non-recoverable creep compliance (J_{nr}) are determined using Eqs. 5-1 and 5-2, respectively, were calculated using the data obtained from the MSCR test. Figure 5-6 shows the picture of the MSCR testing machine, and Figure 5-7 shows the picture of the Servopac gyratory compactor.

$$R(\%) = \frac{(\varepsilon_1 - \varepsilon_{10})}{\varepsilon_1} \times 100 \text{ Servopac gyratory compactor} \quad 5-1$$

where

$R(\%)$ refers to the percentage recovery

ε_1 refers to the strain value at the end of the creep portion

ε_{10} refers to the strain value at the end of the recovery portion

$$J_{nr} = \frac{\text{Non-recoverable strain}}{\text{Stress}} \quad 5-2$$

Table 5-2: Stress levels for the MSCR test

Stress level	0.1	0.5	1.0	1.5	2.0	2.5	3.0	3.2
No of cycles	10	10	10	10	10	10	10	10



Figure 5-6: Multiples stress creep recovery (Anton Paar MCR 302 DSR)



Figure 5-7: Servopac gyrotory compactor

The results of modified bitumen mastic are given and interpreted in Chapter 6, and note that to determine the anisotropy of asphalt mixtures, all samples were prepared using TK fibre modified bitumen mastics

5.3 The anisotropy of asphalt mixture

Chapter 3 modelled the aggregate gradation and packing using realistic aggregate shapes using clumps, controlling IC, densities using optimum porosity. The focus was mainly on the influence of the physical properties of aggregate on mechanical properties. Mineral aggregates have physical and chemical properties, and chemical properties differ from rock origins. Therefore, the effect of chemical properties on physical properties has to be understood. The section aims to investigate the influence of the chemical and physical properties of the aggregate on the microstructural properties of the asphalt mixture. Three different aggregate types from various quarries with different morphologies, compositional oxides and strengths were used to prepare asphalt mixtures.

- The iPAS software (Image Processing Analysis System) centred on Digital image processing (DIP) was utilised to obtain the asphalt mixture's microstructural properties. To capture the cross-sectional images of the microstructures, a two-dimensional (2D) image processing approach based on a CCD, using digital cameras, was utilised (Shaheen, Al-Mayah and Tighe, 2016; Hassan *et al.*, 2021). The following information was obtained: contact properties, orientation, and aggregate distribution.
- Constructed Fabric tensors were used to evaluate aggregate interlocking in asphalt mixture.
- The study used testing parameters including Marshall Stability, dynamic stability and bending stiffness modulus, and complex Poisson's ratio to assess the influence of aggregate's chemical and physical properties on the mechanical performance of the asphalt mixtures. The main objectives of the work presented in this section were as follows, and the scope is given on the flow chart in Figure 5-8:

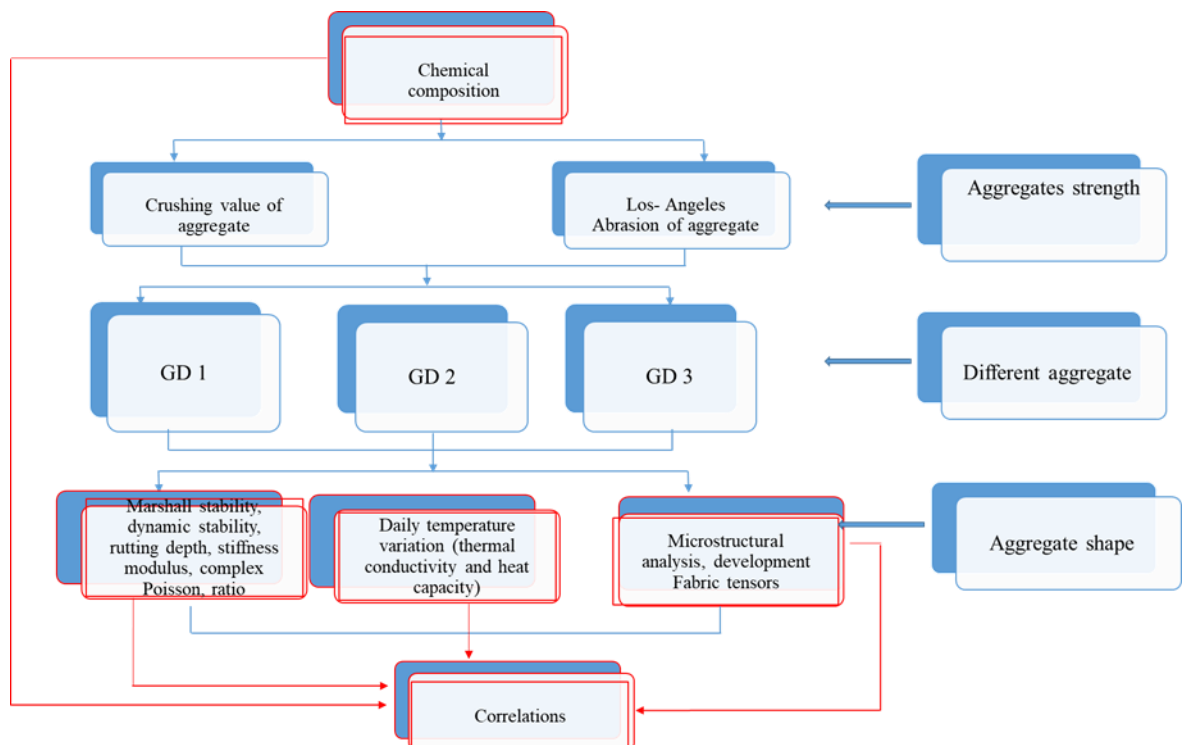


Figure 5-8: The section flow procedure and plans (Busang and Maina, 2022)

The anisotropy of a material is the property of being directionally dependent. The anisotropy of an asphalt mixture can be described as the variation in physical properties, such as modulus and Poisson's ratio, when the asphalt mixture is measured in different directions, and the number of replicates is given in Table 5-3.

Table 5-3: Number of replicates per test

Mixtures	Tests	Number of Replicates
GD1	Marshall stability	3
	Wheel tracking stability	3
GD2	Bending test	10
GD3	Complex Poisson ratio	3

5.3.1 Marshall Stability

To define the deterioration of toughness and the breaking point load of the asphalt mixture, samples were compacted at a temperature range of $180 \pm 0.5^{\circ}\text{C}$. First, the samples were isothermally conditioned for 30 min; the samples were put in a constant temperature water bath until to the temperature of $60 \pm 1^{\circ}\text{C}$. Then samples were set for the Marshall tester machine, as shown in Figure 5-9, and a constant deterioration rate of 50.8 mm/min. The maximum load achieved (i.e. the stability) and the deflection at which the maximum load occurs (i.e. the flow) were recorded on the Marshall Testing Machine (*ASTM D6927, American Society for Testing and Materials, Standard test method for Marshall stability and flow of asphalt mixtures, 2015, Washington, DC., 2015*). Marshall samples were prepared and tested according to the standard test method specified in “Test Methods of Asphalt and Asphalt Mixture for Highway Engineering (JTG E20-2011)” (*Ministry of Transport, Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering, in: China Commun. Press, China Communications Press, Beijing, China, 2011: pp. 1–370, 2011*).



Figure 5-9: Marshall testing machine

5.3.2 Wheel tracking test

Asphalt mixture slabs of 300 mm × 300 mm × 50 mm dimensions were prepared and compacted by a laboratory automatic rolling compaction machine and left for curing. For insulating purposes, all samples were kept for five hours at a temperature of $60 \pm 1^\circ\text{C}$ on a wheel tracking machine test bench. In this study, a temperature of 60°C was selected (Kuo and Freeman, 2002; Cai *et al.*, 2017; Guo and Nian, 2020). Figure 5-10 shows the wheel was traversed in the centre of the sample in both directions for an hour. The wheel was of a

diameter of 200 mm and 50 mm wide, also composed of rubber of a small thick 15 mm. The wheel and sample contact pressure was 0.7 MPa, and the entire forced load was 700 N at a speed of 42 ± 1 cycles/min in one direction (21 cycles in two directions). Dynamic stability (DS) was determined using Eq. (5-3) ('ASTM D6926, American Society for Testing and Materials, Standard practice for preparation of bituminous specimens using Marshall apparatus, 2010, Washington, DC.', 2010; Hassan *et al.*, 2021). The wheel tracking test was conducted according to JTG E20-2011 (*Ministry of Transport, Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering*, in: *China Commun. Press, China Communications Press, Beijing, China, 2011: pp. 1–370*, 2011).

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2 \quad (5-3)$$

where; d_1 and d_2 the extent of deformation at the time t_1 (mm, 45 min) and t_2 (mm, 60 min) respectively; N denotes the rapidity of the tire, 42 passes per 60 seconds; C_1 denotes the coefficient of the alteration connected to the machine, and C_2 is the coefficient of alteration connected to the samples (for this study, it was 1.0).



Figurer. 5-10: Wheel tracking test

5.3.3 Three Bending test

A three-point bending test evaluated the bending failure of the asphalt mixture. Rectangular beam samples of dimensions: length ($L = 250$ mm), width ($b = 30$ mm) and height ($h = 35$ mm) for each type of aggregate were prepared. The samples were soaked in a thermostatic water bath for 1 hour. Then they were loaded at a rate of 50 mm/ min at 10 ± 0.5

°C, and 0 ± 0.5 ° according to the procedure T0715-2011 of the Standard Test Methods of Asphalt and Mixtures for Highway Engineering (JTG E20-2011) (*Ministry of Transport, Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering, in: China Commun. Press, China Communications Press, Beijing, China, 2011: pp. 1–370, 2011*). Eq. (5-4) (Hassan *et al.*, 2021) was used to calculate flexural tensile strength R_B , Eq. (5-5) (Hassan *et al.*, 2021) was used to calculate the maximum flexural tensile strain ε_B , and Eq. (5-6) (Miljkovic and Radenberg, 2011), for the bending stiffness modulus S_B . Figure 5-11 is an illustration of three bending tests.



Figure 5-11: Three bending test

$$R_B = \frac{3 \times L \times P_B}{2 \times b \times h^2} \quad (5-4)$$

$$\varepsilon_B = \frac{6 \times h \times d}{\varepsilon_B} \quad (5-5)$$

$$S_B = \frac{R_B}{\varepsilon_B} \quad (5-6)$$

where, L represents the length b , represents the width, and h represents the height of the samples, P_B represents the maximum load at the time of sample failure, d represents the mid-span deflection at the time of breakage and S_B represents the bending stiffness modulus

5.3.4 Complex modulus and Complex Poisson's ratio

Other anisotropy properties of the asphalt mixture involve; the complex modulus and complex Poisson's ratio. The properties are used to describe the viscoelastic linear response and are obtained by subjecting the samples to sinusoidal loading. Using the tension-compression tests such as the axial stress σ_1 , axial strain ε_1 and radial strain ε_2 as a function of time (t) by Eqs. (5-7) to (5-11) (Tuan *et al.*, 2021), the complex modulus E^* and the complex Poisson's ratio ν^* are obtainable using Eqs. (8) and (9) (Tuan *et al.*, 2021).

$$\sigma_1(t) = \sigma_{01} \sin(2\pi ft + \phi_{\sigma_1}) \quad (5-7)$$

$$\varepsilon_1(t) = \varepsilon_{01} \sin(2\pi ft + \phi_{\varepsilon_1}) \quad (5-8)$$

$$\varepsilon_2(t) = \varepsilon_{02} \sin(2\pi ft + \phi_{\varepsilon_2}) \quad (5-9)$$

$$E^* = \frac{\sigma_{01}}{\varepsilon_{01}} e^{j(\phi_{\sigma_1} - \phi_{\varepsilon_1})} = |E^*| e^{j\phi_E} \quad (5-10)$$

$$\nu^* = \frac{\varepsilon_{02}}{\varepsilon_{01}} e^{j(\phi_{\varepsilon_2} - \phi_{\varepsilon_1})} = \frac{\varepsilon_{02}}{\varepsilon_{01}} e^{j(\phi_{\varepsilon_2} - \phi_{\varepsilon_1} - \pi)} = |\nu^*| e^{j\phi_\nu} \quad (5-11)$$

where, f is frequency; amplitudes σ_{01} , ε_{01} and ε_{02} refer to the stress, axial strain and radial strain, respectively; ϕ_{σ_1} refers to phase angle stress, ϕ_{ε_1} and ϕ_{ε_2} refer to axial and radial strain, respectively; $j^2 = -1$ is a complex number, $|E^*|$, ϕ_E and $|\nu^*|$, ϕ_ν refer to the norm and phase angle of the complex modulus and complex Poisson's ratio, respectively. While the phase lag between σ_1 and ε_1 is characterised by ϕ_E and ϕ_ν refers to the phase lag between ε_1 and opposite of ε_2 .

Figure 5-12 is a schematic of the test equipment used, where all parameters required to determine the complex modulus and complex Poisson's ratio are measured (Nguyen, 2015; Nguyen *et al.*, 2016; Tuan *et al.*, 2021). Briefly, the principles followed were: samples of height and diameter of 140 mm and 75 mm, respectively, are fixed with glue on the load plates. The axial strain was measured using three extensometers, while the radial strain was obtained from two non-contact sensors. It is assumed that the strain is homogeneous in the middle of the samples. Therefore, extensometers (75mm length) were placed in every third part and non-contact in the centre part of the sample to accurately capture the strain.

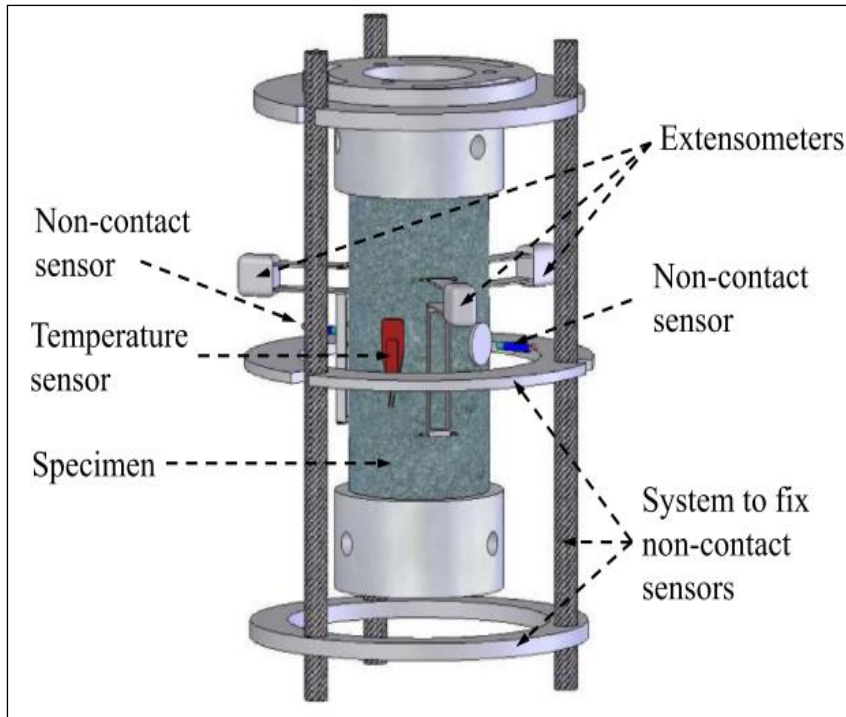


Figure 5-12: Cylindrical samples set for axial and radial strain measurements

5.3.4.1 Applied time - temperature and cyclic loading on samples

An investigation on how time-temperature affect the complex Poisson's ratio was performed. The analysis was conducted at a temperature range of 25°C to 50°C. The frequency is between 0.01Hz and 10Hz, under strain-controlled with a strain amplitude of about 50 $\mu\text{m}/\text{m}$. On the other hand, the two tension-compression fatigue tests were performed to assess the influence of cyclic loading on the complex Poisson's Ratio.

5.3.5 Image analysis and microstructural analysis

The samples were saw-cut using a universal cutting machine G210. Samples were sawed along the horizontal direction, and the slab samples were subdivided into thinner cross-sections. Accordingly, each Marshall sample was saw-cut to 36 circular cross-sections, and each slab sample was saw-cut to 24 rectangular cross-sections, as illustrated in Figure 5-13.

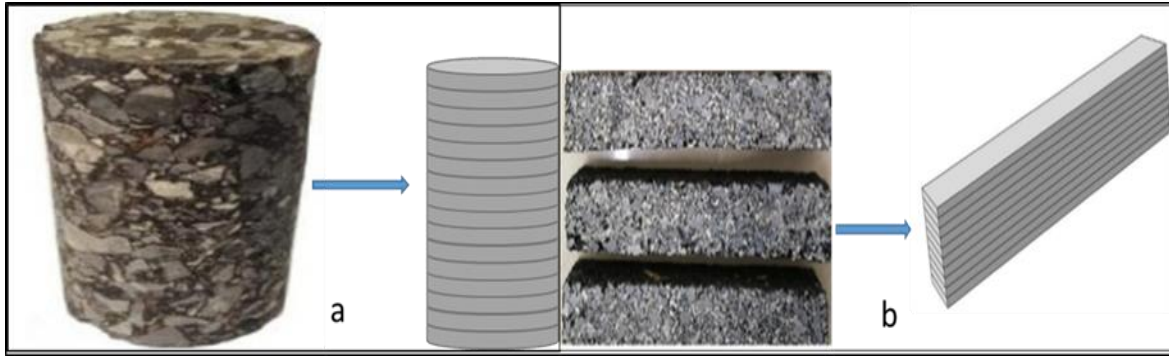


Figure 5-13: Illustration of sawed samples

The recent digital industry is using two processing methods to analyse asphalt mixture images: the three-dimensional (3D) and the 2D image analyses methods are based on X-ray and CCD, respectively (Qiu, *et al.*, 2020; Hassan *et al.*, 2021). This study selected the CCD digital camera-based photography method to acquire various colours and differentiate numerous materials with high-precision cross-sectional photographs at a lower price, quick imaging, and user-friendly equipment (Qiu, *et al.*, 2020; Hassan *et al.*, 2021). Figure 5-14 is an illustration of the slices on a scan scanner.

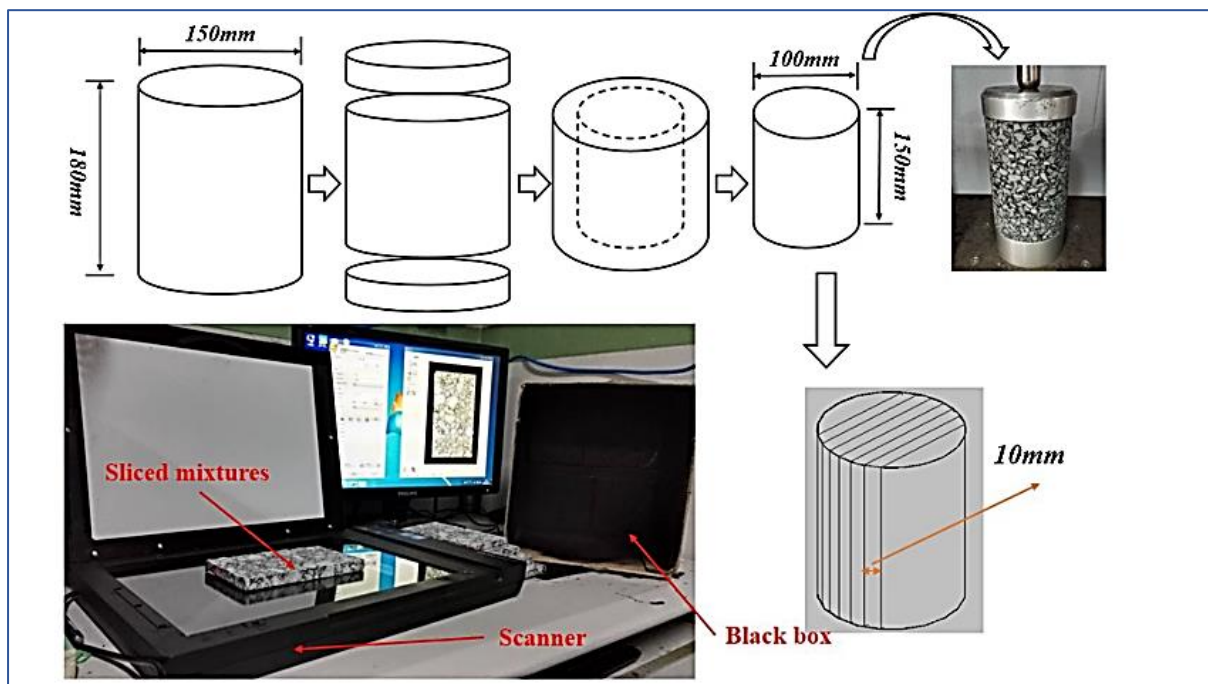


Figure 5-14: Illustration of slice on a scan scanner

Several studies worked on the theory of “join pair” in the examination of the 3-D interaction amongst aggregate particles and considered that two adjacent aggregate contacts each other when the boundary pixel distance is less than a certain threshold (Cai *et al.*, 2018; Hassan *et al.*, 2021). Nevertheless, the asphalt mixture has three-phase constitutes; taking

images using a digital camera may result in some errors, for instance, influencing the acuity of the sample edge of the image caused by the spatial domain's noise. In this study, as shown in Figure 5-15, the following steps were involved in minimising the errors:

- The cross-section images of sawed parts of samples were captured using a CCD digital camera, followed by iPAS (Gao *et al.*, 2020). Initial analyses were achieved by filtering denoising, image improvement, and obtaining the threshold at (2.36 mm) intervals.
- The multi-goal versatile window division calculation was used to capture the aggregate perimeter primarily then the image was set for binarisation.
- Afterwards, virtual screening was performed on the binarised image slices to capture all ranges of aggregate and label them using numbers.
- Lastly, the spatial closeness relationship between adjacent aggregate was measured. Total contact points numbers (N) were counted, the contact orientations were marked, contact line and total contact line length were calculated.

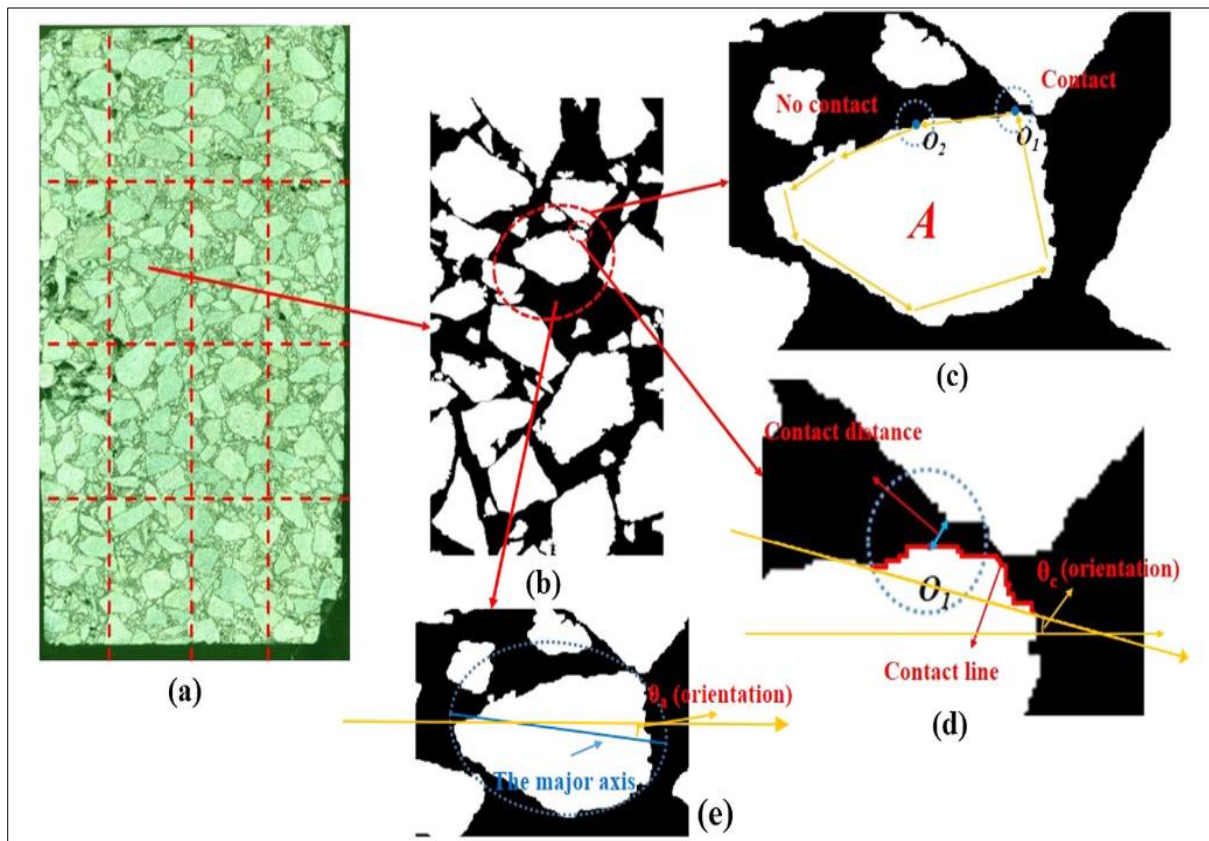


Figure 5-15: Image analysis and processing focus on coarse aggregate particles (a) an example section of UTA-10 with green filter, (b) zoomed binary image, (c) contact judgment processing, (d) definition of the contact indices, (e) orientation (Jiang *et al.*, 2017)

5.4 Contact mapping analyses by fabric tensors

Several studies used the internal structure index (ISI) to evaluate the interlocking of aggregate in asphalt mixture by combining the contact line length and contact orientation (Sefidmazgi, Tashman and Bahia, 2012; Hassan *et al.*, 2021). This study maps the interlocking of aggregate in asphalt mixture by using Fabric tensors, which quantifies the directional distribution of microstructural properties concisely, which is critical to use in constitutive modelling. Another way to define microstructural fabric based on the aggregate gradation packing is to use the plane that describes the direction of the contact, as illustrated in Figure 5-16. This plane can be described as vertical to the contact point and the plane that is tangent to the particles in contact. Contact normal vectors are defined by the two-unit vectors n^c and $-n^c$. The number of aggregates in a microstructure was denoted by N_a aggregate and contact points by N_c . Some methods considered mapping a fabric tensor to a directional in a comparative frequency distribution of contact normal normally using probability density function $E(n)$ (Satake, 1982a). The second-order spherical harmonic sequence for the 3D asphalt mixture can be reduced to Eq (10) (Yuan *et al.*, 2019).

$$E(n) = \frac{1}{4\pi} (1 + F : n^c \otimes n^c) \quad (5-12)$$

where $\otimes$ represents a dyadic product, and as given in Eq. (11), F represents traceless tensor regarded as the second-order fabric tensor of the third type based on unit contact normal (Tatsuoka, 1999). Basically, the fabric tensor (F) can be determined from the second-order tensor N . In this study, F is used to evaluate the anisotropy properties because of the ability to obtain the most important microstructural properties that influence the asphalt mixture performance based on a small number of parameters (Wang *et al.*, 2019). Based on this definition of contact normal plane and on contact normal vectors, the fabric tensor for contact normal vectors (contact normal fabric) can be defined as:

$$F = \frac{15}{2} (N - \frac{1}{3} I) \quad (5-13)$$

where I represent each second-order tensor; N represents a function of the discrete contact normal tensor n in aggregate gradation parking, see Eq. (12) (Hu *et al.*, 2021).

$$N = \frac{1}{N_c} \sum_{c \in N_c} n^c \otimes n^c \quad (5-14)$$

In this study, weight examination was used to determine the relationship between the aggregate and mechanical properties, as already mentioned.

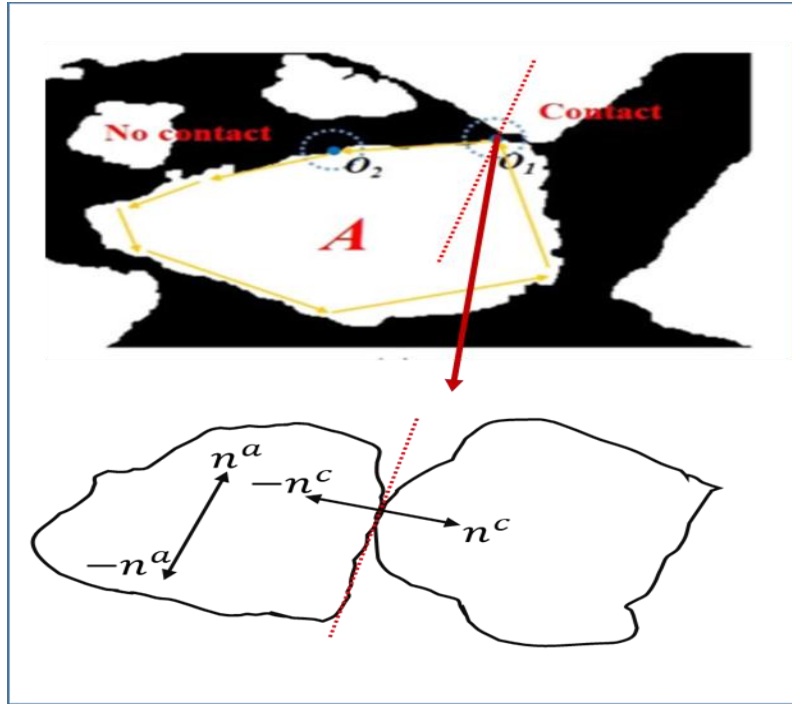


Figure 5-16: Vectors that describe the microstructure of asphalt mixture

5.4.1 Grey relational analysis method

Grey relational analysis provides the opportunity to optimise more than one of an asphalt mixes' mechanical performance properties. The method brings aspects such as (i) experimental design and its application, (ii) Signal- noise (S/N) Ratio calculation, (iii) decision matrix creation, (iv) data normalisation, (v) weighting of normalised, and (vi) Ranking points. The calculation procedures were determined with MATLAB using Eqs tabulated in Table 5-4.

Table 5-4: Steps for Grey relational analysis method (Siddiquee and Khan, 2010)

Steps	Definitions		Equations
Step 1.	The reference sequence of length n is as follows		$x_0 = (x_0(1), x_0(2), x_0(3), \dots, x_0(n)) \quad (1)$
Step 2.	Data Normalization	The Larger -The Better	$x_i(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (2)$
		The small - The better	$x_i(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \dots\dots\dots (3)$
		The Nominal - The Better	$x_i^0(k) = 1 - \frac{ x_i^0(k) - x^0 }{\max x_i^0(k) - 1} \quad (4)$
Step 3.	The m number series going to be compared with x_0 series		$x_i = (x_i(1), x_i(2), x_i(3), \dots, x_i(n)),$ $i = 1, 2, 3 \dots m \quad (5)$
Step 4.	Grey Relational Coefficient is calculated.		$\varepsilon(x_0(k), x_i(k)) = \frac{\Delta_{\min} + \xi \Delta_{\max}}{\Delta_{0i}(k) + \xi \Delta_{\max}} \quad (6)$ $\Delta_{0i}(k) = x_0(k) - x_j(k) \quad (7)$ $\Delta_{\min} = \min_j \min_k x_0(k) - x_j(k) \quad (8)$ $\Delta_{\max} = \max_j \max_k x_0(k) - x_j(k) \quad (9)$
Step 5.	Weights Determination		W
Step 6.	Grey Relational Degree is calculated by Equation	If impact on the performance of the output is equal,	$\gamma(x_0, x_i) = \frac{1}{n} \sum_{k=1}^n \varepsilon(x_0(k), x_i(k)) \quad (10)$
		If impact on the performance of the output is not equal,	$\gamma(x_0, x_i) = \frac{1}{n} \sum_{k=1}^n w_k(x_0(k), x_i(k)) \quad (11)$

Where $x_i(k)$, = after normalisation i series k. value, $x_i^0(k)$ = i series k, $\min x_i^0(k)$ = minimum value in i series, $\max x_i^0(k)$ = maximum value in i series, x^0 = desire deal value, x_i = m series with x^0 series, $\varepsilon(x_0(k), x_i(k))$ = grey relational coefficient at point k.k.k. ranking in n length series, $k = 1, 2, \dots, n$, $j = 1, 2, \dots, m$, ξ = a coefficient between (0,1), $\Delta_{\min}$ = minimum value in the series, $\Delta_{\max}$ = maximum value in the series, $\Delta_{0i}(k)$ = k value in the series, $\gamma(x_0, x_i)$ = grey relation degree in i. rank, W_k = total weight must be 1.

5.5 Preliminary results

5.5.1 Comparison between dem and laboratory porosity in different depths

Figures. 5-17 and 5-18 show permeability results determined using Equation.12 and the laboratory-measured at different depths for all samples scopes. The results show that permeability in the mid-depth is lower than the permeability in the upper and lower samples for both DEM and laboratory. This could be that the aggregates is closely packed in the middle than at the top and bottom; the aggregate and the boundary may not be in contact with the edges. A similar observation was noted by (Kutay, Aydilek and Masad, 2007), who recorded the lowest permeability in the middle for all samples at different compactions. Another important observation was that the laboratory test results were slightly lower than the DEM. During compactions in the laboratory, some aggregate gets crushed to a powder and close some of the voids

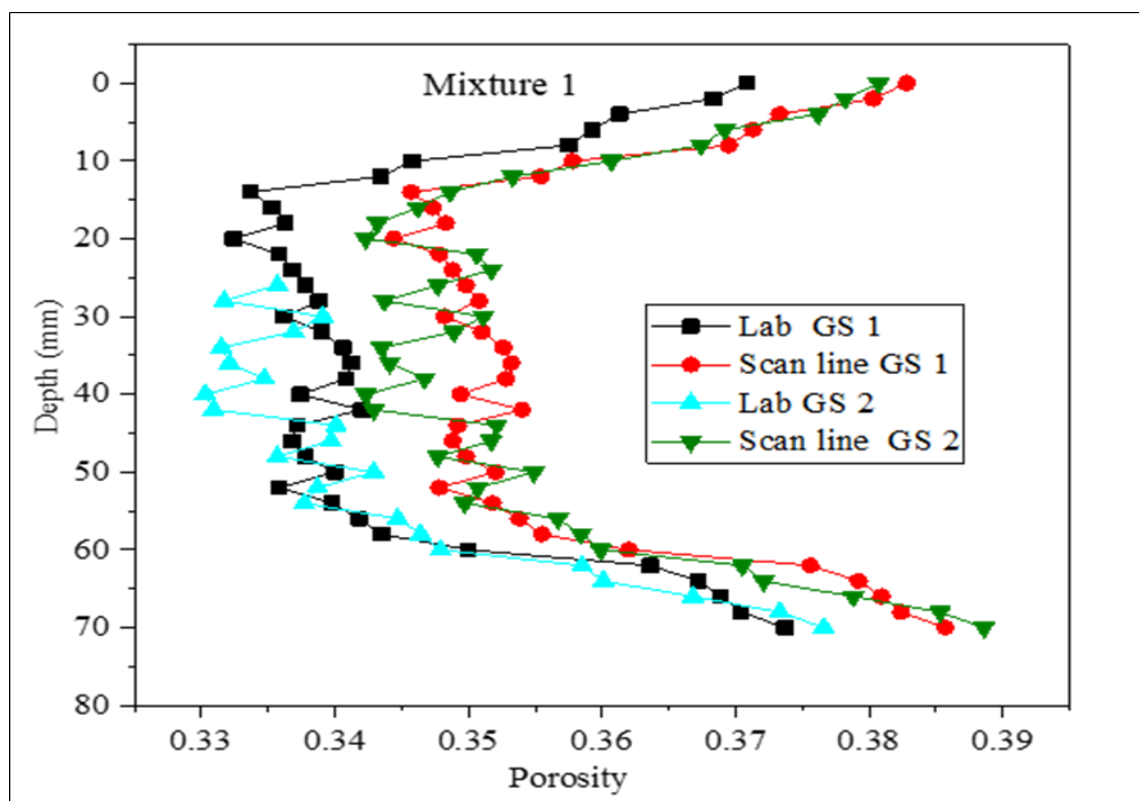


Figure 5-17: Comparison of laboratory and estimated porosity at different depths for mixture 1

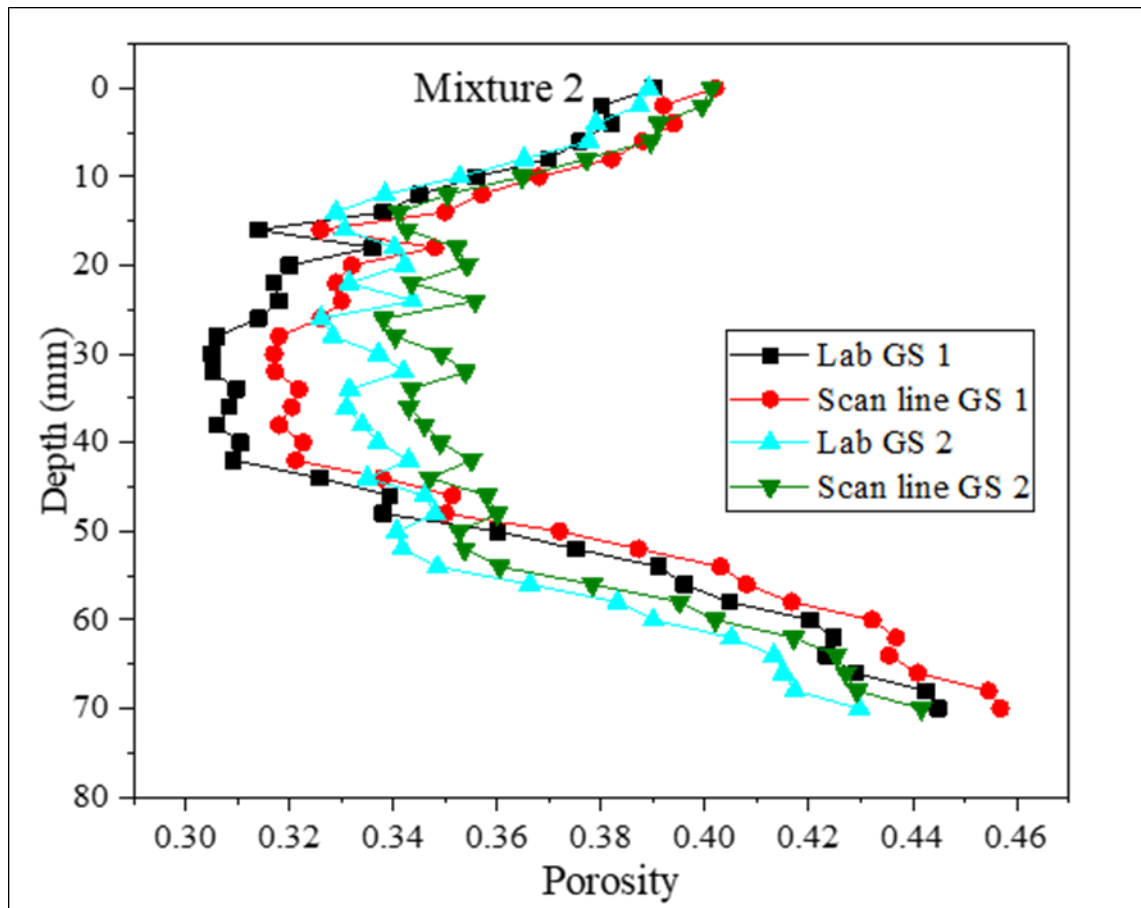


Figure 5-18: Comparison of laboratory and estimated porosity at different depths for mixture 2

Also, it must be noted that natural aggregate has some mineral voids that absorb some moisture into the aggregate; unlike virtual experiments, the pressure is calculated depending on the radius of the interconnected voids. That means the results are realistic. These results are similar to the laboratory permeability of heterogeneous material, which was compared to Lattice Boltzmann (LB) (Kutay, 2005), annealing, and gaussian methods results (Boger *et al.*, 1992; Hilfer, Rage and Virgin, 1997). Results showed that DEM had slightly higher permeability as compared to the laboratory results. Laboratory tests mostly simulate vertical flow, but permeability can have different patterns; fluids can flow in any direction. Kutay *et al.* observed similar results, who simulated moisture transportation in asphalt mixture using the LB method, and the results were slightly higher than laboratory results (Kutay, 2005).

5.5.2 The directional permeability

In Table 5-5, the directional permeability was simulated for samples for all scopes using the APS at different compaction energies. It can be seen that all gradation scopes had relatively similar permeabilities. At the same time, it was observed that the permeabilities of

all samples decreased with increased compaction energy. Kutay, Aydilek and Masad, (2007) also reported reduced porosity with an increased compaction energy amount. It can be seen in Table 5-5 that the x and y directions had permeability almost 10 times of the z -direction. This is consistent with results on the directional permeability test; the horizontal results were almost 10 times the vertical directions (Kutay, 2005).

Table 5-5: Directional permeability for samples

GS 1					
Sampl e	Permeability (mm/s)		Values		Permeability Ratio
	K_{xx}	K_{yy}	K_{zz}	$0.5(K_{xx} + K_{yy})$	$(0.5(K_{xx} + K_{yy}))/K_{zz}$
AC 1	1.47	0.91	0.38	1.19	3.13
AC 2	1.32	1.1	0.29	1.21	4.17
AC 3	1.29	1.12	0.31	1.205	3.89
GS 2					
AC 1	0.92	1.34	0.29	1.13	3.9
AC 2	1.64	1.21	0.36	1.425	3.96
AC 3	1.89	1.28	0.09	1.585	17.61

5.6 Discussion

The experimental works which were conducted are presented in this chapter of the thesis. The chapter commenced with a presentation of permeability testing procedures. After that, samples preparations, testing methods, equipment, procedures and the number of replicates are presented. Preliminary results and briefly discussed. The rest of the results are analysed and discussed in the following chapter, which consists of a detailed analysis and interpretation of the results

CHAPTER 6: RESULTS FROM EXPERIMENTAL WORK

6 RESULTS INTERPRETATION AND DISCUSSION

6.1 Overview of research methodology

Virtual gradation and packing were performed using PFC3D commercial software: percentages of sieve passing and shape percentages were determined. Clumps were created using MATLAB and PFC3D to simulate realistic aggregate shapes, fractions densities per the Bailey method, DARS was incorporated, and IC was optimised. Virtual samples were prepared, and their anisotropy, such as void and normal contact fabric tensors, were determined using a scan line method. Laboratory porosity at different depths and directional permeability were compared to validate the virtual gradation. TK fibre was used to modify two bitumen Pen grades to enhance rheological properties. The gradation obtained from simulation and modified bitumen were used to prepare various samples, and the mechanical properties were determined. Lastly, the normal contact fabric tensors were introduced to quantify the internal structural index using vectors. The laboratory equipment, experimental work, procedures and preliminary results are presented in Chapter 5 of this thesis. Materials and characterisation are presented in Chapter 4. Numerical simulation of aggregate gradation using DEM as presented in Chapter 3. Literature review of microstructural properties and mechanical performance of asphalt mixtures Chapter 2 of this thesis. The importance of aggregate properties to gradation, packing, and microstructural properties is relevant to asphalt pavement performance in this chapter. The importance of modifying bitumen using TK fibres and the benefits to the economy, environment, and safety of using TK fibre as waste materials are presented in Chapter 2.

Therefore, this chapter is dedicated to analysing, interpreting, and presenting the test results from the experimental work and discussing the trends and different investigated mechanical properties of the asphalt mixtures. The chapter commences by presenting, analysing and interpreting the rheological properties such as rutting factor, creep recovery, percentage recovery and non-creep recovery compliance and thermal properties of TK modified fibres. This was followed by an analysis of the influence of aggregate properties on mechanical properties such as Marshall stability, rutting depths, stiffness modulus and dynamic modulus at 0°C and 10°C, and complex Poisson ratio. Grey relational method analysis results were presented in this chapter to show the correlation and influence of the multi

parameters. At the end of the chapter, a discussion summarises the findings and significance of this study.

6.2 Mechanical performance of teak fibre modified bitumen.

6.2.1 Penetration

The simplest way to measure the stiffness of bitumen is by the penetration test. The mean of three penetration readings was calculated. Figure 6-1 shows a significant decrease in value with the addition of TK 1 and less so with the addition of TK 2 for both 40/60 pen and 50/70 pen bitumens. The degree of the reduction in penetration is due to TK content, with fibre length also having a slight effect and the small variation between TK 1 and TK 2. TK 2 are shorter than TK 1 and may be less able to generate stiff networks within the bitumens.

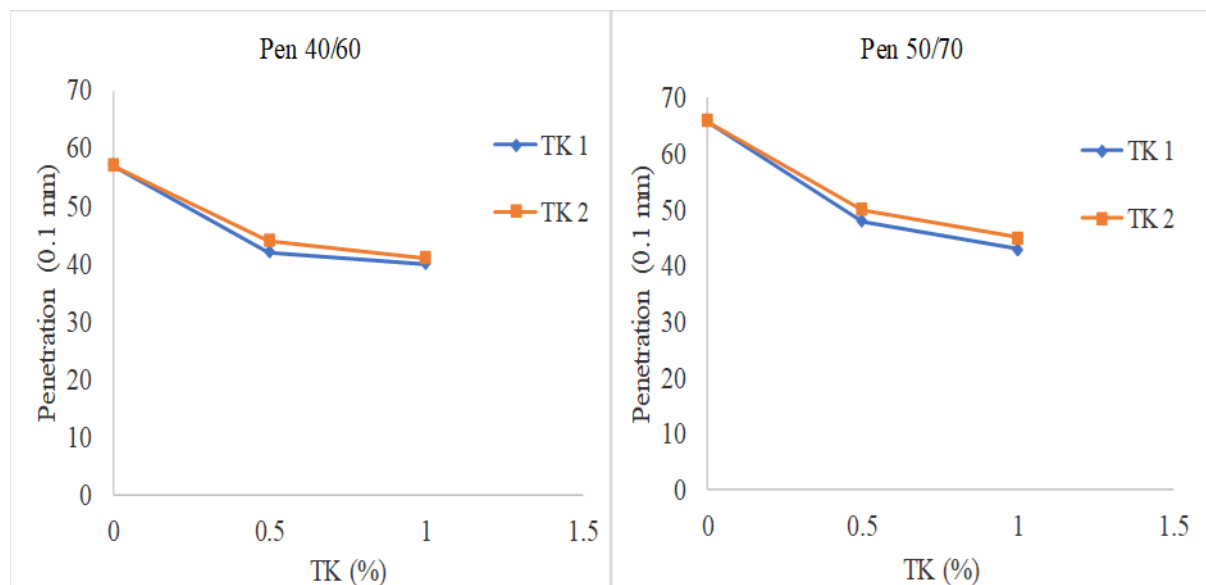


Figure 6-1: Penetration of base and modified bitumens (Busang and Maina, 2021)

6.2.2 Rutting factor

Figure 6-2 illustrates how frequency and temperature govern the rutting parameter ($G^*/\sin\delta$). The rutting parameter ($G^*/\sin\delta$) is a high-temperature specification parameter and rutting performance indicator of the unmodified and fibre modified bitumens. As seen by the upward shift, the addition of TK content enhanced the stiffness of the bituminous binder at high temperatures. The analysis showed that the values of $G^*/\sin\delta$ of TK 1 concentrations for both bitumens were higher than TK 2 for all concentrations, with the lowest value being exhibited by the base bitumens. The rutting parameter was highest with the highest TK concentration and decreased with increasing test temperature. Therefore, information about

the behaviour of the fibre mastics of the bituminous binder is based on the sensitivity at a reference temperature. The results indicate that fibres can increase the permanent deformation resistance of asphalt mixtures at high temperatures.

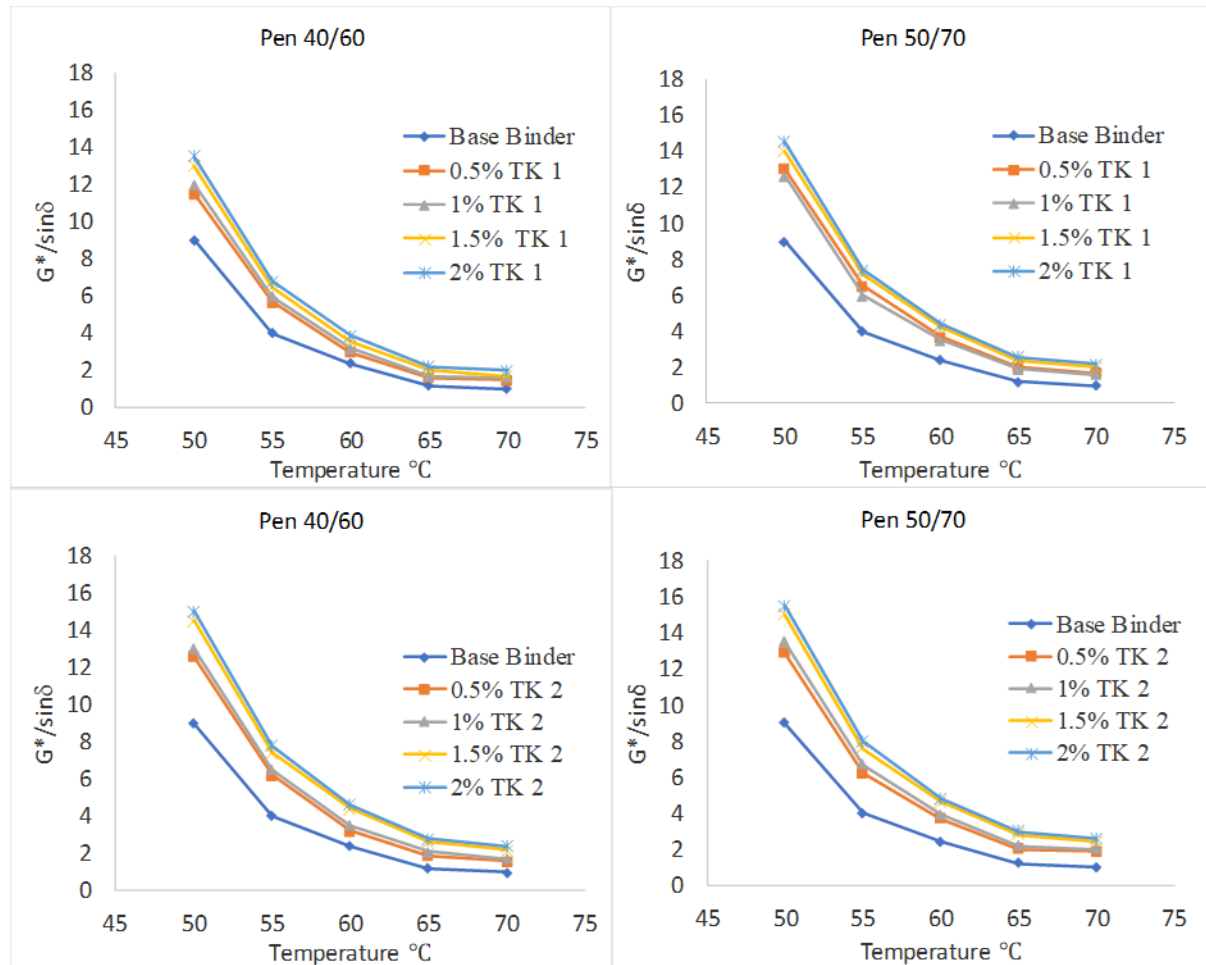


Figure 6-2: Rutting factor of base and modified bitumens (Busang and Maina, 2021)

6.2.3 Thermal conductivity

Semi-arid areas are known for high temperatures. Asphalt layers are dark in colour, which absorbs higher heat levels from the sun and transfers (thermal conductivity) to the lower layers. Applying some treatments or additives to reduce high thermal conductivity is essential to reduce salt transportation in moisture from the underlying layers. Figure 6-3 illustrates that thermal conductivity is reduced with increasing TK content because of its low coefficient of thermal conductivity. It was also observed that TK 1 was more effective than TK 2. Thermal conductivity measurements are an indication that the TK1 provided a better insulation layer. Rahman and Mohajerani conducted a thermal conductivity assessment of cigarette butts (made from cellulose acetate) with modified bitumen (Rahman and Mohajerani, 2021). The test results have demonstrated a significant thermal conductivity reduction due to incorporating

cigarette butts in asphalt. Also, the results suggested that the thermal conductivity of stone mix asphalt (SMA) was reduced by 5%, 7%, and 8% compared to the unmodified SMA when it was modified with the concatenations of 1%, 2%, and 3% cigarette butts (Rahman and Mohajerani, 2021). Low thermal conductivity in material slows down the heat transfer rate, and will potentially last longer in high-temperature exposure. One of the main applications of cellulose is thermal insulation (Uetani and Hatori, 2017) because of their characteristic low thermal conductivities (i.e. high thermal insulation capacities) (Wicklein, Kocjan and Alvarez, 2015).

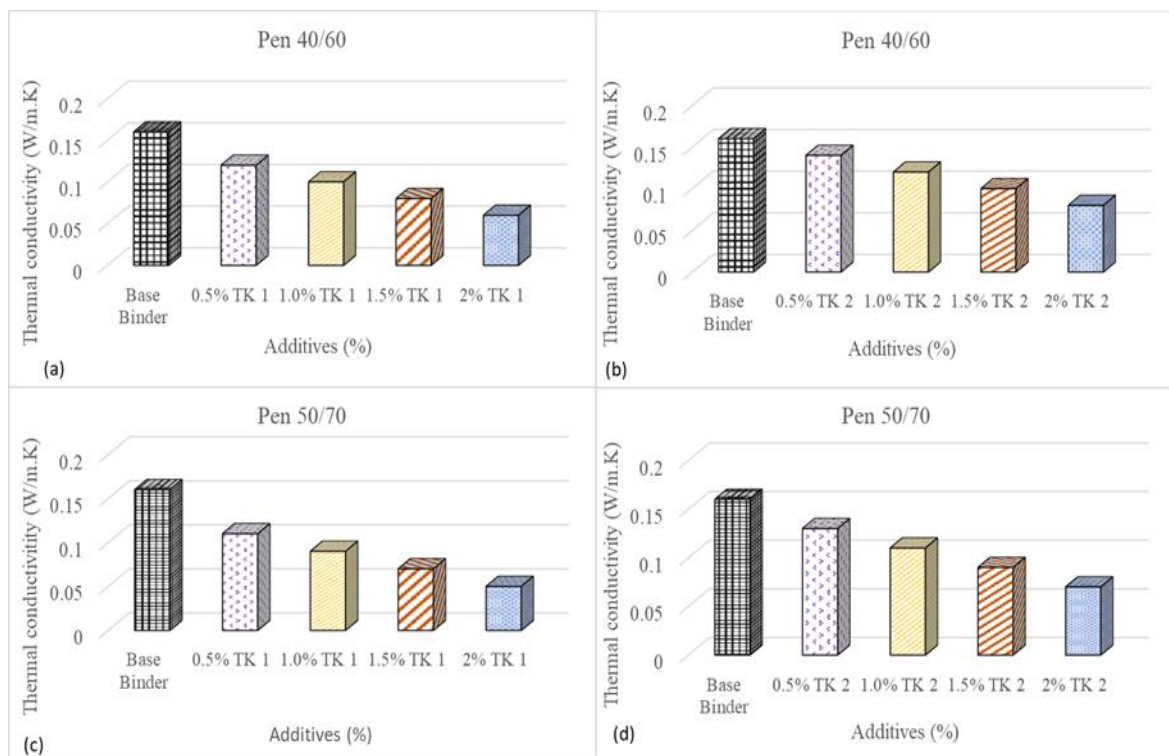


Figure 6-3: Thermal conductivity of base and modified bitumens (Busang and Maina, 2021)

6.2.4 Multiple stress creep recovery test (MSCR)

The MSCR test is an accurate and simple gauge of the permanent deformation behaviour of a bituminous binder or mastic used to make an asphalt mixture. Percentage recovery (%) was used to illustrate the effect of a range of stress levels along with the non-recoverable creep compliance (J_{nr}). These demonstrate the creep-recovery behaviour of base bitumen and TK fibre modified bitumens. Figure 6-4 shows the curve that illustrates the creep-recovery behaviour curves for base and TK modified bitumens at 0.1 kPa. It was observed that in both scenarios, the addition of TK fibres resulted in less shear strain relative to the base

bitumens. A content of 1.5 to 2% TK 1 in bitumen had a minimal percentage of shear strain, whilst 1% and 0.5 % contents exhibit a slightly higher shear strain, and the base bitumen demonstrated the highest shear strain. Figure 6-5 and Figure 6-6 show the percentage recovery and non-recoverable creep compliance obtained at various stress levels. There was a significant increase for TK 2 bitumens and an even higher percentage recovery for TK 1 at all contents. The base bitumens had the lowest percentage recovery.

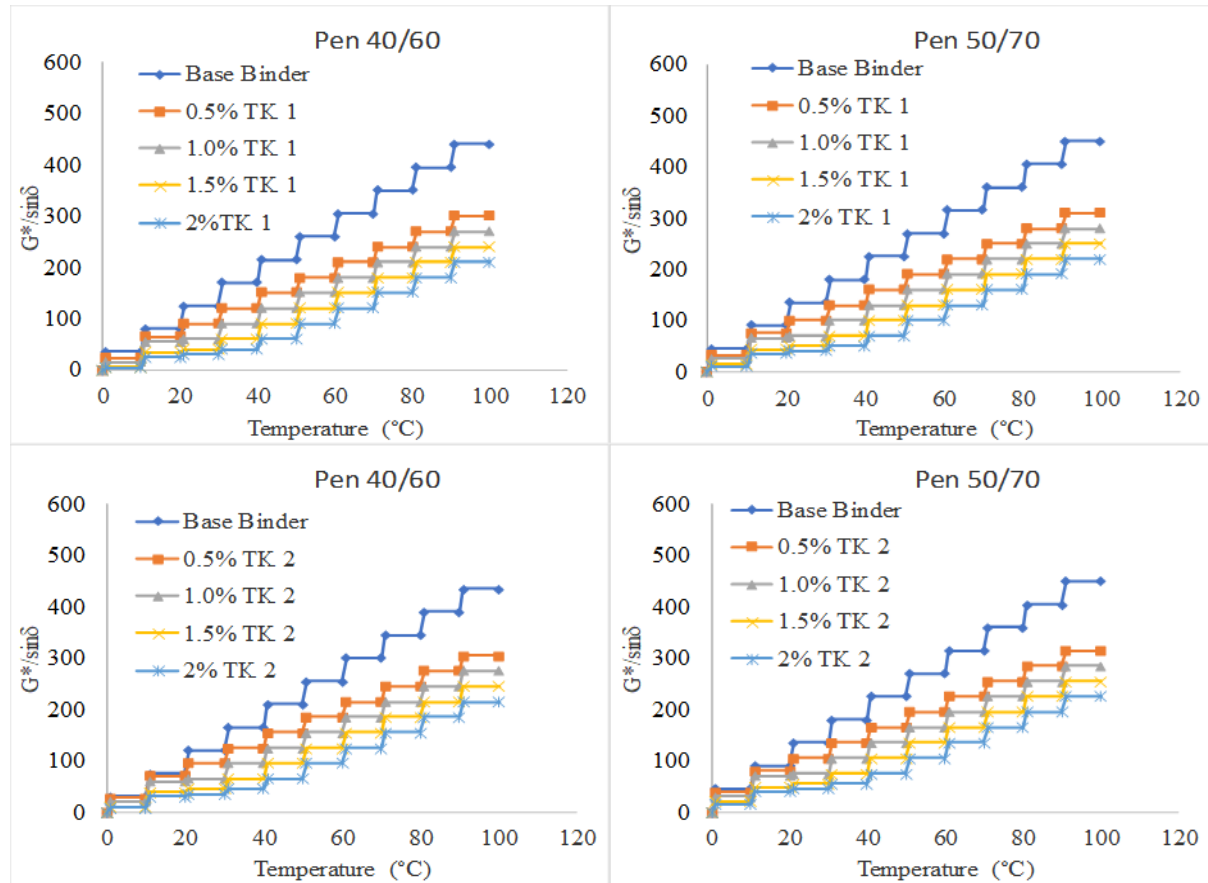


Figure 6-4: Creep-recovery curves of base and modified bitumens (Busang and Maina, 2021)

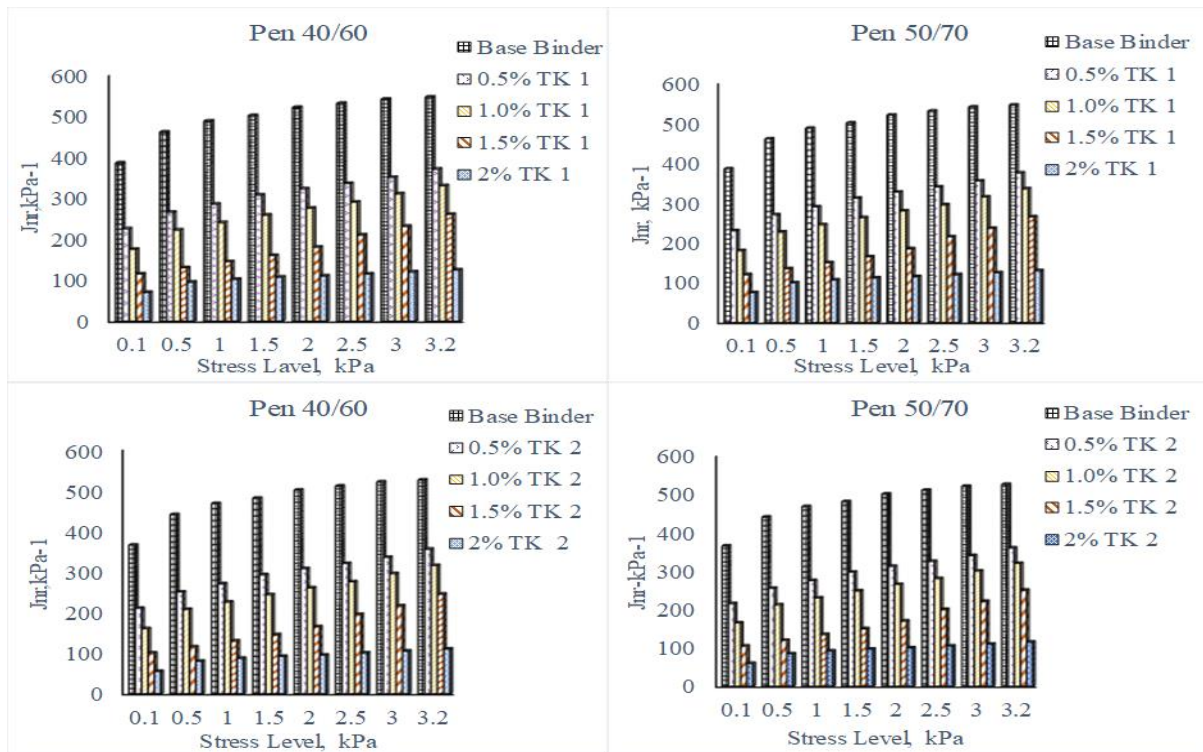


Figure 6-5: Percent recovery at all stress levels (Busang and Maina, 2021)

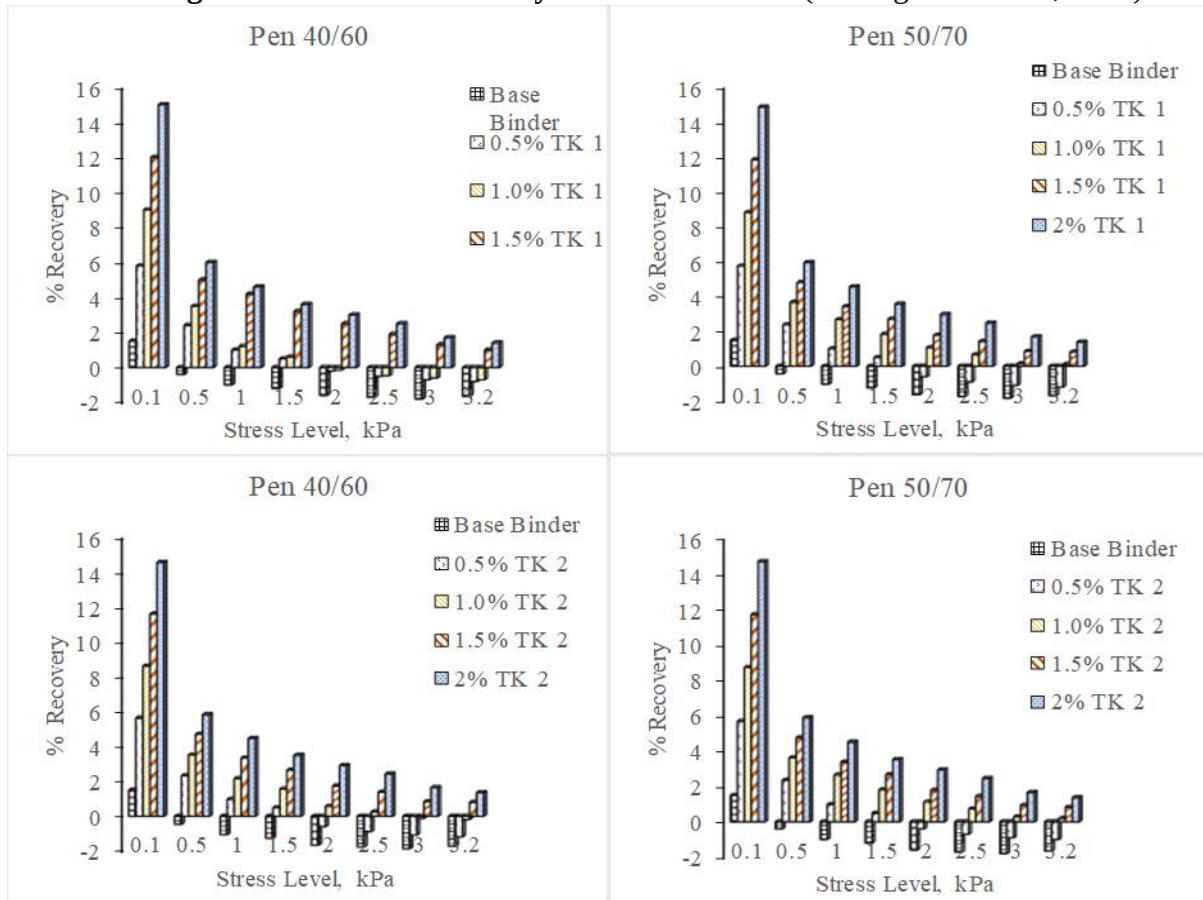


Figure 6-6: Non-recoverable creep compliance at all stress levels (Busang and Maina, 2021)

An ANOVA test called the Kruskal-Wallis test was performed for better accuracy and substantiating recoverable and non-recoverable creep compliance. This method uses a non-

parametric test, and it provides accurate results for TK compatibility at any stress level. The comparisons were at the 95% confidence level. Table 6-1 presents p-values of percentage recovery and Jnr values with TK fibre content and stress level. From the observation, the base bitumen presented recovery values below zero with the increase in stress level, which could have been due to extreme softening at high temperatures (65 °C). This demonstrates strain accumulation with the rest period phase in the absence of a creep load. As shown in Table 6-2, the p-values suggest that the addition of TK at different contents and sizes significantly affects percentage recovery. Another statistical tool called “pair-wise comparison” was used to validate the results. Pair-wise comparison analysis helps to weigh up the overall significance of various choices. The tool gives a structure for comparing every alternative against all others and demonstrates the distinction in significance between factors. Table 6-2 and Table 6-3 show that TK’s addition gave a significant difference between base bitumens and modified bitumens when considering the values of recovery and Jnr. The addition of 2% TK fibres exhibited the highest recovery values, reasonably higher than 1.5% TK. These levels of fibre modification are recommended for improving the performance of asphalt mixture in semi-arid areas. It can be seen that the recovery for a mix with 2% teak has high test value and most importantly the a 0.001 P-value. At dosages between 1.5% and 2%, no significant differences were observed in recovery percentage and Jnr, where these levels were found to be optimum considering rheological improvements.

Table 6-1: Kruskal-Wallis test.

Factor 1: TK Fibres Content				
Bitumen type	Recovery Percentage	Non-recoverable creep compliance	Recovery Percentage	Non-recoverable creep compliance
	Chi-Square degree of freedom		p-value	
Pen 40/60	712.17	1066.22	<0.05	<0.05
Pen 50/70	680.39	1097.21	<0.05	<0.05
Factor 2: Stress level				
Bitumen type	Recovery Percentage	Non-recoverable creep compliance	Recovery Percentage	Non-recoverable creep compliance
	Chi-Square degree of freedom		p-value	

Pen 40/60	74.12	79.19	<0.05	<0.05
Pen 50/70	71.11	76.44	<0.05	<0.05

Table 6-2: Pair-wise comparison of recovery for TK fibres (%)

Pen 50/70			Pen 40/60		
Recovery					
Pairs	Test value	p-value	Pairs	Test value	p-value
Base bitumen -		0.000	Base bitumen -		0.000
0.5% TK 1	-212.32	1	0.5% TK 1	-202.32	1
Base bitumen -		0.000	Base bitumen -		0.000
1% TK 1	-378.68	1	1% TK 1	-371.68	1
Base bitumen -		0.000	Base bitumen -		0.000
1.5% TK 1	-653.23	1	1.5% TK 1	-645.23	1
Base bitumen -		0.000	Base bitumen -		0.000
2% TK 1	-660.07	1	2% TK 1	-651.07	1
0.5% TK 1 - 1%		0.000	0.5% TK 1 - 1%		0.000
TK 1	-166.36	1	TK 1	-169.36	1
0.5% TK 1 -		0.000	0.5% TK 1 - 1.5%		0.000
1.5% TK 1	-440.91	1	TK 1	-442.91	1
0.5% TK 1 - 2%		0.000	0.5% TK 1 - 2%		0.000
TK 1	-447.75	1	TK 1	-448.75	1
1% TK 1 - 1.5%		0.000	1% TK 1 - 1.5%		0.000
TK 1	274.55	1	TK 1	273.55	1
1% TK 1 - 2%			1% TK 1 - 2% TK		
TK 1	281.39	0.001	1	279.39	0.001
2% TK 1 - 1.5%			2% TK 1 - 1.5%		
TK 1	-6.84	0.796	TK 1	-5.84	0.736
Jnr					
Pairs	Test value	p-value	Pairs	Test value	p-value

Base bitumen -	0.000	Base bitumen -	0.000
0.5% TK 1 223.45	1	0.5% TK 1 218.45	1
Base bitumen -	0.000	Base bitumen -	0.000
1% TK 1 209.43	1	1% TK 1 201.43	1
Base bitumen -	0.000	Base bitumen -	0.000
1.5% TK 1 327.89	1	1.5% TK 1 316.89	1
Base bitumen -	0.000	Base bitumen -	0.000
2% TK1 420.23	1	2% TK1 412.23	1
0.5% TK 1 -1%	0.000	0.5% TK 1 - 1%	0.000
TK 1 104.44	1	TK 1 98.44	1
0.5% TK 1 -	0.000	0.5% TK 1 - 1.5%	0.000
1.5% TK 1 196.78	1	TK 1 193.78	1
0.5% TK 1 - 2%	0.000	0.5% TK 1 - 2%	0.000
TK 1 -14.02	1	TK 1 -17.02	1
1% TK 1 - 1.5%	0.000	1% TK 1 - 1.5%	0.000
TK 1 -92.34	1	TK 1 -95.34	1
1% TK 1 - 2%	0.000	1% TK 1 - 2% TK	
TK 1 118.46	1	1 115.46	0.001
2% TK 1 - 1.5%		2% TK 1 - 1.5%	
TK 1 92.34	0.084	TK 1 95.34	0.092

Table 6-3: Pair-wise comparison of Jnr for Recovery TK Content					
Pen 50/70			Pen 40/60		
Pairs	Test value	P-value	Pairs	Test value	P-value
Base bitumen - 0.5% TK 2	-217.32	0.0001	Base bitumen - 0.5% TK 2	-208.32	0.0001
Base bitumen - 1% TK 2	-385.68	0.0001	Base bitumen - 1% TK 2	-375.68	0.0001
Base bitumen - 1.5% TK 2	-659.46	0.0001	Base bitumen - 1.5% TK 2	-650.26	0.0001
Base bitumen - 2% TK 2	-666.07	0.0001	Base bitumen - 2% TK 2	-658.07	0.0001
0.5% TK 1 - 1% TK 2	-168.36	0.0001	0.5% TK 1 - 1% TK 2	-167.36	0.0001
0.5% TK 1 - 1.5% TK 2	-442.14	0.0001	0.5% TK 1 - 1.5% TK 2	-441.94	0.0001
0.5% TK 1 - 2% TK 2	-448.75	0.0001	0.5% TK 1 - 2% TK 2	-449.75	0.0001
1% TK1 - 1.5% TK 2	273.78	0.0001	1% TK 1 - 1.5% TK 2	274.58	0.0001
1% TK 1 - 2% TK 2	280.39	0.001	1% TK 1 - 2% TK 2	282.39	0.001
2% TK 1 - 1.5% TK 2	-6.61	0.696	2% TK 1 - 1.5% TK 2	-7.81	0.816
Jnr					
Pairs	Test value	P-value	Pairs	Test value	P-value
Base bitumen - 0.5% TK 2	229.45	1	Base bitumen - 0.5% TK 2	223.45	0.0001

Base bitumen - 1%	0.000		Base bitumen -		
TK 2	202.43	1	1% TK 2	209.43	0.0001
Base bitumen - 1.5%	0.000		Base bitumen -		
TK 2	319.89	1	1.5% TK 2	327.89	0.0001
Base bitumen - 2%	0.000		Base bitumen -		
TK 2	411.23	1	2% TK 2	420.23	0.0001
0.5% TK 1 - 1% TK	0.000		0.5% TK 1 - 1%		
2	90.44	1	TK 2	104.44	0.0001
0.5% TK 1 - 1.5%	0.000		0.5% TK 1 -		
TK 2	181.78	1	1.5% TK 2	196.78	0.0001
0.5% TK 1 - 2% TK	0.000		0.5% TK 1 - 2%		
2	-27.02	1	TK 2	-14.02	0.0001
1% TK 1 - 1.5% TK	0.000		1% TK 1 - 1.5%		
2	-91.34	1	TK 2	-92.34	0.0001
			1% TK 1 - 2%		
1% TK 1 - 2% TK 2	117.46	0.001	TK 2	118.46	0.001
2% TK 1 - 1.5% TK			2% TK 1 - 1.5%		
2	91.34	0.096	TK 2	92.34	0.796

6.3 Case study

Samples were soaked in the salt (Trona) solution for 7 (d7) and 28 (d28) days. It was observed in Figure 6-7 that from d7, especially at d28, the shear strain increased for both the base and modified bitumens compared to Figure 6-4. Bitumens with 2% TK fibres exhibited the lowest shear strain values, while 1.5% concentration was slightly lower than 1% and 0.5%, respectively. The base bitumens showed the highest shear strain. It was also observed that all base and modified bitumens showed increased shear strain when the salt content was increased. Samples soaked at 5% salt solutions presented the highest shear strain followed by 3%, 1% and 0.3% salt solutions, respectively. This suggests that asphalt pavements modified with TK fibres have better permanent deformation resistance under salt-action. This agrees with the results shown in Figures 6-8 and 6-9 and at d7 for various stress levels, where samples presented increased non-recoverable creep compliance compared to that shown in Figure 6-5. It is clear the values for 2% TK fibres were the lowest for all the ageing levels, while the base

bitumens had the highest values of non-recoverable creep compliance, followed by TK fibre contents of 0.5%, 1% and 1.5%, respectively.

Furthermore, the values for non-recoverable creep compliance decreased with an increase in salt concentration. At 5% salt concentration, the values were the lowest at both ages d7 and d28. The next lowest values were exhibited by 1.5%, 1%, 0.5%, and base bitumens. Lower non-recoverable creep compliance indicates a better resistance to repeated loads under the influence of salt conditions. Similarly, the results depicted in Figure 6-9 shows that the addition of 2% and 1.5% TK fibres had better resistance to deformation across all stress levels..

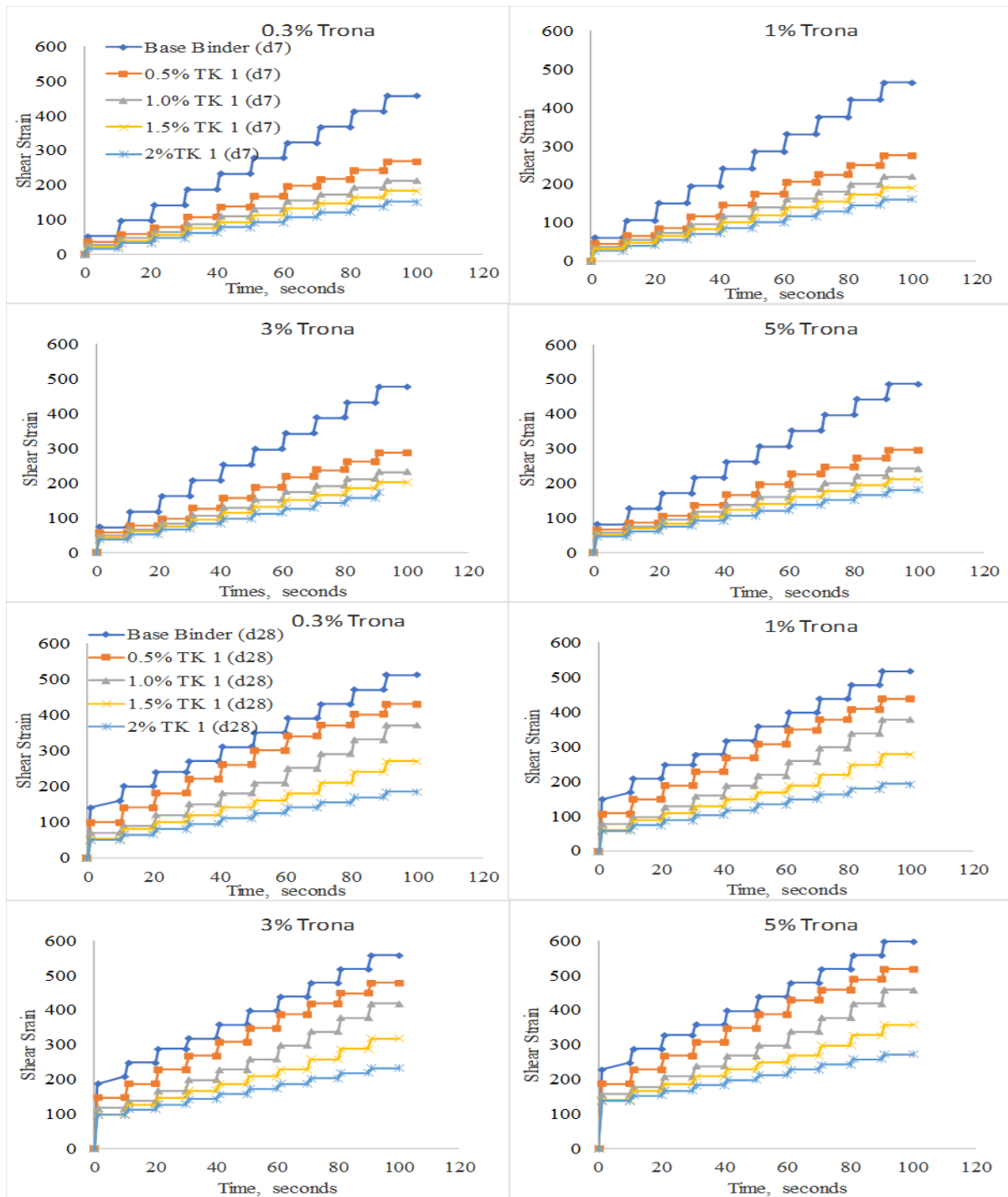


Figure 6-7: Creep-recovery curves of base (Pen 70/80) and TK 1 bitumen at all salt contents and aging times (Busang and Maina, 2021)

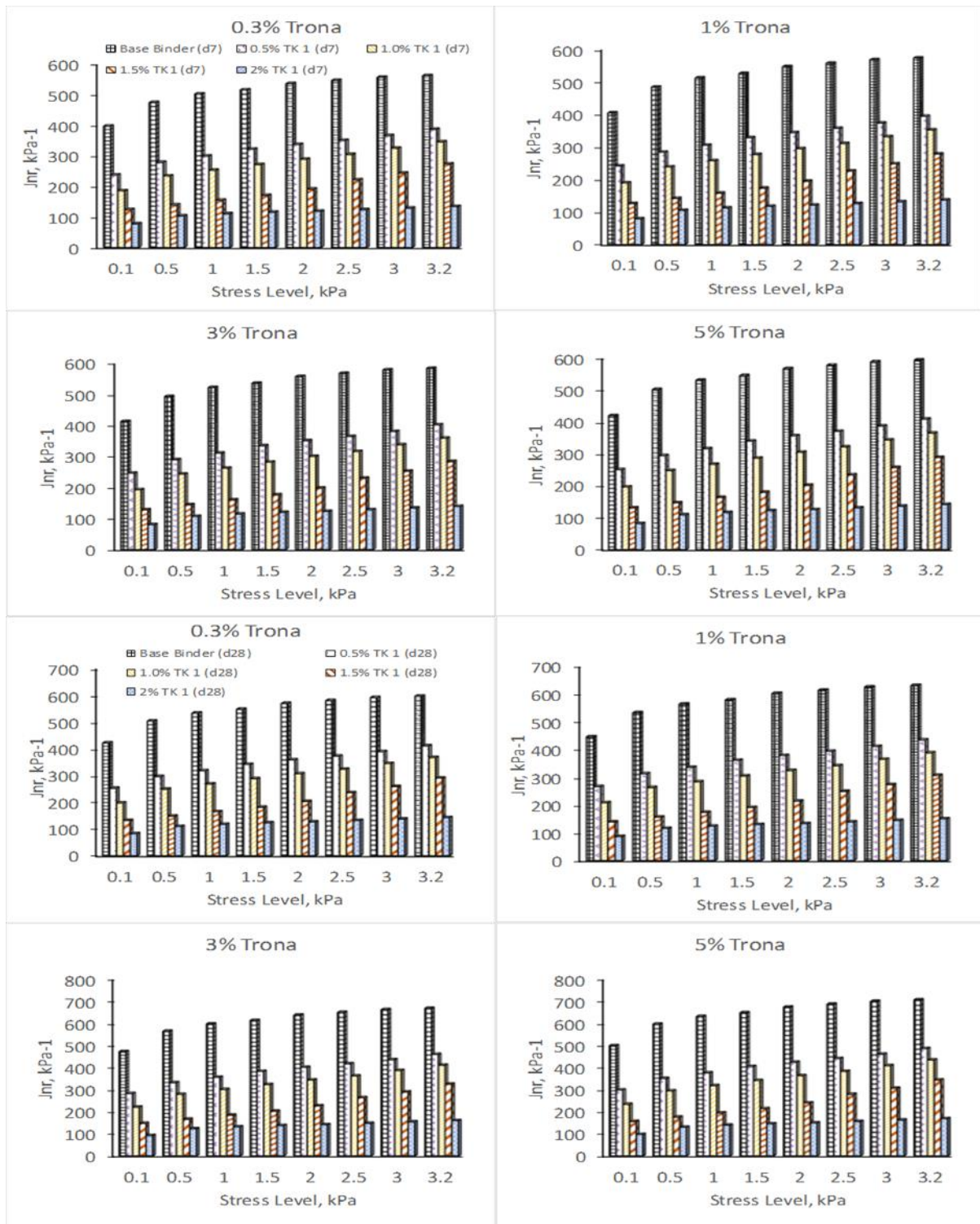


Figure 6-8: Percentage recovery of base (Pen 70/80) and TK 1 bitumens at all salt contents and different ageing times (Busang and Maina, 2021)

However, the resistance decreased with increased salt contents at age d7 and more so at age d28. It was observed that at 0.5 kPa all base bitumens had negative recovery percentages at all salt contents and ageing steps. The addition of 0.5% and 1% TK fibres showed a negative

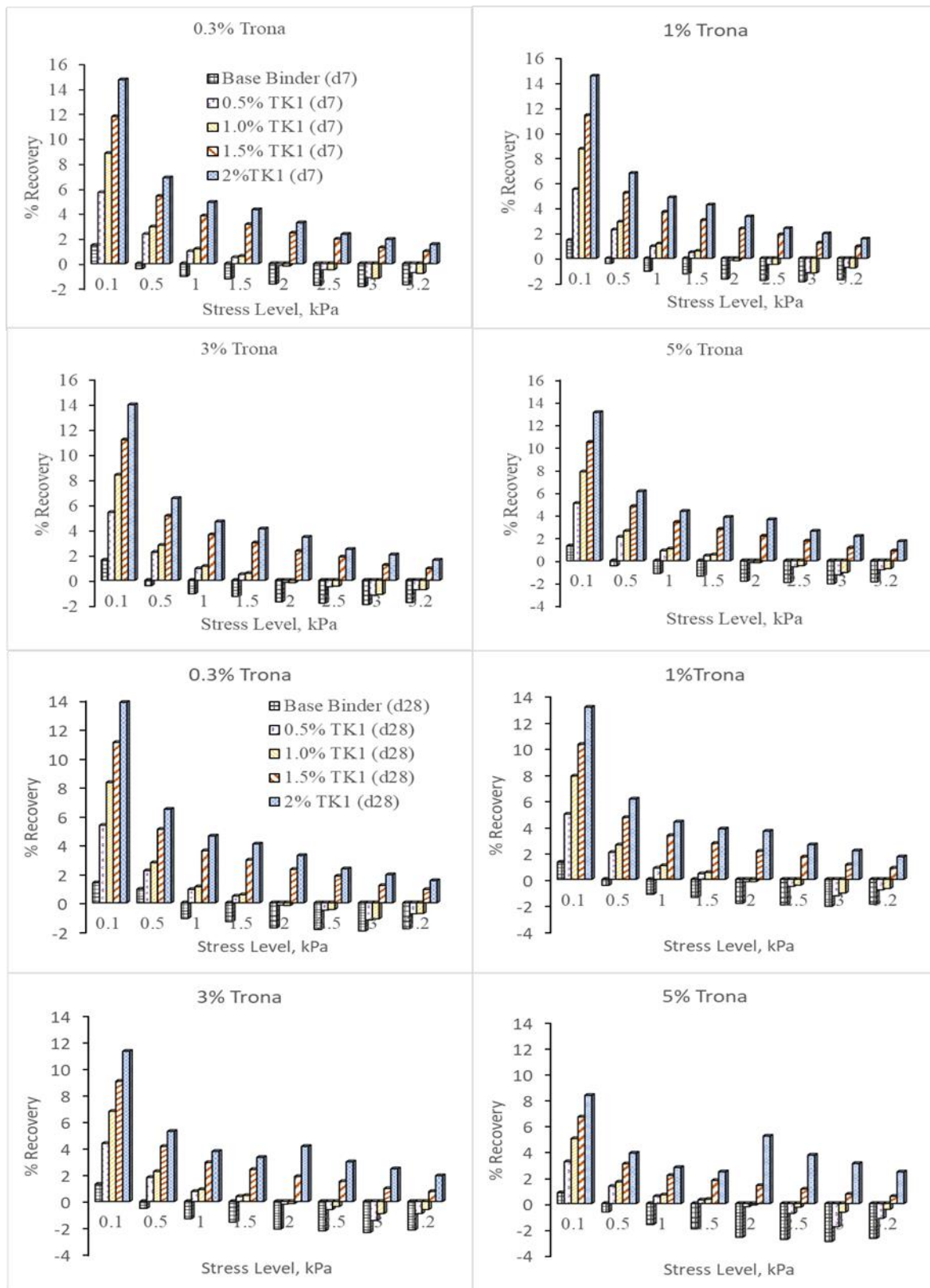


Figure 6-9: Non-recoverable creep compliance of base (Pen 70/80) and TK 1 bitumens at all stress levels, salt concentrations and ageing times

value at a stress level of 2 kPa for all salt contents and all ageing steps. An increase in non-recoverable creep compliance could suggest ascribed to excessive softening after temperature 65°C indicating that strain increasing even in the rest period phase, where the creep load was

absent. At night, at low temperatures, bitumen will transition from the viscous phase to a glassy state. This can lead to a loss of adhesion between aggregates and the bitumen. There is a suggestion that the material will become more brittle by changing from viscous to a glassy state (Croll, 2008). Chowdhury *et al.*, (2013) indicated that laboratory test results showed gradually increased value of the penetration and specific gravity and flash point, fire point. They then gradually decreased softening point due to the increasing salts content in the bituminous mixture. Cui *et al.*, (2017) highlighted that salt solution concentration mostly affects the elastic parameters and also that a 4 % salt concentration had the least significant influence on the elasticity of asphalt mortar. The Botswana Road Department (BRD) observed salt damage in the form of blistering, doming, and powdering. This occurred in the second seal of the carriageway along sections of the first 12 km of the Sekoma - Kang road (Ministry of Works, Transport & Communications Botswana, 2001). This could indicate that under the action of traffic loading on a materials section in its glassy phase, it is susceptible to breaking down by powdering. Also, some studies pointed out that the deterioration of asphalt mixture due to de-icing salt solution immersion performance led to the stripping, cracking, and permanent deformation of asphalt pavement (Wei *et al.*, 2011; Guo *et al.*, 2019). Accordingly, the deterioration mechanism of de-icing salts on asphalt mixture primarily reduces adhesion between bitumen and aggregates. This may be due to the longer size of TK 1 fibres, meaning they could form longitudinal networks within the bitumen and exhibit better tensile capacity. The results show that TK fibres can enhance the deformation resistance of asphalt mixtures. The MSCR test successfully demonstrated the likely behaviour of asphalt mixtures under the action of salt.

6.4 Influence of aggregate properties on microstructural properties and mechanical performance of asphalt mixtures

6.4.1 Influence of chemical properties to angularity, strength and shape

This study captured the physical and chemical properties of aggregate particles to evaluate their influence on microstructural properties. The microstructural properties were used to predict the mechanical performance of asphalt mixtures. As indicated in Table 4-3, the general chemical oxide composition of the GD 1 and GD 2 as granite samples have shown that silicon, calcium, and aluminium are the three major elements in the granite aggregate particles. The silicon and aluminium concentrates were approximately 16% to 70% by weight, respectively. The high amount of silicon, aluminium and calcium suggests high pozzolanic

content and hence fewer mineral voids. (Yagüe *et al.*, (2020) used chemical and morphological analysis of granite sawdust waste as pozzolan material. The results suggested that the granite sawdust rich in silicates (quartz, feldspars, phyllosilicates) provides commercial ordinary Portland cement (rich in alkalis). Also, it was observed that when Si and Al are the major constituents, the properties of cement are improved to generate a pozzolanic cement of an ecological nature. Also, the study found that alkaline elements contents are larger than 5%, the acid composition and the particle size has shown noteworthy pozzolanic activity. The major chemical oxide composition of GD 3 is calcium and silicon, which also suggest a high strength. Table 4-5 provides the aggregate' shape and properties; GD 1 has shown the highest values of CV and LAA, followed by GD 2 and the least values for GD 3. The values indicate high strength as a high amount of silicon and aluminium provides good hardening with small crystallinity of the rock. Also, GD 1 has shown the lowest value of WA and the highest value of FI. This means GD 1 does not easily absorb water because the crystals are well compacted due to the high amount of silicon and aluminium. It can also be seen that GD 2 has a high amount of FI than GD 3; the higher the FI and lower WA, the stronger is the material. Calcium oxide (CaO) and silicon dioxide (SiO₂) minerals result in a fundamental change in the hydrophilic or hydrophobic properties of the asphalt mixture. The higher the silicon dioxide content, the greater the hydrophilicity of aggregate, and vice versa. Conversely, the higher the percentage of the calcium oxide mineral, the better the hydrophobicity of the aggregate, and vice versa (Arambula, 2007).

The three important parameters, the sum of contact points N_c , the contact orientation to the next corresponding contact aggregate and the contact line were captured based on the optimal contact distance threshold (0.5428 mm) using iPAS software (Gao *et al.*, 2018; Hassan *et al.*, 2021). The distribution of contact line orientation at intervals from an angle 15°C to 90°C for all samples are presented in Figure 6-10. It can be seen that the concentrates of the orientation of contact lines of various mixtures increased with increasing the angle range. For all mixtures, the percentage concentrates of the orientation of contact at angles between 75° and 90° were high, and the orientation percentage reduced as the angles reduced. In contrast, Figure 6-10 shows the percentage distribution contact length of all samples. The contact line length was divided into five different ranges, 0.5 – 1, 1 – 3.5, 3.5 – 8, 8 – 12 and >12, and these were used to determine the total contacts line length. The graph indicates that the range of 1–3 m has the highest contact length line for all mixtures. Figure 6-11 demonstrated that GD 1 has the highest percentage of contact line length, followed by GD 2 while GD 3 showed the lowest percentage.

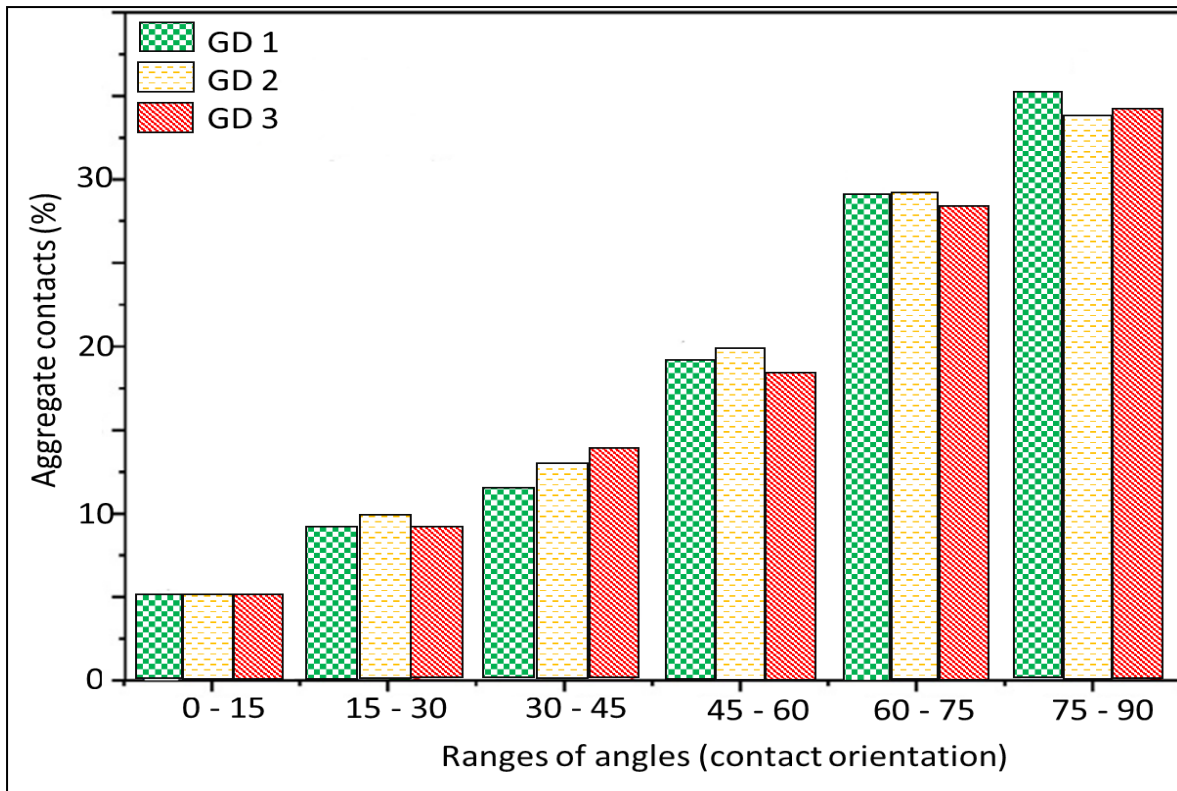


Figure 6-10: Range of contact orientation of different gradations (Busang and Maina, 2022)

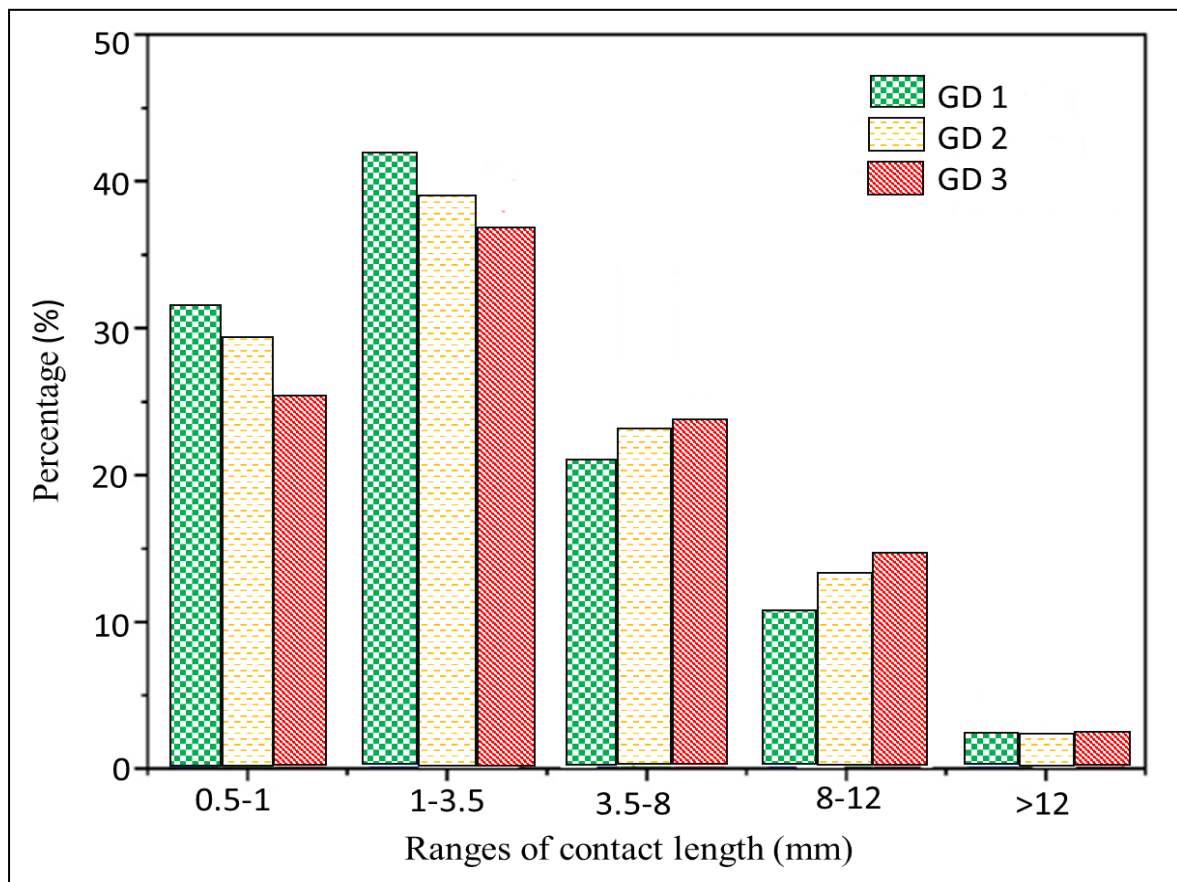


Figure 6-11: Range of contact length for different gradations (Busang and Maina, 2022)

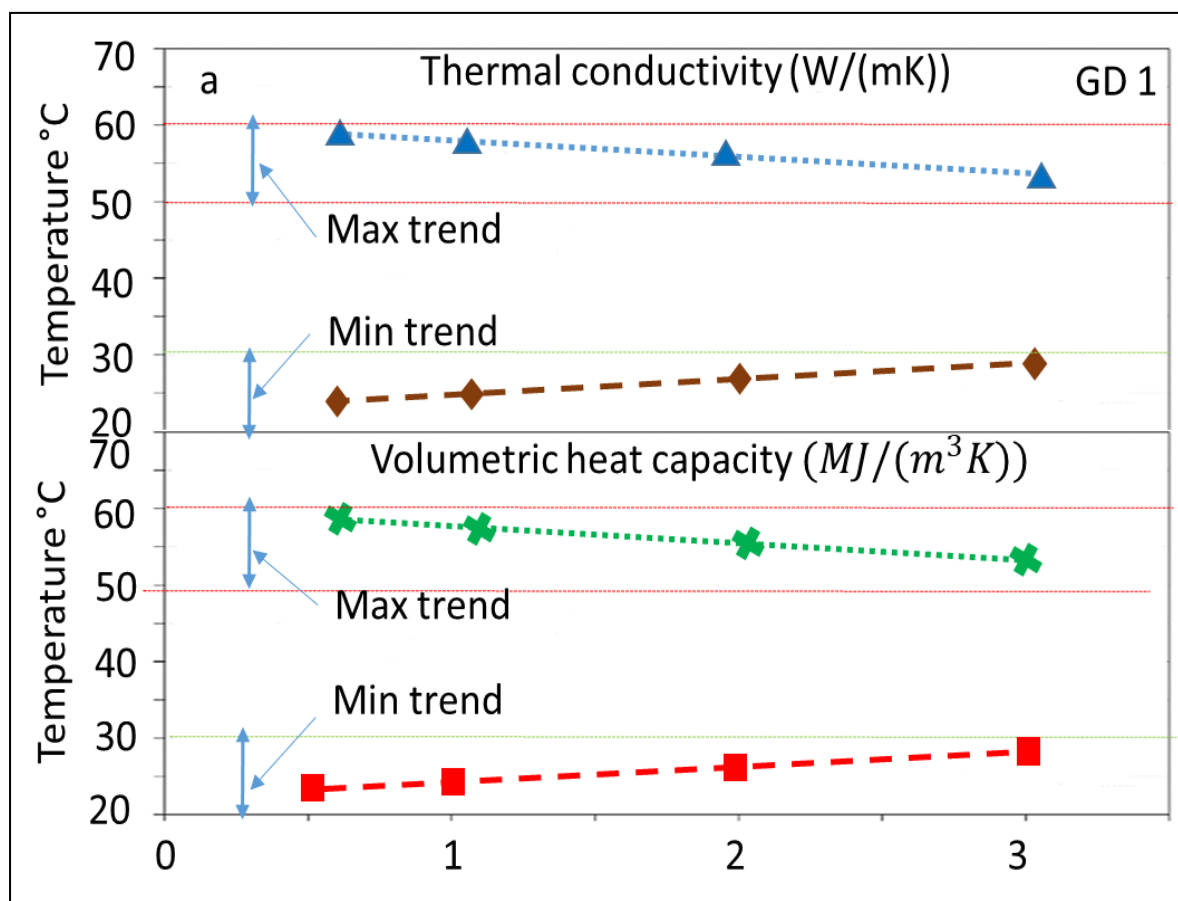
6.4.2 Thermal conductivity and volumetric heat capacity

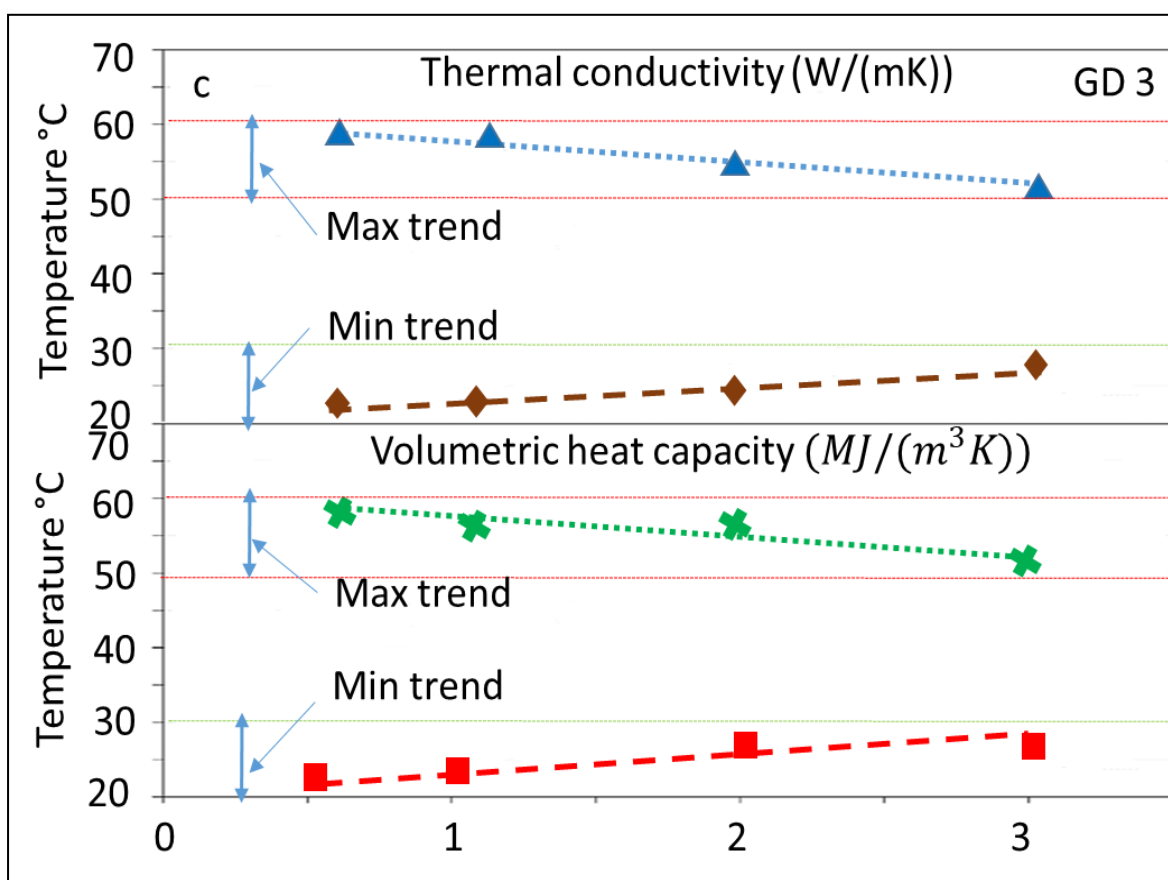
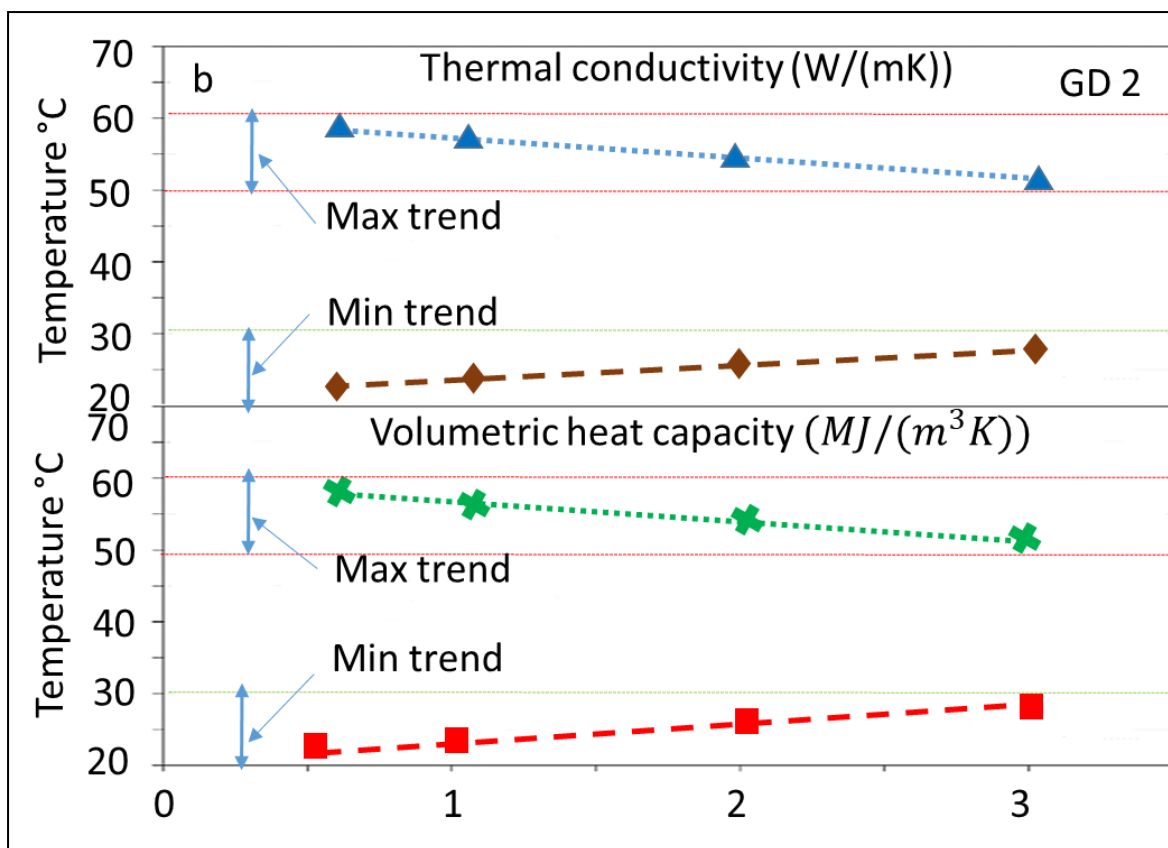
Several factors that influence the thermal conductivity of aggregate are rock origin and deposition environments and related lithology, mineralogy and texture, and thermal state and as well as thermodynamic conditions (Ramazanov and Emirov, 2012; Chen *et al.*, 2015). The microstructural properties of asphalt mixture such as aggregate size, contacts number, aggregate contact line length and air void contribute to thermal conductivity and volumetric heat capacity (Shi *et al.*, 2017). The effect of contact line length and chemical composition on all mixtures' thermal conductivity and volumetric heat capacity was assessed.

Figures. 6-12a, 6-12b and 6-12c present the relationship between the minimum and maximum thermal conductivity trends and minimum and maximum volumetric heat capacity trends for all samples. It can be seen that the minimum thermal conductivity trends are proportional to the minimum volumetric heat capacity trends. A similar observation can be seen that maximum thermal conductivity trends are almost the same as maximum volumetric heat capacity trends. The effects of thermal conductivity and heat capacity on the pavement surface temperature are almost similar to both trends for both samples. Since the volumetric heat capacity is a scalar, it is therefore expected that the anisotropic properties of thermal diffusivity to be similar to those of thermal conductivity. In this regard, the results suggest less than 5% of the anisotropy in the thermal conductivity and thermal diffusivity. Generally, the amplitude of the pavement surface temperature variation decreases with the increase of both thermal conductivity and heat capacity. It can be seen that GD 1 exhibits the highest thermal conductivity, followed by GD 2, while GD 3 has the lowest thermal conductivity, which suggests that the heat was easily conducted between aggregate as a result of a high percentage of contact line length. The higher the thermal conductivity of the asphalt mixture could enhance the heat sink effect of the asphalt mixture and make urban heat islands indifferent from flexible pavement researchers' perspectives. Dai et al. (Dai *et al.*, 2014) highlighted that $(\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO})/\text{SiO}_2$ has a significant influence on the electrical conductivity of granite samples at high temperatures and pressure. The impurity conduction is possible charge carriers such as K^+ , Na^+ , Ca^{2+} , H^+ , which have lower conduction mechanisms. In comparison, Ionic conduction is possible charge carriers such as K^+ , Na^+ and Ca^{2+} and higher conduction mechanisms at higher temperature ranges.

Due to the interest of environmental health and safety, the urban heat island impact, solar radiation, and air temperature during summer were measured, and the results are presented in Figures.6-13 for all samples, respectively. There is a clear indication that at 00:00

hrs, the urban heat island effect is the lowest because temperatures are low, leading to low radiation and low pavement temperatures. The curve shows that the pavement temperature rises from 07:00 hrs peaking at midday. It gradually drops until it gets cool after 19:00 hrs. It can be seen that pavement surface temperatures has a similar pattern with the curves for solar radiation and consequently the curve trend for air temperature. When the pavement surface temperature increases, the heat energy will be emitted to the environment. The speed of thermal cracking is influenced by the daily pavement amplitude of temperature variation (i.e. highest and lowest daily temperature at the pavement top layer) and temperature slope along the pavements depths. Pavement surface temperature relates to the urban heat island impact during summer and significantly impacts the rutting distress. The asphalt binder becomes less viscous at high temperatures and affects the adhesion between aggregate and bitumen. Note that the focus was on summer temperatures because Botswana is a semi-arid area temperature with relatively cool temperatures (0°C) during winter.





Figures 6-12a, b and c: The highest and lowest the daily surface temperature: (upper) difference of the thermal conductivity in summer, (bottom) difference of the volumetric heat capacity in summer (Busang and Maina, 2022)

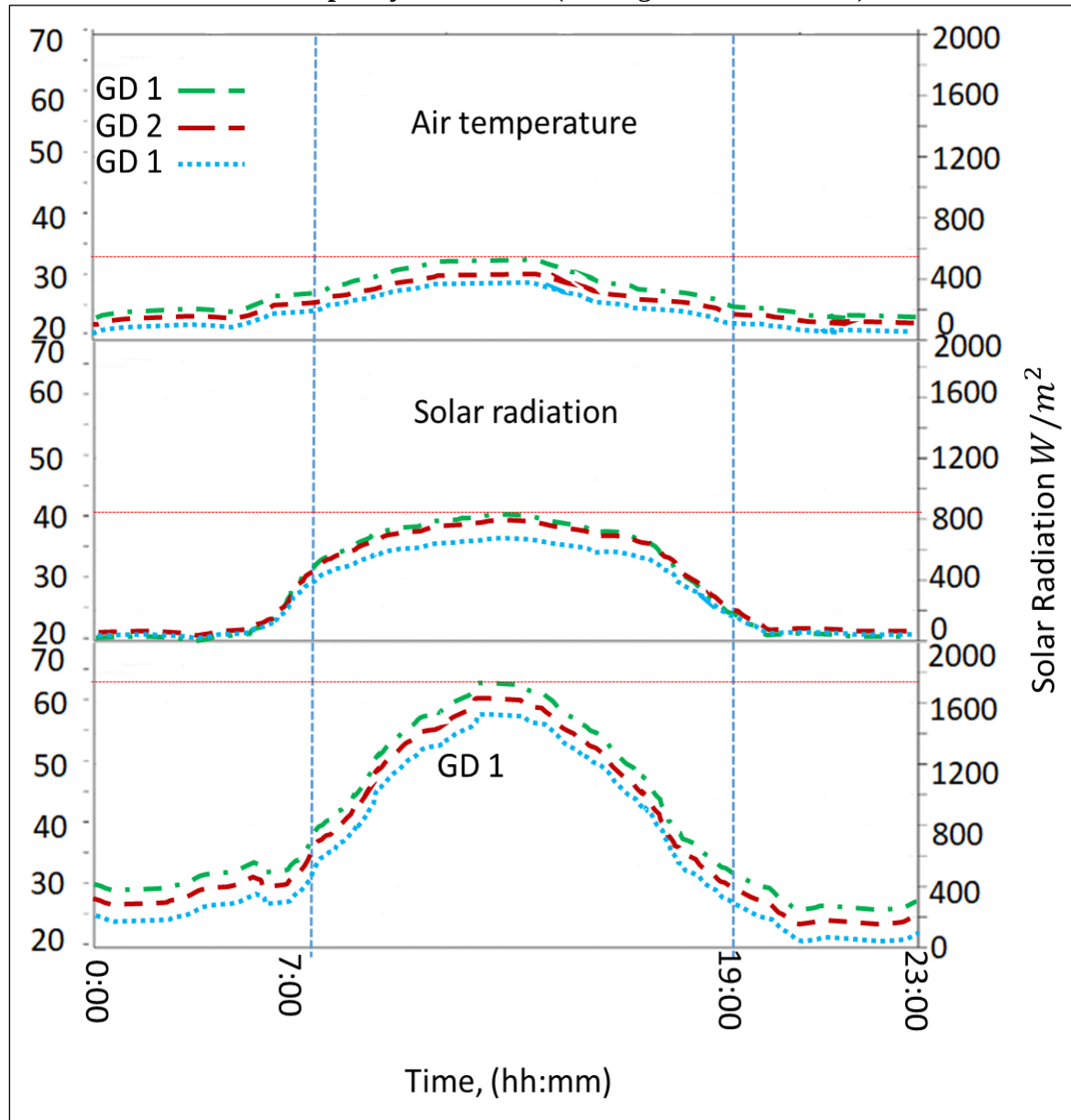


Figure 6-13: The urban heat island impact, solar radiation, and air temperature for all mixtures (Busang and Maina, 2022)

6.4.3 Influnce of angularity to mechanical properties

The dynamic stability order for these selected samples is GD 1, GD 2, and GD 3, and the deformation percentage order is GD 1, GD 2 and GD 3, respectively. Table 6-4 presented the contact number correlation with Marshall stability and showed the maximum value for the stability of 8.4 kN, 7.4 kN, and 7.1 kN for GD 1, GD 2 and GD 3, respectively. GD 1, GD 2 and GD 3 strengths are relatively the same, and they provide high stability because of the angular shapes or high contact point number. GD 1 and GD 2, granite mixture, have better

stability than GD 3. A high number of contact line lengths and texture of granite provide a good interlocking structure with the ability to transfer load easily among aggregate. Several studies have made a similar observation that angular aggregate particles improve the structural stability of asphalt mixture (Pan *et al.*, 2006; Li *et al.*, 2020). As shown in Table 6-4, GD 1, GD 2, and GD 3 samples have high Marshall ratios of 3.18, 2.72 and 2.63, respectively, representing the ratio of Marshall stability to flow value. Few studies have highlighted that high Marshall stability indicates high stiffness, thus resistance to permanent deformation (Cai *et al.*, 2018; Xiao, *et al.*, 2020). As indicated in Table 6-4, results obtained from the three-point bending test were -197, 165 and 151Mpa at temperature 10 °C and 1745, 1700 and 1650 at temperature 0 °C for GD 1, GD 2 and GD 3. These results indicate that The GD 1 samples have the highest bending stiffness modulus at 10 °C, followed by GD 2 and GD 3, respectively, for 10°C and 0°C. Also, all mixtures have a excellent influence at 10 °C and 0 °C. Granite, like Portland cement, contains SiO₂, Al₂O₃, K₂O and CaO prove to have higher external compression force resistance.

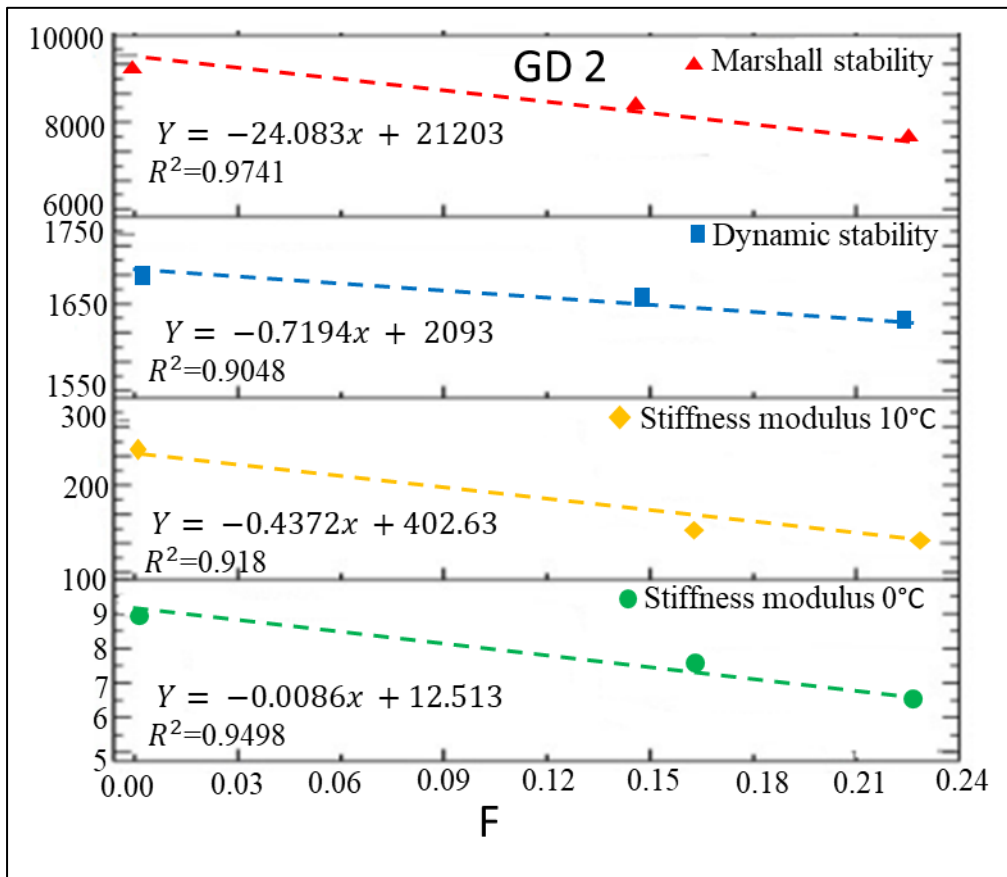
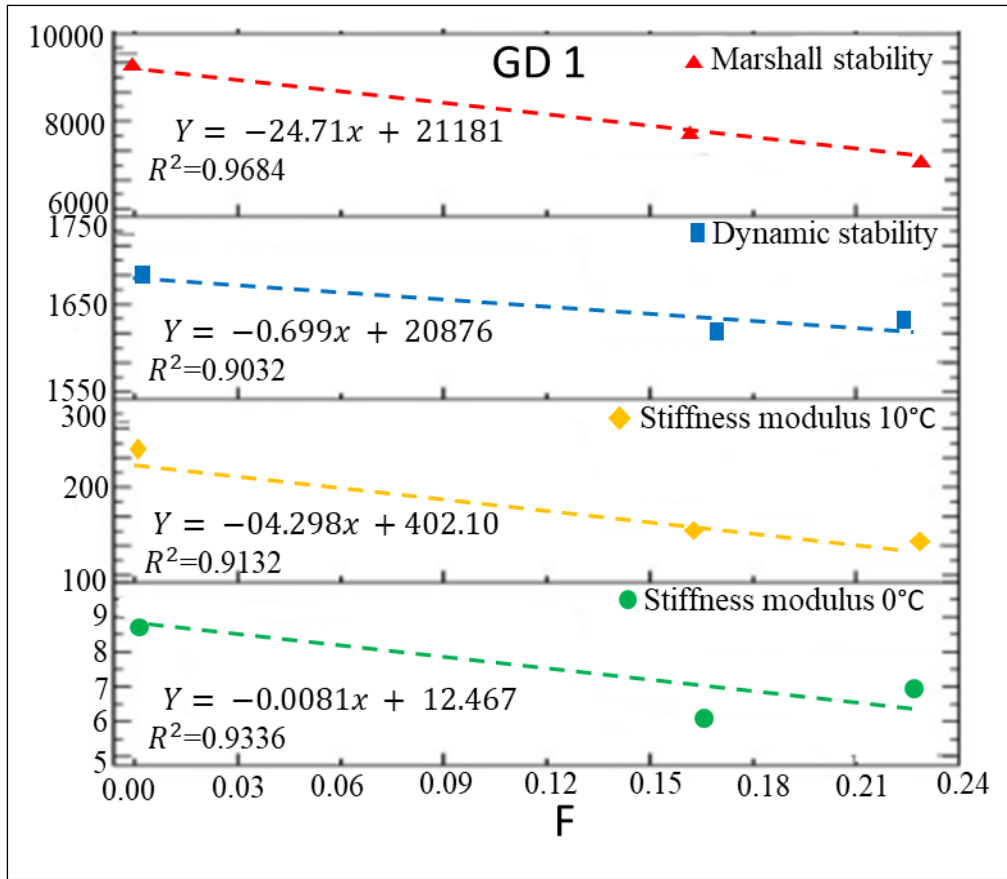
Table 6-4: Number of contact points and mechanical properties

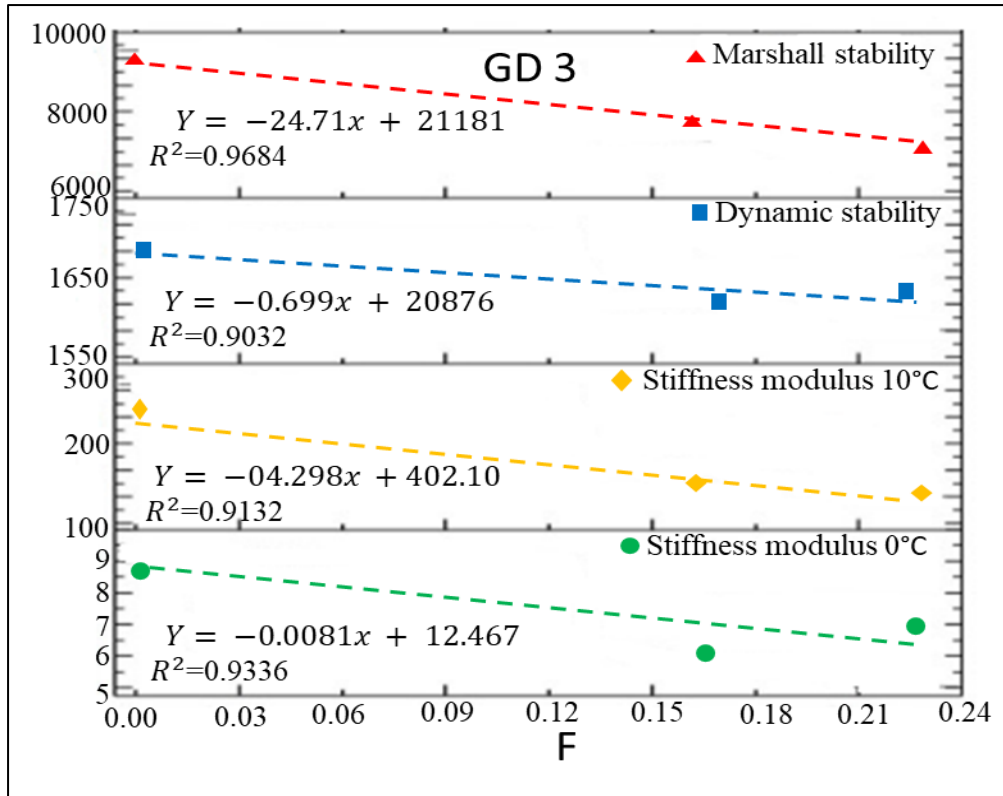
	GD 1	GD 2	GD 3
	N_c		
	253	246	248
	Mechanical Properties		
Marshall Stability (kN)	8.4	7.6	7.1
Martial Ratio (kN/mm)	3.18	2.72	2.63
Rut Depth (mm)	1.32	1.36	1.51
Dynamic Stability (passes/mm)	9750	8218	6923
SB (MPa) 10 °C	197	165	151
SB (MPa) 0 °C	1745	1700	1650

Granite has excellent Marshall stability and a low flow of cubical shaped particles that easily contact each other and form a good microstructure. Generally, limestone has a spherical shape that provides less internal friction between aggregate and contains fewer pozzolanic elements such as Al₂O₃ and SiO₂, improving aggregate-binder adhesion while lowering bitumen stiffness (softening).

6.4.3.1 Correlation of normal contact fabric tensors and mechanical properties

The anisotropy of the solid phase of the aggregate structure was quantified using F (a graphical and statistical approach) in a vector form. It can be observed from Figures. 6-14a, 6-14b and 6-14c present the linear F relation with Marshall stability, dynamic stability and stiffness modulus. R^2 for dynamic stability is 0.9048, 0.9032 and 0.921 for GD 1, GD 2 and GD 3, respectively. The R^2 bending stiffness modulus at temperature 10 °C is 0.918, 0.932 and 0.9132 for GD 1, GD 2 and GD 3, respectively. At temperature 0°C is 0.949, 0.934 and 0.930 for GD 1, GD 2 and GD 3, respectively. Granite aggregate exhibit a cubical shape with a large number of contacts point and a high contact line to provide a good interlocked aggregate structure that, under repeated stress, will not easily slip and change the tangential plane. Limestone with more of spherical shape has less texture to give stability like granite. Sukhwani et al. used image analysis technologies to determine angularity and texture gradient for granite and limestone (Sukhwani, 2006). They found that granite aggregate have a high texture and, thus, demonstrated better adherence characteristics with asphalt binder than limestone aggregate with lower angularity and lower texture gradients. These results suggest a recommendable linear relationship between F with dynamic stability and bending stiffness modulus. There is evidence that F provides an alternative way to analyse the microstructure to examine the mechanical properties of asphalt mixture to a reasonable and comprehensive extent. For the asphalt mixtures to carry a high load, aggregate particles must be supported, at least the contact angle at approximately 90°. The aggregate skeleton has a major influence on the mechanical properties and durability of the asphalt mixture (Maina, Ozawa and Matsui, 2009; Horak *et al.*, 2017). As shown Table 6-4, wheel tracking test results show the DS value, 9750, 8218, and 6923 passes/mm for GD 1, GD 2 and GD 3 samples. These results indicate the highest value for GD 1 samples and the lowest for GD 3 samples. The recorded values for rutting depth were 1.32 mm, 1.36 mm and 1.51 mm. This indicates that the GD 1 samples have the lowest rutting depth, and the GD 3 has the highest rut depth value in return. The values are above the standard specification of 2800 passes/mm (*Ministry of Transport, Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering, in: China Commun. Press, China Communications Press, Beijing, China, 2011: pp. 1–370, 2011*). This suggests a good performance by all mixtures at high-temperature areas (Hassan *et al.*, 2021). For past studies with a similar aim, the results have shown a similar trend shown in this study (Mashaan *et al.*, 2014; Hassan *et al.*, 2021).

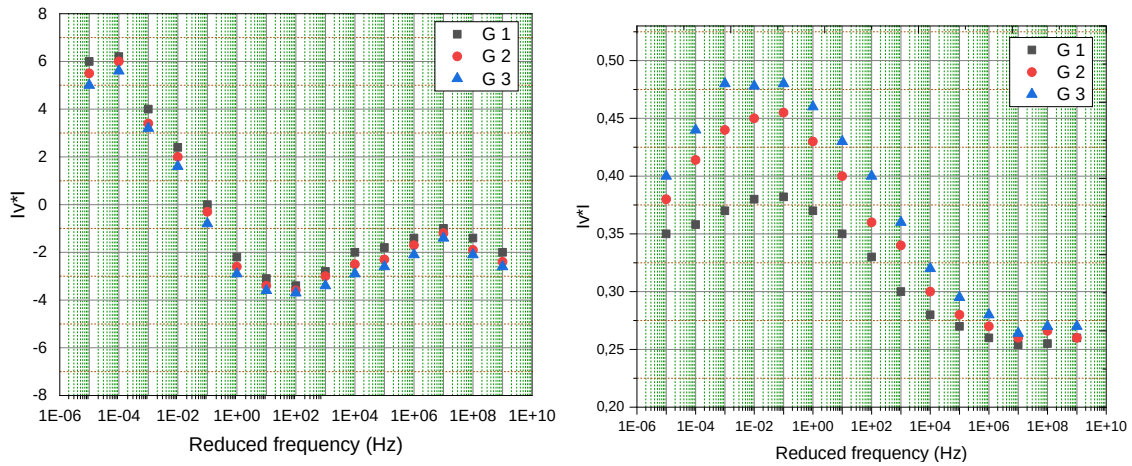




Figures .6-14, 11b and 11c: Correlation between F and Marshal stability, dynamic stability and stiffness modulus (Busang and Maina, 2022)

6.4.4 Complex Poisson's ratio

This study generated the complex Poisson's ratio's master curves using the complex modulus test. Figure 6-15 depicts the change in frequency and temperature significantly influencing the complex Poisson's ratio norm. Several studies found similar observations; results from the norm of the complex Poisson's ratio showed a clear, dynamic dependency on the frequency and temperature (Pouget *et al.*, 2011; Graziani, Bocci and Canestrari, 2014). At low temperature and high frequency, the value of $|v^*|$ raised by about 0.15, 0.13, and 0.125 for GD 1, GD 2, and GD 3, respectively. At high temperature and low-frequency values of ϕ_v are raised with 0.45, 0.4 and 0.35 for GD 1, GD 2, and GD 3, respectively. It can be seen that the phase angles are very small and, to an extent, negative (except for only a few angles at high temperature). It can be seen that GD 1 samples had a better complex Poisson's ratio, followed by GD 2 and GD 3 been the lowest among the three types of samples, which suggest that the higher the aggregate contact, the higher the stiffness modulus. Both GD 1 and GD 2 are granite aggregate samples, but GD 1 has higher strength, contact point number, and better F than GD 2. This indicates that aggregate strength and shape can influence the nature of different rock sources and the environment.



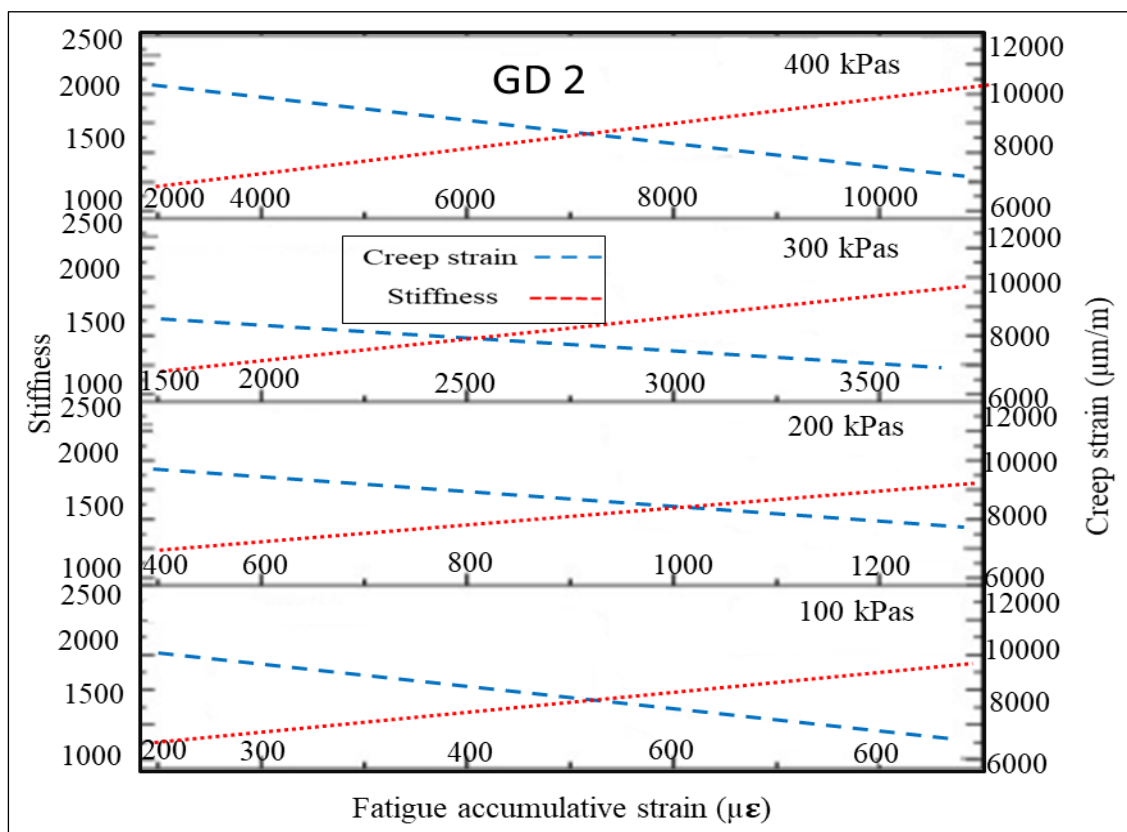
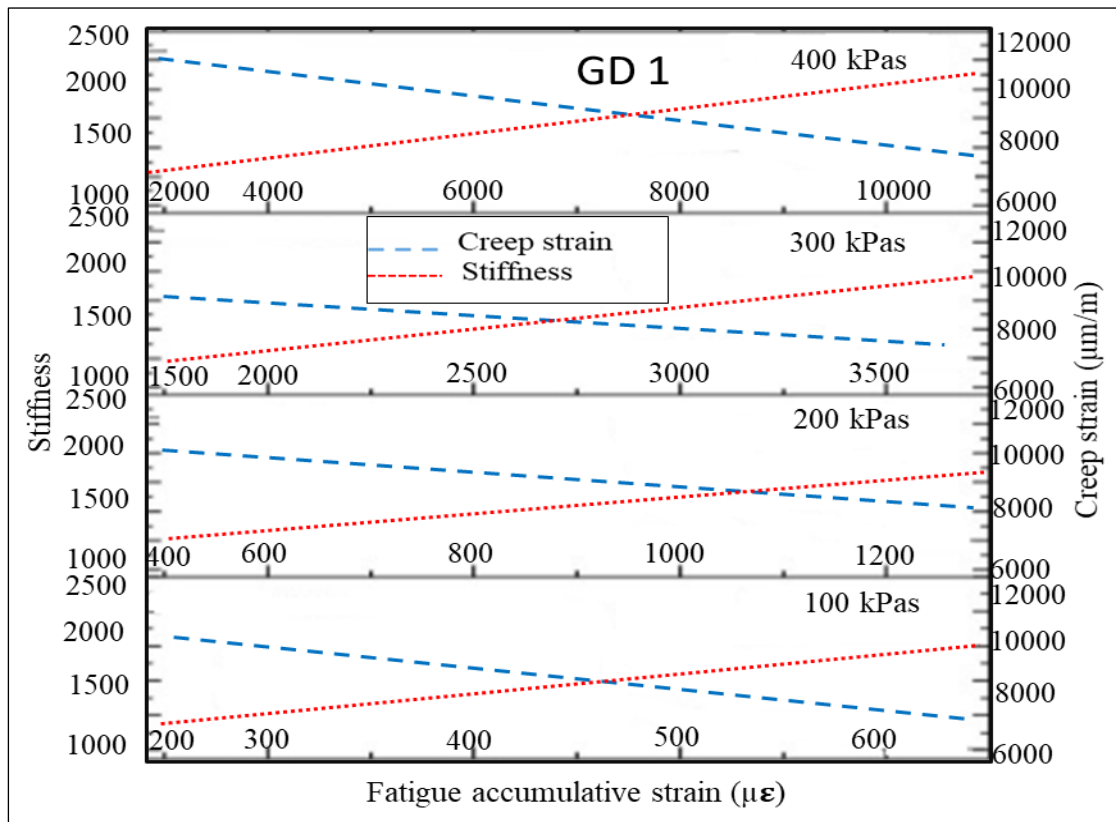
Figures. 6-15: Master curves of the complex Poisson's ratio of GD 1, GD 2 and GD 3 asphalt (a) mixtures for norm and (b) phase angle (Busang and Maina, 2022)

Poisson's ratio parameter is always assumed to be constant in pavement engineering; this assumption always causes some errors because the parameter plays a good role performance of civil engineering structure. Pouget *et al.* (2012) performed a simulation to analyse the effect of time-frequency reliant on linear viscoelastic Poisson ratio. The results indicated that the behaviour of the orthotropic steel bridge has some variation. Figures. 6-15a and 6-15b, with the master curves such as a norm and phase angle, depict evidence of the time-temperature superposition principle (TTSP) on the complex Poisson's ratio. In this study, the identical alteration factors a_T was utilised used to generate the complex modulus and the complex Poisson's ratio's master curves. Several researchers to the same conclusion (Graziani, Bocci and Canestrari, 2014; Cedri, 2015; Ce *et al.*, 2016). Granite has the highest pozzolanic elements such as Al_2O_3 and SiO_2 to enhance the adhesion strength between aggregate and bitumen bonds. On the other hand to granite has a lower CaO chemical composition than limestone, reducing bitumen stiffness. Thus, an indication that when low CaO content and high Al_2O_3 and SiO_2 are combined, it leads to increased bitumen softening, henceforth improving aggregate coating during the mixing procedure.

6.4.4.1 Fatigue accumulative

The study applied the stress of 100 kPa, 200 kPa, 300 kPa, and 400 kPa to evaluate the fatigue accumulated strain against creep permanent strain and stiffness modulus, as shown in Figures. 16a, 16b and 16c for GD 1, GD 2 and GD 3, respectively. It very well may be seen that the weakness amassed strain of the samples leads to a close connection with the creep permanent of the mixes. These results are consistent with the results from dynamic stability

because GD 1 always show the highest stiffness modulus, followed by GD 2 and GD 3 as the least. GD 1 has high contact point weight, thus higher weight contact followed by GD 2 and GD 3.



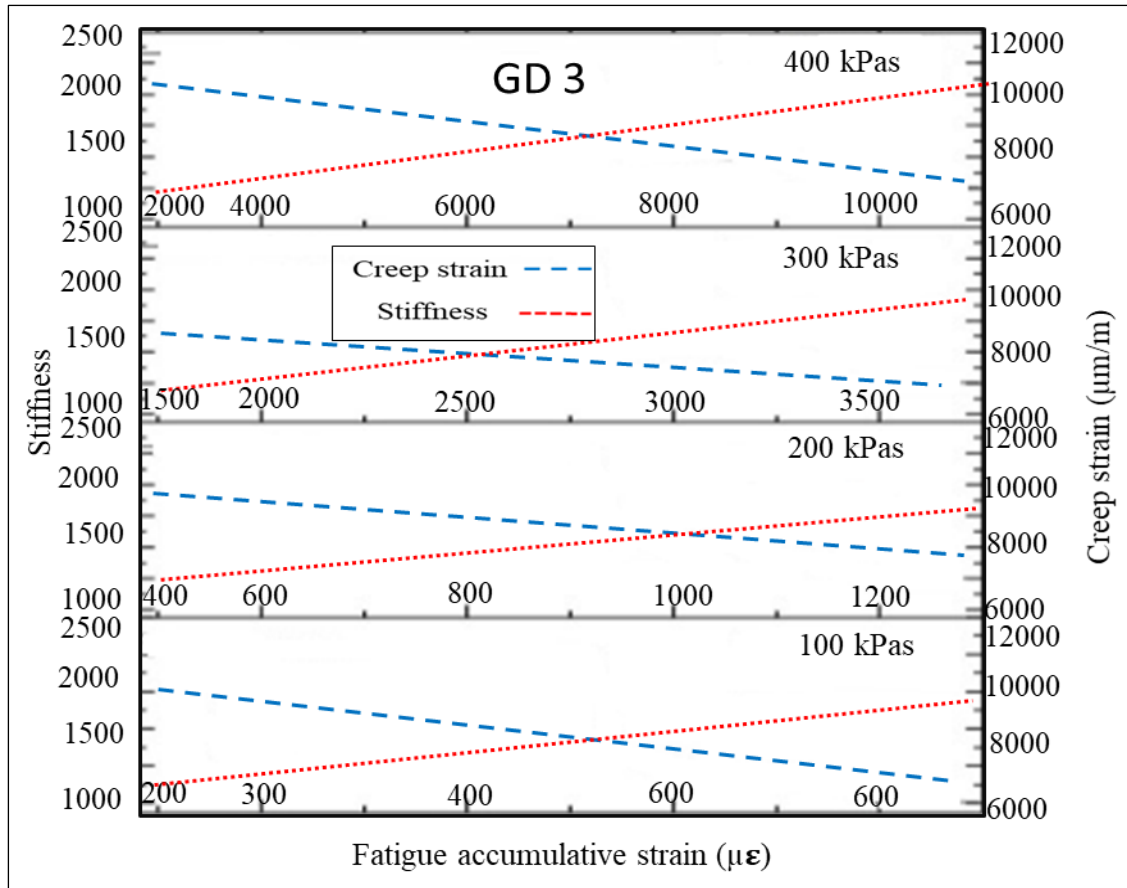


Figure 6-16: Correlation between fatigue accumulative strain with stiffness modulus and creep strain for (a) GD 1, (b) GD 2 and (c) GD

The results showed that the fatigue accumulated strain of the samples resulted in a correlation with the creep strain of the mixes. In contrast, an inverse correlation was obtained between the fatigue and stiffness properties. The results have shown that the less fatigue accumulated strain due by granite provided a decreased creep strain of the GD 1 and increased the stiffness properties. GD 3 asphalt mixture has higher accumulative fatigue and low creep modulus than GD 1 and GD 2 asphalt mixture. Granite with lower accumulative micro-strain leads to higher creep modulus, indicating low rutting potential. The results indicate a correlation of higher stability and lower flow of GD 1 and GD 2 compared to GD 3, as granite is mainly composed of SiO_2 , Al_2O_3 , K_2O , and a small amount of CaO , which is a similar composition to Portland cement.

6.4.5 Grey relational grade

In order to statistically analyse the influence of physical and chemical properties of aggregate on the microstructural properties and mechanical performance, the Grey relational grade analysed to closer to one (1); or else, the grey relational grade will be analysed closer to

zero (0). Chemical compositions such as SiO_2 , Al_2O_3 , K_2O , and CaO , strength property of aggregate including CV and LAA, daily temperature variation and mechanical properties such as Marshall stability, dynamic stability, bending point beam at different temperatures and complex Poisson ratio were incorporated for the grey relational analysis. Table 6-5, Table 6-6 and Table 6-7 present data normalisation and Grey relational coefficients, respectively and grey relational grade, respectively. Results indicate that GD 1 and GD 2 have the highest values of Grey relational coefficients, equivalent to 1, and the least was GD 3 in all of the microstructure and mechanical performance indices, therefore suggesting that granites are granites have a good mechanical performance. The results showed that SiO_2 , Al_2O_3 , K_2O , and a small amount of CaO significantly influence the shape and strength. The aggregate structure will affect the surface roughness, which will affect adhesion to bitumen. GD 1 is ranked 1, indicating excellent performance led by its roughest texture and cubical shape with many contacts points and longer contact line length. Consequently, high contact normal fabric tensors led to high stability. GD 2 as granite is ranked 2 because of its similar chemical and physical properties but a little bit less GD 1. GD 3 showed the least ranking.

Table 6-5: Data normalization

Material	Chemical composition				Strength		Microstructural properties		Environmental condition	Mechanical properties				
	Na2O	K2O	CaO	SiO2	C.V	LAA	N_c	F	DT	MS	DS	BP 0°C	BP 0°C	CPR
GD 1	0.335	0.335	0.212	0.315	0.079	0.098	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
GD 2	0.014	0.021	0.318	0.300	0.065	0.034	0.900	1.000	1.000	1.000	1.000	1.000	1.000	1.000
GD 3	0.190	0.080	0.200	0.280	0.035	0.200	0.430	0.100	0.027	0.080	0.100	0.010	0.042	0.150

Note DT = Daily temperature variation, MS = Marshall Stability, DS = Dynamic stability, BP = Bending point, CPR = Complex Poisson ratio

Table 6-6: Grey relational coefficient

Material	Chemical composition				Strength		Microstructural properties		Environmental condition	Mechanical properties				
	Na2O	K2O	CaO	SiO2	C.V	LAA	N_c	F	DT	MS	DS	BP 0°C	BP 0°C	CPR
GD 1	0.126	0.144	0.014	0.098	0.388	0.365	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
GD 2	0.098	0.122	0.111	0.212	0.245	0.314	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
GD 3	0.100	0.010	0.000	0.167	0.000	0.234	0.356	0.467	0.366	0.370	0.350	0.334	0.343	0.340

Table 6-7: Grey relational degree

Grey relational analysis	GD 1	GD 2	GD 3
Chemical composition – strength	0.721	0.691	0.512
Chemical composition - microstructural properties	0.700	0.646	0.536
Chemical composition - mechanical properties	0.647	0.613	0.582
Strength - microstructural properties	0.564	0.501	0.453
Microstructural properties - mechanical properties	0.556	0.510	0.467
Chemical composition and strength -microstructural properties	0.819	0.723	0.634
Chemical composition and strength -mechanical properties	0.855	0.656	0.600
Ranking	1	2	3

6.5 The significance of the research and contribution to the body of knowledge

The study describes the factors that affect the asphalt mixture's microstructural properties and mechanical performance. An excellent gradation with good strength aggregate morphology and quality binder significantly affect the microstructural properties, which affects the mechanical performance of asphalt pavements. The permanent deformation of asphalt mixtures in the top layers of pavement can contribute substantially to rutting. Many factors were shown to significantly affect the asphalt mixture and decrease the resistance to permanent deformation. Aggregate particle orientations should withstand the repeated traffic load since they are the highest asphalt mixture. Binder properties contribute to the resistance to fatigue at low temperatures and rutting at high temperatures.

This study introduced a model incorporating aggregate shape, morphology, strength, fraction densities and IC amount using DEM utilising the PFC3D software to develop a robust aggregates gradation and packing. The scan line approach was introduced to the asphalt technology to determine the anisotropy of virtual samples based on fabric tensors to measure porosity. The study used TK fibre as an alternative material to improve rutting factor, percentage recovery, creep compliance and penetration point. Additionally, the normal contact fabric tensor was developed to evaluate aggregate interlocking in asphalt mixtures, and the correlation with the mechanical performance was performed. The higher amount of silicon and aluminium in aggregate, the better the aggregate texture and the high contact points weight. In addition, high contact points weight has a notable impact on the Marshall stability, rutting depth, dynamic stability, stiffness modulus and complex Poisson's ratio at high and low temperatures.

The significance of the study is that it optimises the microstructural properties to enhance the mechanical performance of the asphalt mixture. MATLAB coupled with PFC3D software can be used to create realistic aggregate shapes. Several factors affecting gradation incorporated for Gradation using PFC3D and a scan line method can be used to evaluate the anisotropy of the aggregate skeleton, for example, void scan line and normal contact fabric tensors. iPAS software (Image Processing Analysis System) based on DIP is an alternative approach that can use microstructural properties such as contact properties, orientation and distribution of aggregate. The normal contact fabric tensors can be created using iPAS and correlated to mechanical properties to evaluate the ISS.

CHAPTER 7: CONCLUSIONS

7 CONCLUSIONS AND RECOMMENDATIONS

The main conclusions of this thesis are summarised per objective as follows:

7.1 Numerical modelling of anisotropy of microstructural properties asphalt

- Parameters that influence the microstructure stability, such as aggregate size fraction range, shape percentage, dominant aggregate size range (DASR), aggregate densities, and destructive factor (DF), were successfully optimised for all gradations scopes based on DEM using PFC3D.
- DEM analysis using the scan line approach can easily characterise the anisotropy microstructural properties of the aggregate skeleton, including normal contact fabric. There is a linear correlation between normal contact and void fabric evolution.
- The fabric tensor presented in this study is another approach that can be used to ensure packing efficiency in aggregate gradation
- A scan line approach can be used as an alternative approach to analysing the void phase of microstructure

7.2 Rheological properties of TK fibre modified bitumen mastic

- TK fibres can significantly improve bitumen mastic penetration point. TK 1 showed the greatest decrease in penetration and thermal conductivity. This indicates improved bitumen stiffness, mainly at high temperatures, which is beneficial to mastic strength. Decrease penetration point could lead to reduced drain down and permanent deformation of asphalt mixture.
- The rutting parameters increased significantly with the increase in fibre content at moderate and high temperatures. This indicates that the addition of fibres may lead to improved rutting resistance of asphalt mixtures.
- At all stress levels, salt concentrations, and soaking duration, samples modified with TK fibres exhibited lower shear strain values than the base bitumens. The addition of 2% TK fibres gave the best results.

- The bitumens modified with TK fibres had better performance under the action of salt as compared to the base bitumens but showed an increase in shear strain, reduction in percent recovery and increased in non-recoverable creep compliance under the action of salt.
- At the stress level 0.5 kPa, the value of non-recoverable creep compliance of base bitumen was negative. The addition of salt leads to high non-recoverable creep compliance due to the transition from the viscous phase to the glassy state. The glassy state can lead to loss of adhesion between aggregate and bitumens.
- The addition of 1.5 and 2% TK fibres had a positive value of non-recoverable creep compliance throughout the testing showing that they can be used to improve the performance of asphalt mixtures under the action of salt.
- TK1 showed the best results throughout the study, meaning the 13 mm length of TK fibre is more suitable for reinforcing bituminous binder and would be recommended for use in semi-arid areas at an optimum content of 2% TK fibres

7.3 Influence of aggregate properties on microstructure properties and mechanical properties

- GD 1 has the highest amount of silicon and aluminium; hence the good compaction and highest strength, followed by GD 2, and the least was GD 3.
- A well compacted and high-strength aggregate rock increased the contact points weight for the aggregate particles, whereas surface texture increased friction and enhanced the interlocking of the aggregate particles. A reasonable amount of silicon and aluminium in the filler provided a high amount of pozzolan, thus strengthening the mastic strength.
- There are close linear relationships between shape properties and microstructural properties, which indicate that shape has a great influence on the performance of asphalt mixture. G1 had a high angular shape and makes excellent interlocking between aggregate particles, subsequent in an excellent mechanical performance of asphalt mixture.
- The contact weight of aggregate particles influences the microstructural properties of the asphalt mixture. Deformation of the asphalt mixture due to loading becomes less when the loading direction is near the aggregate contact plane orientation.

- High angularity of aggregate provide a better Marshall stability, rutting depth, dynamic stability, and stiffness modulus at high and low temperatures. All samples presented excellent mechanical performance at all temperatures because of the increased contact weight of the aggregate particles.
- GD 1 presented a higher grey relational grade value then GD 2 and GD 3 indicating that Granite had excellent mechanical performance based on the chemical properties and shape parameters

7.4 Remarks and recommendations

The fabric tensor presented in this study is another approach that can evaluate the packing of aggregate in asphalt mixtures. The study established that aggregate contact properties directly influence the Marshall, rutting, and bending stiffness modulus for both low- and high-temperature performance of asphalt mixtures. The results for F are consistent with for aggregate contact point number results. Therefore, F can also be used to evaluate the internal structural index.

In this study, the MSCR test was found to be suitable for investigating the performance of fibre modified bitumen mastics under the influence of salt solutions. The performance of these bitumens could indicate how they would perform in asphalt mixtures to help prevent blistering caused by salt in moisture from underlying layers.

This investigation established that adding TK fibre to bitumen enhanced its toughness, which could improve asphalt fatigue performance, with the optimum level of TK fibres being 2% by mass of bitumen

7.5 Future works

DEM using PFC3D can be used to understand the anisotropy of underlying layers such as base course, sub base and road bed.

The microstructure analysis was based on the influence of contact phase of aggregate to the performance of asphalt mixture based on normal contact fabric tensors. The future studies can extended the fabric tensors to analysis microstructure by focusing on magnitude of solid phase (aggregate magnitudes).

REFERENCES

- Abiola, O. (2014) ‘Utilisation of natural fibre as modifier in bituminous mixes : A review’, *Construction and Building Materials*, 54, pp. 305–312. doi: 10.1016/j.conbuildmat.2013.12.037.
- Abo-Qudais, S. and Al-Shweily, H. (2007) ‘Effect of aggregate properties on asphalt mixtures stripping and creep behavior’, *Construction and Building Materials*, 21(9), pp. 1886–1898. doi: 10.1016/j.conbuildmat.2005.07.014.
- Abu Al-Rub, R. K. *et al.* (2012) ‘Comparing finite element and constitutive modelling techniques for predicting rutting of asphalt pavements’, *International Journal of Pavement Engineering*, 13(4), pp. 322–338. doi: 10.1080/10298436.2011.566613.
- Adhikari, S. and You, Z. (2010) ‘3D discrete element models of the hollow cylindrical asphalt concrete specimens subject to the internal pressure’, 8436(May). doi: 10.1080/10298436.2010.489114.
- Ahmad Nazki, M., Chopra, T. and Chandrappa, A. K. (2020) ‘Rheological properties and thermal conductivity of bitumen binders modified with graphene’, *Construction and Building Materials*, 238, p. 117693. doi: 10.1016/j.conbuildmat.2019.117693.
- Airey, G. D. (1997) ‘Airey , Gordon Dan (1997) Rheological characteristics of polymer modified and aged bitumens . PhD thesis , University of Nottingham .’, *Thesis*.
- Airey, G. D. (2002) ‘Use of Black Diagrams to Identify Inconsistencies in Rheological Data’, *Road Materials and Pavement Design*, 3(4), pp. 403–424. doi: 10.1080/14680629.2002.9689933.
- Airey, G. D. (2003) ‘Rheological properties of styrene butadiene styrene polymer modified road bitumens q’, 82, pp. 1709–1719. doi: 10.1016/S0016-2361(03)00146-7.
- Airey, G. D. *et al.* (2008) ‘The influence of aggregate, filler and bitumen on asphalt mixture moisture damage’, *Construction and Building Materials*, 22(9), pp. 2015–2024. doi: 10.1016/j.conbuildmat.2007.07.009.
- Al-qadi, I. L., Xie, W. and Elseifi, M. A. (2008) ‘Frequency Determination from Vehicular Loading Time’, *Journal of the Association of Asphalt Paving Technologists*, 77, pp. 739–772.
- American concrete institute 544 (1976) *Status Report on Fiber Reinforced Concretes., Concrete Construction - World of Concrete.*

Apeagyei, A. K., Grenfell, J. R. A. and Airey, G. D. (2014) 'Moisture-induced strength degradation of aggregate-asphalt mastic bonds', *Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions*, 83(January), pp. 549–582. doi: 10.1080/14680629.2014.927951.

Arafat, S. *et al.* (2019) 'Sustainable lignin to enhance asphalt binder oxidative aging properties and mix properties', *Journal of Cleaner Production*, 217, pp. 456–468. doi: 10.1016/j.jclepro.2019.01.238.

Arambula, E. (2007) 'Influence of fundamental material properties and air void structure on moisture damage of asphalt mixes', *Thesis, Doctor of Philosophy in Civil engineering, Texas A&M University*, (January).

'American Society for Testing and Materials (2010) 'ASTM D6926: Standard practice for preparation of bituminous specimens using Marshall apparatus,' Washington, DC. p. 6926

American Society for Testing and Materials (2015) 'ASTM D6927 - Standard test method for Marshall stability and flow of asphalt mixtures,' Washington, DC

Batista, K. B. *et al.* (2018) 'High-temperature, low-temperature and weathering aging performance of lignin modified asphalt binders', *Industrial Crops and Products*, 111(April 2017), pp. 107–116. doi: 10.1016/j.indcrop.2017.10.010.

Bear J & Y. Bachmat Y 1990. Introduction to Modeling of Transport Phenomena in Porous Media. xxiv 553 pp. Dordrecht, Boston, London: Kluwer. Price Dfl. 340, US \$198, £124 (hard covers). ISBN 0 7923 0557 4. Geological Magazine, 129(3), 373-374. doi:10.1017/S0016756800019336

Bear, J. (1972) 'Dynamics of Fluids in Porous Media', American Elsevier Publishing Company, New York.

Behbahani (2007) 'Effect of fiber type and content on the rutting performance of stone matrix asphalt', pp. 708–715.

Behbahani, H., Nowbakht, S., Fazaeli, H. and Rahmani, J. (2009) 'Effects of Fiber Type and Content on the Rutting Performance of Stone Matrix Asphalt.' *Journal of Applied Sciences*, 9: doi: 10.3923/jas.2009.1980.1984

Bell, N., Yu, Y. and Mucha, P. J. (2005) 'Particle-based simulation of granular materials', *Computer Animation, Conference Proceedings*, (January 2005), pp. 77–86. doi: 10.1145/1073368.1073379.

Bellatrache, Y. *et al.* (2020) 'Effects of the addition of date palm fibers on the physical, rheological and thermal properties of bitumen', *Construction and Building Materials*, 239, p. 117808. doi: 10.1016/j.conbuildmat.2019.117808.

Bengtsson, M. and Evertsson, C. M. (2006) ‘Measuring characteristics of aggregate material from vertical shaft impact crushers’, *Minerals Engineering*, 19(15), pp. 1479–1486. doi: 10.1016/j.mineng.2006.08.003.

Bijwe, J. (1997) ‘Composites as friction materials: Recent developments in non-asbestos fiber reinforced friction materials - A review’, *Polymer Composites*, 18(3), pp. 378–396. doi: 10.1002/pc.10289.

Blow, J. and Binstock, A. J. (2004) ‘How to find the inertia tensor (or other mass properties) of a 3D solid body represented by a triangle mesh’, url: <http://number-none.com/blow/inertia/index.html>, .

Boger, F. *et al.* (1992) ‘Microstructural sensitivity of local porosity distributions’, *Physica A: Statistical Mechanics and its Applications*, 187(1–2), pp. 55–70. doi: 10.1016/0378-4371(92)90408-I.

Bradford, J. M. (1976) ‘Fundamentals of Soil Behavior’, *Soil Science Society of America Journal*, p. iv. doi: 10.2136/sssaj1976.03615995004000040003x.

Britannica, E. (2021) ‘Britannica, The Editors of Encyclopaedia. “Roman road system”.Encyclopedia Britannica, 3 Apr. 2018, <https://www.britannica.com/technology/Roman-road-system..>

Brown, A.B. & Sparks, J.W. 1958. Viscoelastic properties of a penetration grade paving asphalt at winter temperatures. Proceedings, Association of Asphalt Paving Technologists 27: 35–51

Burland, J. B. (1970) ‘On the generalized stress-strain behavior of “wet” clay’, *Journal of Terramechanics*, 7(2), pp. 107–108. doi: 10.1016/0022-4898(70)90160-6.

Busang, S. and Maina, J. (2021) ‘Laboratory simulation and mechanical performance of asphalt materials under the action of saline’, *Construction and Building Materials*, 313(October), p. 125387. doi: 10.1016/j.conbuildmat.2021.125387.

Busang, S. and Maina, J. (2022) ‘Influence of aggregates properties on microstructural properties and mechanical performance of asphalt mixtures’, *Construction and Building Materials*, 318(December 2021), p. 126002. doi: 10.1016/j.conbuildmat.2021.126002.

Cai, X. *et al.* (2017) ‘Evaluation of Rutting Performance of Asphalt Mixture with Driving Wheel Pavement Analyzer’, *Advances in Materials Science and Engineering*, .

Cai, X. *et al.* (2018) ‘Study on the correlation between aggregate skeleton characteristics and rutting performance of asphalt mixture’, *Construction and Building Materials journal*, 179, pp. 294–301. doi: 10.1016/j.conbuildmat.2018.05.153.

Candy, I. (2002) ‘Formation of a rhizogenic calcrete during a glacial stage (Oxygen

Isotope Stage 12): Its palaeoenvironmental stratigraphic significance', *Proceedings of the Geologists' Association*, 113(3), pp. 259–270. doi: 10.1016/S0016-7878(02)80028-1.

Castro, M. and Sánchez, J. A. (2006) 'Fatigue and healing of asphalt mixtures: Discriminate analysis of fatigue curves', *Journal of Transportation Engineering*, 132(2), pp. 168–174. doi: 10.1061/(ASCE)0733-947X(2006)132:2(168).

Perraton D. *et al.* (2016) '3Dim experimental investigation of linear viscoelastic properties of bituminous mixtures', pp. 4813–4829. doi: 10.1617/s11527-016-0827-3.

Nguyen Q.T., Benedetto D.H. and Sauze C. (2015) 'Linear and nonlinear viscoelastic behaviour of bituminous mixtures', *Materials and Structures*, pp. 2339–2351. doi: 10.1617/s11527-014-0316-5.

Celauro, C. and Praticò, F. G. (2018) 'Asphalt mixtures modified with basalt fibres for surface courses', *Construction and Building Materials*, 170, pp. 245–253. doi: 10.1016/j.conbuildmat.2018.03.058.

Chatzis, I. and Dullien, F. A. L. (2014) 'Modelling Pore Structure By 2- D and 3- D Networks With Application To Sandstones', *Journal of Canadian Petroleum Technology*, (January 1977). doi: 10.2118/77-01-09.

Chen, H. *et al.* (2009) 'Evaluation and design of fiber-reinforced asphalt mixtures', *Materials and Design*, 30(7), pp. 2595–2603. doi: 10.1016/j.matdes.2008.09.030.

Chen, J.-S., Chang, M. and Lin, K. (2005) 'Influence of Coarse Aggregate Shape on the Strength of Asphalt Concrete Mixtures', *Journal of the Eastern Asia Society for Transportation Studies*, 6, pp. 1062–1075. doi: 10.11175/easts.6.1062.

Chen, J. *et al.* (2015) 'Evaluation of thermal conductivity of asphalt concrete with heterogeneous microstructure', *Applied Thermal Engineering*, 84, pp. 368–374. doi: 10.1016/j.applthermaleng.2015.03.070.

Chen, J., Huang, B. and Shu, X. (2013) 'Air-Void Distribution Analysis of Asphalt Mixture Using Discrete Element Method', *Journal of Materials in Civil Engineering*, 25(10), pp. 1375–1385. doi: 10.1061/(asce)mt.1943-5533.0000661.

Chen, J. S. and Lin, K. Y. (2005) 'Mechanism and behavior of bitumen strength reinforcement using fibers', *Journal of Materials Science*, 40(1), pp. 87–95. doi: 10.1007/s10853-005-5691-4.

Cheng, Y. *et al.* (2015) 'Influence of diatomite and mineral powder on thermal oxidative ageing properties of asphalt', *Advances in Materials Science and Engineering*, 2015. doi: 10.1155/2015/947834.

Cherry, R. A., and Freeze, J. A. (1979) 'Groundwater, Englewood Cliffs, NJ: Prentice

Hall.’

Cheung, C. Y. and Cebon, D. (1997a) ‘Deformation Mechanisms of Pure Bitumen’, *Journal of Materials in Civil Engineering*, 9(3), pp. 117–129. doi: 10.1061/(asce)0899-1561(1997)9:3(117).

Cheung, C. Y. and Cebon, D. (1997) ‘Experimental study of pure bitumens in tension, compression, and shear’, *Journal of Rheology*, 41, pp. 45–74. <https://doi.org/10.1122/1.550858>

Cheung, C. Y. and Cebon, D. (1997b) ‘Thin Film Deformation Behavior of Power-Law Creeping Materials’, *Journal of Engineering Mechanics*, 123(11), pp. 1138–1152. doi: 10.1061/(asce)0733-9399(1997)123:11(1138).

Christy, C. and Tensing, D. (2010) ‘Greener building material with flyash’, *Asian Journal of Civil Engineering*, 12(1), pp. 87–105.

Chun, S. et al. (2012) ‘Predictive relationships for HMA fracture properties based on mixture component characteristics’, *Road Materials and Pavement Design*, 13(Suppl. 1), pp. 140–160. doi: 10.1080/14680629.2012.657039.

Ciolacu .D., Ciolacu. F* and Popa V.I (2011) ‘Amorphous cellulose – structure and characterization’, *cellulose chemistry and technology amorphous*, 45, pp. 606–614.

Coenen, A. R. et al. (2012) ‘Aggregate structure characterisation of asphalt mixtures using two-dimensional image analysis’, *Road Materials and Pavement Design*, 13(3), pp. 433–454. doi: 10.1080/14680629.2012.711923.

Shell Pavement Design Manual (1978): Asphalt Pavements and Overlays for Road Traffic. Shell International Petroleum Company. Available at: <https://books.google.co.bw/books ID:YXOLbwAACAAJ>.

Consolmagno, G. J., Britt, D. T. and Macke, R. J. (2008) ‘The significance of meteorite density and porosity’, *Chemie der Erde*, 68(1), pp. 1–29. doi: 10.1016/j.chemer.2008.01.003.

Cooley, L.A., Brown, E. R. and Watson, D. E. (2000) ‘Evaluation of open-graded friction course mixtures containing cellulose fibers’, *Transportation Research Record*, (1723), pp. 19–25. doi: 10.3141/1723-03.

Cooley, L. A. et al. (2002) ‘Issues pertaining to the permeability characteristics of coarse-graded superpave mixes’, *Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions*, 71(July), pp. 1–29.

Croll, J. G. A. (2008) ‘A new hypothesis for the development of blisters in asphalt pavements’, *International Journal of Pavement Engineering*, 9(1), pp. 59–67. doi: 10.1080/10298430701204736.

Cui, S. *et al.* (2014) ‘Durability of asphalt mixtures: Effect of aggregate type and adhesion promoters’, *International Journal of Adhesion and Adhesives*, 54, pp. 100–111. doi: 10.1016/j.ijadhadh.2014.05.009.

D’Angelo, J. A. (2009) ‘The relationship of the MSCR test to rutting’, *Road Materials and Pavement Design*, 10(SPECIAL ISSUE), pp. 61–80. doi: 10.3166/RMPD.10HS.61-80.

Dai, L. *et al.* (2014) ‘Influence of temperature , pressure , and chemical composition on the electrical conductivity of granite’, *American Mineralogist, GeoScienceWorld*, 99(7), pp. 1420–1428.

Delgadillo, R., Nam, K. and Bahia, H. (2006) ‘Why do we need to change $g^*/\sin\delta$ and how?’, *Road Materials and Pavement Design*, 7(1), pp. 7–27. doi: 10.1080/14680629.2006.9690024.

Denneman, E., Verhaeghe, B. M. J. A. and Sadzik, E. S. (2007) ‘Aggregate packing characteristics of good and poor performing asphalt mixes’, *SATC 2007 - 26th Annual Southern African Transport Conference: The Challenges of Implementing Policy*, (July), pp. 213–224.

Dill, H. G. *et al.* (2014) ‘Provenance analysis and thermo-dynamic studies of multi-type Holocene duricrusts (1700 BC) in the Sua Salt Pan, NE Botswana’, *Journal of African Earth Sciences*, 96, pp. 79–98. doi: 10.1016/j.jafrearsci.2014.03.014.

Diógenes, L. *et al.* (2021) ‘The influence of crushing processes and mineralogy of aggregates on their shape properties and susceptibility to degradation’, *Construction and Building Materials*, 284. doi: 10.1016/j.conbuildmat.2021.122745.

Drucker, D. C. and Prager. W. (2013) ‘Soil mechanics and plastic analysis for limit design’, *Theoretical soil mechanics*, John Wiley and Sons, 2, pp. 157–165.

Dukatz, E. . (1989) ‘Aggregate Properties Related to Pavement Performance’, *Proceedings of Association of Asphalt Paving Technologist*, 10(3), pp. 492–502.

Dullien, F. A. L. (1979) ‘Porous media: fluid transport and pore structure.’

Dunhill, S. T. (2002) ‘Quasi-static characterisation of asphalt mixtures’, *Thesis, Doctor of Philosophy in Civil engineering*. Available at: <http://etheses.nottingham.ac.uk/1898/> University of Nottingham.

Elnasri, M. M. H. (2015) ‘From binder to mixture: experimental programme on permanent deformation behaviour’, *PQDT - UK & Ireland*, Ph.D, University of Nottingham.

Elshaer, M. and Daniel, J. S. (2018) ‘Impact of pavement layer properties on the structural performance of inundated flexible pavements’, *Transportation Geotechnics*, 16(March), pp. 11–20. doi: 10.1016/j.trgeo.2018.06.002.

EN 1427 (2015) 'Bitumen and bituminous binders — Determination of the softening point — Ring and Ball method', 3, p. 18.

European Committee for Standardisation (2018) 'BS EN 13302:2018 Bitumen and bituminous binders - Determination of dynamic viscosity of bituminous binder using a rotating spindle apparatus', British Standards Institution, London, UK, 2018.

'European Committee and British Standard (2007), 1426: Bitumen and bituminous binders—determination of needle penetration, British Standards..

Fakhri, M. and Hosseini, S. A. (2017) 'Laboratory evaluation of rutting and moisture damage resistance of glass fiber modified warm mix asphalt incorporating high RAP proportion', *Construction and Building Materials*, 134, pp. 626–640. doi: 10.1016/j.conbuildmat.2016.12.168.

Fu, P. and Dafalias, Y. F. (2015) 'Relationship between void- and contact normal-based fabric tensors for 2D idealized granular materials', *International Journal of Solids and Structures*, 63, pp. 68–81. doi: 10.1016/j.ijsolstr.2015.02.041.

Fung, W. W. S. and Kwan, A. K. H. (2014) 'Effect of particle interlock on flow of aggregate through opening', *Powder Technology*, 253, pp. 198–206. doi: 10.1016/j.powtec.2013.11.024.

Valdes-Vidal G., Calabi-Floody A and Sanchez-Alonso, E. R. M. (2019) 'Effect of aggregate type on the fatigue durability of asphalt mixtures', *Construction and Building Materials journal*, 224(124–131), pp. 1–20.

Gao, J. *et al.* (2018) 'Effects of coarse aggregate angularity on the microstructure of asphalt mixture', *Construction and Building Materials*, 183, pp. 472–484. doi: 10.1016/j.conbuildmat.2018.06.170.

Gao, J. *et al.* (2020) 'Influence of Coarse-Aggregate Angularity on Asphalt Mixture Macroperformance : Skid Resistance , High-Temperature , and Compaction Performance', *American Society of Civil Engineers*, 32(2011), pp. 1–11. doi: 10.1061/(ASCE)MT.1943-5533.0003125.

Gao, Y. *et al.* (2012) 'Calculating the Anisotropic Permeability of Porous Media Using the Lattice Boltzmann Method and X-ray Computed Tomography', *Transport in Porous Media*, 92(2), pp. 457–472. doi: 10.1007/s11242-011-9914-7.

Gao, Z. and Zhao, J. (2015) 'Constitutive Modeling of Anisotropic Sand Behavior in Monotonic and Cyclic Loading', *Journal of Engineering Mechanics*, 141(8), p. 04015017. doi: 10.1061/(asce)em.1943-7889.0000907.

Ge, H. *et al.* (2018) 'Three-dimensional characterization of morphology and abrasion

decay laws for coarse aggregates', *Construction and Building Materials*, 188, pp. 58–67. doi: 10.1016/j.conbuildmat.2018.08.110.

Ghedia, R. and Sullivan, C. O. (2012) 'Quantifying void fabric using a scan-line approach', *Computers and Geotechnics*, 41, pp. 1–12. doi: 10.1016/j.compgeo.2011.10.008.

Gibb, J. M. (1996) *Evaluation of resistance to permanent deformation in the design of bituminous paving mixtures*. University of Nottingham.

Golalipour, A. et al. (2012) 'Effect of Aggregate Gradation on Rutting of Asphalt Pavements', *Procedia - Social and Behavioral Sciences*, 53, pp. 440–449. doi: 10.1016/j.sbspro.2012.09.895.

Goli, A. et al. (2019) 'Comparison of various rutting parameters and modelling of creep and recovery behaviour of high modulus bituminous binders', *International Journal of Pavement Research and Technology*, 12(6), pp. 648–658. doi: 10.1007/s42947-019-0077-1.

Gong, F. et al. (2018) 'Lab assessment and discrete element modeling of asphalt mixture during compaction with elongated and flat coarse aggregates', *Construction and Building Materials*, 182, pp. 573–579. doi: 10.1016/j.conbuildmat.2018.06.059.

González, A. et al. (2018) 'Self-healing properties of recycled asphalt mixtures containing metal waste: An approach through microwave radiation heating', *Journal of Environmental Management*, 214, pp. 242–251. doi: 10.1016/j.jenvman.2018.03.001.

Government of Botswana (2019) 'Botswana Environment Statistics Climate Digest', Report, (March), pp. 1–21.

Graziani, A., Bocci, M. and Canestrari, F. (2014) 'Complex Poisson's ratio of bituminous mixtures: measurement and modeling', *Materials and Structures*, 47, pp. 1131–1148. doi: 10.1617/s11527-013-0117-2.

Greene, J., Chun, S. and Choubane, B. (2014) 'Enhanced gradation guidelines to improve asphalt mixture performance', *Transportation Research Record*, 2456(2456), pp. 3–10. doi: 10.3141/2456-01.

Guarin, A. et al. (2013) 'Disruption factor of asphalt mixtures', *International Journal of Pavement Engineering*, 14(5), pp. 472–485. doi: 10.1080/10298436.2012.727992.

Guo, P. (2012) 'Dependency of Tortuosity and Permeability of Porous Media on Directional Distribution of Pore Voids', pp. 285–303. doi: 10.1007/s11242-012-0043-8.

Guo, Q. et al. (2015) 'Laboratory evaluation on performance of diatomite and glass fiber compound modified asphalt mixture', *Materials and Design*, 66(PA), pp. 51–59. doi: 10.1016/j.matdes.2014.10.033.

Guo, R. and Nian, T. (2020) 'Analysis of factors that influence anti-rutting

performance of asphalt pavement’, *Construction and Building Materials*, 254, p. 119237. doi: 10.1016/j.conbuildmat.2020.119237.

Gyurkó, Z. and Nemes, R. (2018) ‘Discrete Element Modelling of Compressive Strength Testing of No-Fines Concrete www.mdpi.com/journal/proceedings’, in *the 18th International Conference on Experimental Mechanics, MDPI*. doi: 10.3390/ICEM18-05470.

Hainin, M. R, Cooley, L. A., and Prowell, B. D. (2003) ‘An Investigation of Factors Influencing Permeability of SuperPave Mixes. Transportation Research Board. National Center for Asphalt Technology. Auburn, AL’,

Hall, M. (1971) ‘Mechanical Properties of Solid Polymers.’, *British Polymer Journal*, 1012, p. 325.

Hamed, G. H., Sakanlou, F. and Sohrabi, M. (2019) ‘Laboratory investigation of using liquid anti-stripping additives on the performance characteristics of asphalt mixtures’, *International Journal of Pavement Research and Technology*, 12(3), pp. 269–276. doi: 10.1007/s42947-019-0033-0.

Han, D., Yuan, M. and Hu, H. (2021) ‘Establishing prediction master curve of dynamic modulus of asphalt mixture considering randomness of aggregate morphology’, *Construction and Building Materials*, 294, p. 123575. doi: 10.1016/j.conbuildmat.2021.123575.

Wang H *et al.* (2016) ‘Electrical and mechanical properties of asphalt concrete containing conductive fibers and fillers’, *Construction and Building Materials*, 122, pp. 184–190. doi: 10.1016/j.conbuildmat.2016.06.063.

Hassan, A.-M. (2016) *Prediction of permanent deformation in asphalt mixtures. PhD thesis, University of Nottingham*. doi: 10.1186/s12876-018-0767-1.

Hassan, H. M. Z. *et al.* (2021) ‘Study on the influence of aggregate strength and shape on the performance of asphalt mixture’, *Construction and Building Materials*, 294, p. 123599. doi: 10.1016/j.conbuildmat.2021.123599.

Hendriks, A. T. W. M. and Zeeman, G. (2009) ‘Pretreatments to enhance the digestibility of lignocellulosic biomass’, *Bioresource Technology*, 100(1), pp. 10–18. doi: 10.1016/j.biortech.2008.05.027.

Hilfer, R. (2007) ‘Local Porosity Theory and Stochastic Reconstruction for Porous Media’, *Statistical Physics and Spatial Statistics*, pp. 203–241. doi: 10.1007/3-540-45043-2_8.

Hilfer, R., Rage, T. and Virgin, B. (1997) ‘Local percolation probabilities for a natural sandstone’, 241, pp. 105–110.

Hills, J. F. (1973) ‘The Creep of Asphalt Mixes.pdf’, *The journal of the institutes of*

Petroleum, 59(570).

Hofstra, A. and Klop, A. J. G. (1972) 'Permanent deformation of flexible pavements under simulated road traffic conditions', in *Third International Conference on the Structural Design of Asphalt Pavements*.

Horak, E. *et al.* (2017) 'Relationship Between Bailey and Dominant Aggregate Size Range', in *36th Southern African Transport Conference*, pp. 245–263.

Hu, H. (2011) 'The influence of granite microstructure on the properties of pavement material', *2011 International Conference on Electric Technology and Civil Engineering (ICETCE)*, pp. 6311–6314. doi: 10.1109/ICETCE.2011.5774436.

Hu, N. *et al.* (2021) 'On the evolution law of a contact normal-based fabric tensor for granular materials', *Computers and Geotechnics*, 132(February), p. 103857. doi: 10.1016/j.compgeo.2020.103857.

Hu, S., Zhou, F. and Scullion, T. (2011) 'Factors that affect cracking performance in hot-mix asphalt mix design', *Transportation Research Record*, (2210), pp. 37–46. doi: 10.3141/2210-05.

Huang, H. and White, T. D. (1996) 'Dynamic properties of fiber-modified overlay mixture', *Transportation Research Record*, (1545), pp. 98–104. doi: 10.3141/1545-13.

Inglis, D. and Pietruszczak, S. (2003) 'Characterization of anisotropy in porous media by means of linear intercept measurements', *International Journal of Solids and Structures*, 40(5), pp. 1243–1264. doi: 10.1016/S0020-7683(02)00595-4.

The Asphalt Institute. (2007) *The Asphalt Institute*.

Khavassefat P, V. P. (2008) *Vehicle-Pavement Interaction*.

Long, X. R. *et al.* (2011) 'Research on Performance of Asphalt Concrete Under the Action of Freeze - thaw and Corrosion Abstract ', *J. Wuhan Univ. Technol*, 2(33), pp. 72–76.

Ismael, M. Q., Fattah, M. Y. and Jasim, A. F. (2021) 'Improving the rutting resistance of asphalt pavement modified with the carbon nanotubes additive', *Ain Shams Engineering Journal*, 12(4), pp. 3619–3627. doi: 10.1016/j.asej.2021.02.038.

Thermal insulation ISO 8301 (1991): Determination of steady-state thermal resistance and related properties. Heat flow meter apparatus', *International Organization for Standardization*, p. 8301.

Jahromi, S. G. (2015) 'Effect of Carbon Nanofiber on Mechanical Behavior of Asphalt Concrete', *International Journal of Sustainable Construction Engineering & Technology*, 6(2), pp. 57–66.

Jahromi, S. G. and Khodaii, A. (2008) 'Carbon fiber reinforced asphalt concrete',

Arabian Journal for Science and Engineering, 33(2 B), pp. 355–364.

Jamal Khattak, M., Khattab, A. and R. Rizvi, H. (2013) ‘Characterization of carbon nano-fiber modified hot mix asphalt mixtures’, *Construction and Building Materials*, 40, pp. 738–745. doi: 10.1016/j.conbuildmat.2012.11.034.

Ji, J. J. *et al.* (2019) ‘Prevalence of gingival recession after orthodontic treatment of infraversion and open bite’, *Journal of Orofacial Orthopedics*, 80(1), pp. 1–8. doi: 10.1007/s00056-018-0159-8.

Jiang, J. *et al.* (2017) ‘Effect of the contact structure characteristics on rutting performance in asphalt mixtures using 2D imaging analysis’, *Construction and Building Materials*, 136, pp. 426–435. doi: 10.1016/j.conbuildmat.2016.12.210.

Jongepier, R. and Kuilman, B. (1969) ‘Characteristics of the rheology of bitumens’, *Association of Asphalt*, pp. 98–122. Available at: <http://trid.trb.org/view.aspx?id=101204>.

Kandhal, P. S. and. Cooley, L..A. (2001) *The Restricted Zone In The Superpave Aggregate Gradation Specification*.

Khanzada, S. (2000) *Permanent deformation in bituminous mixtures*. The University of Nottingham.

Khodary, F., Hamed, M. and Straßenwesen, F. (2010) *Evaluation of Fatigue Resistance for Modified Asphalt Concrete Mixtures Based on Dissipated Energy Concept*.

Khosla, N. P, and Sadasivam. S. (2005) ‘Determination of Optimum Gradation for Resistance To Permeability , Rutting and Fatigue Cracking’, Final report FHWA/NC/2004-12, North Carolina Department of Transportation.

Kim, J. and Koh, C. (2012) ‘Development of a predictive system for estimating fatigue life of asphalt mixtures using the indirect tensile test’, *Journal of Transportation Engineering*, 138(12), pp. 1530–1540. doi: 10.1061/(ASCE)TE.1943-5436.0000452.

Kim, S. (2006) *Identification and assessment of the dominant aggregate size range of asphalt mixture*, PhD, thesis, University of florida..

Kuang, D. *et al.* (2019) ‘Influence of angularity and roughness of coarse aggregates on asphalt mixture performance’, *Construction and Building Materials*, 200, pp. 681–686. doi: 10.1016/j.conbuildmat.2018.12.176.

Kuhn, M. R. (2003) ‘Heterogeneity and patterning in the quasi-static behavior of granular materials’, *Granular Matter*, 4(4), pp. 155–166. doi: 10.1007/s10035-002-0118-2.

Kuo, C. and Freeman, R. B. (2002) ‘Imaging Indices for Quantification of Shape , Angularity , and Surface Texture of Aggregates’, *Transportation Research Record* 1721, (00–0686), pp. 57–65.

Kutay, M. E. (2005) *Modeling Moisture Transport in Asphalt pavement*, Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, Department of Civil and Environmental Engineering, Doctor of Philosophy.

Kutay, M. E., Aydilek, A. H. and Masad, E. (2007) 'Estimating directional permeability of hot-mix asphalt by numerical simulation of microscale water flow', *Transportation Research Record*, (2001), pp. 29–36. doi: 10.3141/2001-04.

Kwan, A. K. H., Wong, V. and Fung, W. W. S. (2015) 'A 3-parameter packing density model for angular rock aggregate particles', *Powder Technology*, 274, pp. 154–162. doi: 10.1016/j.powtec.2014.12.054.

Laranjeira, P. and Mata, T. M. (2009) *Modeling of transport phenomena in porous media using network*.

Lee, J. and Hogan, C. J. (2021) 'Computational predictions of porosities, pore size distributions, and conductivities of aerosol deposited particulate films', *Powder Technology*, 378, pp. 400–409. doi: 10.1016/j.powtec.2020.09.078.

Li, P. *et al.* (2020) 'Effect of aggregate contact condition on skeleton stability in asphalt mixture', *International Journal of Pavement Engineering*, 8436, pp. 1–7. doi: 10.1080/10298436.2018.1450503.

Li, X. *et al.* (2008) 'Effect of reclaimed asphalt pavement (proportion and type) and binder grade on asphalt mixtures', *Transportation Research Record*, (2051), pp. 90–97. doi: 10.3141/2051-11.

Liu, Y. *et al.* (2009) 'Viscoelastic Model for Discrete Element Simulation of Asphalt Mixtures', 135(4), pp. 324–333. doi: 10.1061/(ASCE)0733-9399(2009)135.

Liu, Y. (2015) *Permeability and pore structure of materials, doctor of philosophy, (Civil Engineering)*, McMaster University Hamilton, Ontario, 2015. Available at: PhD thesis, McMaster University.

Liu, Y. *et al.* (2017) 'Discrete element modeling of realistic particle shapes in stone-based mixtures through MATLAB-based imaging process', *Construction and Building Materials*, 143, pp. 169–178. doi: 10.1016/j.conbuildmat.2017.03.037.

Liu, Y. *et al.* (2020) 'applied sciences Porosity Prediction of Granular Materials through Discrete Element Method and Back Propagation Neural Network Algorithm', *Appl. Sci.* www.mdpi.com/journal/applsci, 10.

Lou, K. *et al.* (2021) 'Experimental study on road performance of basalt fiber reinforced Bitumen mastics', *Construction and Building Materials*, 313(August), p. 125439. doi: 10.1016/j.conbuildmat.2021.125439.

Loulizi, A. *et al.* (2002) 'Measurement of vertical compressive stress pulse in flexible pavements: Representation for dynamic loading tests', *Transportation Research Record*, (1816), pp. 125–136. doi: 10.3141/1816-14.

Lu, Z. *et al.* (2018) 'Field evaluation and analysis of road subgrade dynamic responses under heavy duty vehicle', *International Journal of Pavement Engineering*, 19(12), pp. 1077–1086. doi: 10.1080/10298436.2016.1240560.

Luo, D. *et al.* (2019) 'The performance of asphalt mixtures modified with lignin fiber and glass fiber: A review', *Construction and Building Materials*, 209, pp. 377–387. doi: 10.1016/j.conbuildmat.2019.03.126.

Maggiore, C. (2014) *A comparison of different test and analysis methods for asphalt fatigue*, Phd thesis, University of Nottingham.

Maina, J. W., Ozawa, Y. and Matsui, K. (2009) 'Axi-symmetric analyses of vertically inhomogeneous elastic multilayered systems', - *Proceedings of the 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields*, 1, pp. 561–570. doi: 10.1201/9780203865286.ch61.

Masanobu Oda and Hideo Nakayama (1989) 'Yield function for soil with anisotropic fabric', *ASCE library*, 115(1).

Masanobu Oda, S. N.-N. and J. K. (1985) 'Stress-Induced Anisotropy In Granular Masses', *Soil and foundation. Japanese Society of Soil Mechanics and Foundation Engineering*, 25(No 3), pp. 85–97. doi: 10.3208/sandf1972.25.3.

Mashaan, N. S. *et al.* (2014) 'Evaluation of Fatigue Life of CRM-Reinforced SMA and Its Relationship to Dynamic Stiffness', *The Scientific World Journal*. doi: 10.1155/2014/968075.

McCready, N. S. and Williams, R. C. (2008) 'Utilization of biofuel coproducts as performance enhancers in asphalt binder', *Transportation Research Record*, (2051), pp. 8–14. doi: 10.3141/2051-02.

McDaniel, R. S. (2015) *Fiber Additives in Asphalt Mixtures; National Academies of Sciences, Engineering, and Medicine 2015. Fi*. doi: 10.17226/22191.

Miljkovic, M. and Radenberg, M. (2011) 'Rutting mechanisms and advanced laboratory testing of asphalt mixtures resistance against permanent deformation', *Facta universitatis - series: Architecture and Civil Engineering*, 9(3), pp. 407–417. doi: 10.2298/FUACE1103407M.

Ministry of Transport, *Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering*, in: *China Commun. Press, China Communications Press, Beijing*,

China, 2011: pp. 1–370 (2011).

Ministry of Works, Transport & Communications Botswana, R. department (2001) *The Prevention and Repair of Salt Damage to Roads and Runways: Report and Guideline*.

Mohammed, M. *et al.* (2020) ‘Microstructure and mechanical properties of fibre reinforced asphalt mixtures’, *Construction and Building Materials*, 240, p. 117932. doi: 10.1016/j.conbuildmat.2019.117932.

Mohammed, M., Parry, T. and Grenfell, J. (J R. A.). (2018) ‘Influence of fibres on rheological properties and toughness of bituminous binder’, *Construction and Building Materials*, 163, pp. 901–911. doi: 10.1016/j.conbuildmat.2017.12.146.

Morea, F. and Zerbino, R. (2018) ‘Improvement of asphalt mixture performance with glass macro-fibers’, *Construction and Building Materials*, 164, pp. 113–120. doi: 10.1016/j.conbuildmat.2017.12.198.

Moreno, F. and Rubio, M. C. (2013) ‘Effect of aggregate nature on the fatigue-cracking behavior of asphalt mixes’, *Materials and Design*, 47, pp. 61–67. doi: 10.1016/j.matdes.2012.12.048.

Moriyoshi, A. *et al.* (2014) ‘Construction and pavement properties after seven years in porous asphalt with long life’, *Construction and Building Materials*, 50, pp. 401–413. doi: 10.1016/j.conbuildmat.2013.09.023.

Motoc, D. L., Santiago, F. B. and Pop, P.A. (2018) ‘Thermal degradation and stability of wood particle composites deployed as decorative components’, *MATEC Web of Conferences*, 184. doi: 10.1051/mateconf/201818401016.

Moutassem, F. (2016) ‘Assessment of Packing Density Models and Optimizing Concrete Mixtures’, *International Journal of Civil, Mechanical and Energy Science (IJCMES)*, 2(4), pp. 29–36.

Nash, D. J. and McLaren, S. J. (2003) ‘Kalahari valley calcretes: Their nature, origins, and environmental significance’, *Quaternary International*, 111(1), pp. 3–22. doi: 10.1016/S1040-6182(03)00011-9.

Nield, J. M. *et al.* (2016) ‘Evaporative sodium salt crust development and its wind tunnel derived transport dynamics under variable climatic conditions’, *Aeolian Research*, 23, pp. 51–62. doi: 10.1016/j.aeolia.2016.09.003.

Oda, S. (2012) ‘Analysis of use of natural fibers and asphalt rubber binder in discontinuous asphalt mixtures’, *Construction and Building Materials*, (April 2019). doi: 10.1016/j.conbuildmat.2011.06.030.

Olard, F. *et al.* (2003) ‘Linear Viscoelastic Properties of Bituminous Binders and

Mixtures at Low and Intermediate Temperatures’, *Road Materials and Pavement Design*, 4(1), pp. 77–107. doi: 10.1080/14680629.2003.9689941.

Özgan, E. *et al.* (2013) ‘Multi-faceted investigation of the effect of de-icer chemicals on the engineering properties of asphalt concrete’, *Cold Regions Science and Technology*, 87, pp. 59–67. doi: 10.1016/j.coldregions.2012.11.003.

Özgan, E., Serin, S. and Kap, T. (2013) ‘Multi-faceted investigation into the effects of hot-mix asphalt parameters on Marshall Stability’, *Construction and Building Materials*, 40, pp. 419–425. doi: 10.1016/j.conbuildmat.2012.11.002.

Pan, T. *et al.* (2006) ‘Effect of Coarse Aggregate Morphology on Permanent Deformation Behavior of Hot Mix Asphalt’, *American Society of Civil Engineers*, 132(7), pp. 580–589. doi: 10.1061/(ASCE)0733-947X(2006)132.

Pan, T. (2012) ‘A first-principles based chemophysical environment for studying lignins as an asphalt antioxidant’, *Construction and Building Materials*, 36, pp. 654–664. doi: 10.1016/j.conbuildmat.2012.06.012.

Pape, H. *et al.* (2009) ‘Permeability Prediction for Low Porosity Rocks by Mobile NMR’, *International Journal of Rock Mechanics and Mining Sciences*, 3(November). doi: 10.1007/978-3-0346-0122-1.

Peña, A. A. *et al.* (2008) ‘Biaxial test simulations using a packing of polygonal particles’, *International Journal for Numerical and Analytical Methods in Geomechanics*, 32(2), pp. 143–160. doi: 10.1002/nag.618.

Pérez-J, F. *et al.* (2013) ‘Effect of load application rate and temperature on the fracture energy of asphalt mixtures. Fénix and semi-circular bending tests’, *Construction and Building Materials*, 48, pp. 1067–1071. doi: 10.1016/j.conbuildmat.2013.07.084.

Pérez, J. F. *et al.* (2002) ‘Biodegradation and biological treatments of cellulose, hemicellulose and lignin: An overview’, *International Microbiology*, 5(2), pp. 53–63. doi: 10.1007/s10123-002-0062-3.

Pouget, S., Sauzéat, C., & Di Benedetto, H. and Olard, F. (2012) ‘Modeling of viscous bituminous wearing course materials on orthotropic steel deck.’ *Materials and Structures*. 45. doi:10.1617/s11527-011-9820-z

Pouget S, (2011) ‘From the Behavior of Constituent Materials to the Calculation and Design of Orthotropic Bridge Structures’, *Road Materials and Pavement Design*, 0629, pp. 2164–0629. doi: 10.3166/RMPD.11HS.111-144.

Pouranian, M. R. and Haddock, J. E. (2018) ‘Determination of voids in the mineral aggregate and aggregate skeleton characteristics of asphalt mixtures using a linear-mixture

packing model', *Construction and Building Materials*, 188, pp. 292–304. doi: 10.1016/j.conbuildmat.2018.08.101.

Pouranian, M. R. and Haddock, J. E. (2021) 'A new framework for understanding aggregate structure in asphalt mixtures', *International Journal of Pavement Engineering*, 22(9), pp. 1090–1106. doi: 10.1080/10298436.2019.1660340.

Pouranian, M. R., Imaninasab, R. and Shishehbor, M. (2020) 'The effect of temperature and stress level on the rutting performance of modified stone matrix asphalt', *Road Materials and Pavement Design*, 21(5), pp. 1386–1398. doi: 10.1080/14680629.2018.1546221.

Pouranian, M. R., Shishehbor, M. and Haddock, J. E. (2020) 'Impact of the coarse aggregate shape parameters on compaction characteristics of asphalt mixtures', *Powder Technology*, 363, pp. 369–386. doi: 10.1016/j.powtec.2020.01.014.

Rahman, M. T. and Mohajerani, A. (2021) 'Thermal conductivity and environmental aspects of cigarette butt modified asphalt', *Case Studies in Construction Materials*, 15(March), p. e00569. doi: 10.1016/j.cscm.2021.e00569.

Rajan, B. and Singh, D. (2017) 'Comparison of Shape Parameters and Laboratory Performance of Coarse Aggregates Produced from Different Types of Crushing Operations', *Journal of Materials in Civil Engineering*, 29(7), p. 04017044. doi: 10.1061/(asce)mt.1943-5533.0001874.

Ramazanov, A. E. and Emirov, S. N. (2012) 'Baric and Temperature Dependences for the Thermal Conductivity of Sedimentary Rocks', *Bulletin of the Russian Academy of Sciences. Physics*, 76(10), pp. 1283–1287. doi: 10.3103/S1062873812100103.

Read, J. (1996) Fatigue cracking of bituminous paving mixtures. PhD thesis, University of Nottingham.'

Read, J. and Whiteoak, D. (2003) *The Shell bitumen handbook*, Read, J., & Whiteoak, D. (2003). *The Shell bitumen handbook*. Thomas Telford. doi: 10.1680/sbh.32200.

Samkin, P. (2006) 'Sensitivity of hma performance to aggregate shape measured using conventional and image analysis methods', *Report*, 7(2).

Rinaldi, R. et al. (2016) 'Paving the Way for Lignin Valorisation: Recent Advances in Bioengineering, Biorefining and Catalysis', *Angewandte Chemie - International Edition*, 55(29), pp. 8164–8215. doi: 10.1002/anie.201510351.

Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D. Y., and Kennedy, T. W. (1996) *Hot mix asphalt materials, mixture design, and construction*, 2nd Ed., NAPA Research and Education Foundation, Lanham, MD. Book.

Roquier, G. (2016) 'The 4-parameter Compressible Packing Model (CPM) including a new theory about wall effect and loosening effect for spheres', *Powder Technology*, 302, pp. 247–253. doi: 10.1016/j.powtec.2016.08.031.

Roquier, G. (2017) 'The 4-parameter Compressible Packing Model (CPM) for crushed aggregate particles', *Powder Technology*, 320, pp. 133–142. doi: 10.1016/j.powtec.2017.07.028.

Roscoe, K. H., Schofield, A. N. and Wroth, C. P. (1958) 'On the yielding of soils', *Geotechnique*, 8(1), pp. 22–53. doi: 10.1680/geot.1958.8.1.22.

Rowe, G. (1996) 'PhD_Thesis', p. 525, Nottingham.

Samson, E. *et al.* (1999) 'Modelling ion diffusion mechanisms in porous media', *International Journal for Numerical Methods in Engineering*, 46(12), pp. 2043–2060. doi: 10.1002/(SICI)1097-0207(19991230)46:12<2043::AID-NME795>3.0.CO;2-7.

Satake, M. (1982a) 'Fabric tensor in granular materials.', in *Proceedings IUTAM conference on deformation and failure of granular materials, Delft*, p. 1982.

Satake, M. (1982b) 'Fabric tensor in granular materials. In: Vermeer, P.A., Luger, H.J. (Eds.), *Deformation and Failure of Granular Materials*. Balkema publishers, Rotterdam, pp.63–68.', *IUTAM Symposium on Deformation and Failure of Granular Materials*, pp. 62–68.

Sefidmazgi, N. R., Tashman, L. and Bahia, H. (2012) 'Internal structure characterization of asphalt mixtures for rutting performance using imaging analysis', *Road Materials and Pavement Design*, 13(SUPPL. 1), pp. 21–37. doi: 10.1080/14680629.2012.657045.

Segal, L. *et al.* (1959) 'An Empirical Method for Estimating the Degree of Crystallinity of Native Cellulose Using the X-Ray Diffractometer', *Textile Research Journal*, 29(10), pp. 786–794. doi: 10.1177/004051755902901003.

Setswalo, K. *et al.* (2019) 'Effect of Particle size and Alkali-Laccase on the Properties of Pterocarpus Angolensis (Mukwa) Wood Flour', *Procedia Manufacturing*, 35, pp. 465–470. doi: 10.1016/j.promfg.2019.05.068.

Shackleton, C. M. (2002) 'Growth patterns of Pterocarpus angolensis in savannas of the South African lowveld', *Forest Ecology and Management*, 166(1–3), pp. 85–97. doi: 10.1016/S0378-1127(01)00676-4.

Shaheen, M., Al-Mayah, A. and Tighe, S. (2016) 'A novel method for evaluating hot mix asphalt fatigue damage: X-ray computed tomography', *Construction and Building Materials*, 113, pp. 121–133. doi: 10.1016/j.conbuildmat.2016.03.030.

Shephard, M. S., Sander, E. A. and Barocas, V. H. (2008) 'Permeability calculations in three-dimensional isotropic and oriented fiber networks', *Physics of fluids* 20, 20 (January). doi: 10.1063/1.3021477.

Shi, X, Shu Wei G. and Michelle A. (2012) 'Exploring the Interactions of Chloride Deicer Solutions with Nanomodified and Micromodified Asphalt Mixtures Using Artificial Neural Networks', *American Society of Civil Engineers*, 24(July), pp. 805–815. doi: 10.1061/(ASCE)MT.1943-5533.0000452.

Shi, X. *et al.* (2017) 'Effects of thermally modified asphalt concrete on pavement temperature', *International Journal of Pavement Engineering*, 8436, pp. 1–13. doi: 10.1080/10298436.2017.1326234.

Si, Z., Little, D. N. and Lytton, R. L. (2002) 'Characterization of microdamage and healing of asphalt concrete mixtures', *10.1061/(ASCE)0899-156 (2002)14:6(461)*, 14(December), pp. 461–470.

Siddiquee, A. N. and Khan, Z. A. (2010) 'Grey relational analysis coupled with principal component analysis for optimisation design of the process parameters in in-feed centreless cylindrical grinding', *The International Journal of Advanced Manufacturing Technology*, (February). doi: 10.1007/s00170-009-2159-8.

Slebi-Acevedo, C. J. *et al.* (2019) 'Mechanical performance of fibers in hot mix asphalt: A review', *Construction and Building Materials*, 200, pp. 756–769. doi: 10.1016/j.conbuildmat.2018.12.171.

Sobolev, K. *et al.* (2014) 'The effect of fly ash on the rheological properties of bituminous materials', *Fuel*, 116, pp. 471–477. doi: 10.1016/j.fuel.2013.07.123.

Soenen, H. *et al.* (2013) 'The multiple stress creep-recovery test: A detailed analysis of repeatability and reproducibility', *Road Materials and Pavement Design*, 14(SUPPL.1), pp. 2–11. doi: 10.1080/14680629.2013.774742.

Souza, F. V. and Castro, L. S. (2012) 'Effect of temperature on the mechanical response of thermo-viscoelastic asphalt pavements', *Construction and Building Materials*, 30, pp. 574–582. doi: 10.1016/j.conbuildmat.2011.11.048.

Sreedhar, S. and Coleri, E. (2018) 'Effects of Binder Content, Density, Gradation, and Polymer Modification on Cracking and Rutting Resistance of Asphalt Mixtures Used in Oregon', *Journal of Materials in Civil Engineering*, 30(11), p. 04018298. doi: 10.1061/(asce)mt.1943-5533.0002506.

Stahle, D. W. *et al.* (1999) 'Management implications of annual growth rings in *Pterocarpus angolensis* from Zimbabwe', *Forest Ecology and Management*, 124(2–3), pp.

217–229. doi: 10.1016/S0378-1127(99)00075-4.

Stovall, T., Larrard, F. D. E. and Buil, M. (1986) ‘Linear Packing Density Model of Grain Mixtures’, *Powder Technology*, 48, pp. 1–12.

Subhy, A. *et al.* (2021) ‘Rutting analysis of different rubberised stone mastic asphalt mixtures : from binders to mixtures Rutting analysis of different rubberised stone mastic asphalt’. doi: 10.1080/14680629.2021.1950818.

Sun, Y. *et al.* (2017) ‘Self-healing performance of asphalt mixtures through heating fibers or aggregate’, *Construction and Building Materials*, 150, pp. 673–680. doi: 10.1016/j.conbuildmat.2017.06.007.

Chiu S. N., (2013) *Stochastic geometry and its applications*.

Taherkhani, H. (2006) *Experimental Characterisation of the Compressive Permanent Deformation Behaviour in Asphaltic Mixtures* Department of civil engineering, Unuversity of Nottigham.

Tanzadeh, J. and Shahrezagamasaei, R. (2017) ‘Laboratory Assessment of Hybrid Fiber and Nano-silica on Reinforced Porous Asphalt Mixtures’, *Construction and Building Materials*, 144, pp. 260–270. doi: 10.1016/j.conbuildmat.2017.03.184.

Tapkin, S. (2008) ‘The effect of polypropylene fibers on asphalt performance’, *Building and Environment*, 43(6), pp. 1065–1071. doi: 10.1016/j.buildenv.2007.02.011.

Tatsuoka, F. (1999) ‘Small strain behaviour of granular materials.: Introduct.’, *Mech. Granular Mater*, pp. 299 – 308.

Thanh, D. V., Feng P. C. and Long L. H (2011) ‘Analysis of High Temperature Stability and Water Stability of SMA Mixture using Orthogonal Experiments’, *International journal of civil and structural engineering Volume 2, No 2, 2011, 2(2)*, pp. 626–638.

Theocharis, A. (2015) *Comparison of fabric tensors for granular materials - A scan line void based approach*.

Theocharis, A. I., Vairaktaris, E. and Dafalias, Y. F. (2017) ‘Scan line void fabric anisotropy tensors of granular media’, *Granular Matter*, 19(4), pp. 1–12. doi: 10.1007/s10035-017-0752-3.

Topal, A. and Sengoz, B. (2005) ‘Determination of fine aggregate angularity in relation with the resistance to rutting of hot-mix asphalt’, *Construction and Building Materials*, 19(2), pp. 155–163. doi: 10.1016/j.conbuildmat.2004.05.004.

Tsai, B. W., Harvey, J. T. and Monismith, C. L. (2002) ‘WesTrack fatigue performance prediction using Miner’s law’, *Transportation Research Record*, (1809), pp. 137–147. doi: 10.3141/1809-16.

Tuan, Q. *et al.* (2021) 'Effect of time – temperature , strain level and cyclic loading on the complex Poisson ' s ratio of asphalt mixtures', *Construction and Building Materials*, 294, p. 123564. doi: 10.1016/j.conbuildmat.2021.123564.

Uetani, K. and Hatori, K. (2017) 'Thermal conductivity analysis and applications of nanocellulose materials', *Science and Technology of Advanced Materials*, 18(1), pp. 877–892. doi: 10.1080/14686996.2017.1390692.

Vaitkus, A. and Paliukaite, M. (2013) 'Evaluation of time loading influence on asphalt pavement rutting', *Procedia Engineering*, 57, pp. 1205–1212. doi: 10.1016/j.proeng.2013.04.152.

Van der Poel (1954) 'Representation of rheological properties of bitumens over a wide range of temperatures and loading times. In: Proc of 2nd Int Congress on Rheology, pages 331–337. Academic Press Inc., New York.', pp. 331–337.

Van der Poel (1955) 'Time and temperature effects on the deformation of as- phaltic bitumens and bitumen-mineral mixtures, *Society of Petroleum Engineers Journalociety of Petroleum Engineers Journal*, pp. 47–53.

Valdés-vidal, G. *et al.* (2015) 'Mechanical behavior of asphalt mixtures with different aggregate type', 101, pp. 474–481. doi: 10.1016/j.conbuildmat.2015.10.050.

Valdés-vidal, G. *et al.* (2014) 'Effect of the physical properties of aggregates on aggregate-asphalt bond measured using the UCL method', *Construction and Building Materials*, 73, pp. 399–406. doi: 10.1016/j.conbuildmat.2014.09.098.

Vavrik W. R., (2001) 'The Bailey Method of Gradation Evaluation: The Influence of Aggregate Gradation and Packing Characteristics on Voids in the Mineral Aggregate', *Journal of the Association of Asphalt Paving Technologists*, 70(July), pp. 1–23.

Wang, D. *et al.* (2019) 'Laboratory Investigation of Lignocellulosic Biomass as Performance Improver for Bituminous Materials', *MDPI/Polymers/ www.mdpi.com/journal/polymers*, pp. 1–18.

Wang, H. *et al.* (2016) 'The effect of morphological characteristic of coarse aggregates measured with fractal dimension on asphalt mixture's high-temperature performance', *Advances in Materials Science and Engineering*, 2016. doi: 10.1155/2016/6264317.

Wang, R. *et al.* (2019) 'Dependency of Dilatancy Ratio on Fabric Anisotropy in Granular Materials', 10.1061/(ASCE)EM.1943-7889.0001660, 145(10), pp. 1–13. doi: 10.1061/(ASCE)EM.1943-7889.0001660.

Wang, Z. *et al.* (2016) 'Investigation of microwave healing performance of electrically conductive carbon fiber modified asphalt mixture beams', *Construction and Building*

Materials, 126, pp. 1012–1019. doi: 10.1016/j.conbuildmat.2016.09.039.

Wang, Z. *et al.* (2019) ‘Blistering Mechanism Analysis of Hydraulic Asphalt Concrete Facing’, *MDPI, Applied sciences*, pp. 1–13.

Watkins, D. *et al.* (2015) ‘Extraction and characterization of lignin from different biomass resources’, *Journal of Materials Research and Technology*, 4(1), pp. 26–32. doi: 10.1016/j.jmrt.2014.10.009.

Wei, S. *et al.* (2011) ‘Effect of deicing solutions on the tensile strength of micro- or nano-modified asphalt mixture’, *Construction and Building Materials*, 25(1), pp. 195–200. doi: 10.1016/j.conbuildmat.2010.06.038.

Weise, C. and Zeissler, A. (2016) ‘Effects of fiber reinforcement on the fatigue and rutting performance of asphalt mixes’, in *6th Eurasphalt & Eurobitume Congress* |. doi: 10.14311/ee.2016.015.

Wicklein B, *et al.* (2015) ‘Thermally insulating and fire-retardant lightweight anisotropic foams based on nanocellulose and graphene oxide. *Nat Nanotechnol.*’, *Nature Nanotechnology*, 10, pp. 277 – 283.

Wong, V. and Kwan, A. K. H. (2014) ‘A 3-parameter model for packing density prediction of ternary mixes of spherical particles’, *Powder Technology*, 268, pp. 357–367. doi: 10.1016/j.powtec.2014.08.036.

Woodbridge M.E and Obika, R. F.-H. (1994) *Avoiding salt damage to bituminous surfacings: Result from a road trial in Botswana, Report.*

Woodbridge M.E, and Obika, R. F.-H.. (1994) ‘Salt damage to bituminous surfaces: result from road in Botswana’, *Proceedings of the* Available at: <http://trid.trb.org/view.aspx?id=453177>.

Wu, M. *et al.* (2014) ‘Reinforcement effect of fiber and deoiled asphalt on high viscosity rubber/SBS modified asphalt mortar’, *Petroleum Science*, 11(3), pp. 454–459. doi: 10.1007/s12182-014-0361-2.

Yang, X. H. (2016) ‘Impacts of aggregate morphological characteristics on asphalt mixture performance based on experimental tests’, in: *4th Geo-China International Conference on Sustainable Civil Infrastructure - Innovative Technologies for Severe Weathers and Climate Changes, Shandong*, 266, pp. 34–41.

Bolin X., *et al* (2017) ‘Discussion on packing density models of combined aggregate and a new solution’, *Mat*, 10.11896/j(14.014), pp. 1005--023.

Xiao, H. *et al.* (2020) ‘Analysis of Composite Skeleton Characteristics of Recycled Asphalt Mixture via Weight Analysis Method’, *Structural Materials, a section of the journal*

Frontiers in Materials, 7(July), pp. 1–9. doi: 10.3389/fmats.2020.00203.

Xiao, H., Qiu, Y., *et al.* (2020) ‘Analysis of Composite Skeleton Characteristics of Recycled Asphalt Mixture via Weight Analysis Method’, *Frontiers in Materials*, 7. doi: 10.3389/fmats.2020.00203.

Xue, Y. and Qian, Z. (2016) ‘Development and performance evaluation of epoxy asphalt concrete modified with mineral fiber’, *Construction and Building Materials*, 102, pp. 378–383. doi: 10.1016/j.conbuildmat.2015.10.157.

Yagüe, S. *et al.* (2020) ‘Sustainable Ecocements: Chemical and Morphological Analysis of Granite Sawdust Waste as Pozzolan Material’, *MDPI, Materials*, pp. 1–15.

Yang, Z., Zhang, Y. and Shi, X. (2018) ‘Impact of nanoclay and carbon microfiber in combating the deterioration of asphalt concrete by non-chloride deicers’, *Construction and Building Materials*, 160, pp. 514–525. doi: 10.1016/j.conbuildmat.2017.11.059.

Yaro, N. S. A. *et al.* (2021) ‘Performance evaluation of waste palm oil fiber reinforced stone matrix asphalt mixtures using traditional and sequential mixing processes’, *Case Studies in Construction Materials*, 15(November 2021), p. e00783. doi: 10.1016/j.cscm.2021.e00783.

Yefremov, S. (2020) ‘Influence of genesis of mineral components of asphalt concrete for its durability in aggressive environments’, *IOP Conference Series: Materials Science and Engineering*, 907(1). doi: 10.1088/1757-899X/907/1/012029.

Yi-qiu, T., Li, X. and Zhou, X. (2010) ‘Interactions of Granite and Asphalt Based on the Rheological Characteristics’, *Journal of Materials in Civil Engineering*, 22(8), pp. 820–825. doi: 10.1061/(asce) mt.1943-5533.0000014.

Yu, L.-L. F. (1955) ‘Petrography’, (*Moscow: Publishing House of the Academy of Sciences of the USSR*), p. 447.

Yu, X. *et al.* (2013) ‘The effects of salt on rheological properties of asphalt after long-term aging’, *The Scientific World Journal*, 2013. doi: 10.1155/2013/921090.

Yuan, R. *et al.* (2019) ‘On a fabric evolution law incorporating the effects of b-value’, *Computers and Geotechnics*, 105(October 2017), pp. 142–154. doi: 10.1016/j.compgeo.2018.09.019.

Zachariah, J. P. *et al.* (2018) ‘Effect of polypropylene fibres on bituminous concrete with brick as aggregate’, *Construction and Building Materials*, 168, pp. 867–876. doi: 10.1016/j.conbuildmat.2018.02.016.

Zhan, L., Nan, Z. and Jixiong, Z. (2013) ‘Random gravel model and particle flow based numerical biaxial test of solid backfill materials’, *International Journal of Mining Science and Technology*, 23(4), pp. 463–467. doi: 10.1016/j.ijmst.2013.07.001.

Zhang, Z., Roque, B. Birgisson, and B. S. (2001) ‘Identification and Verification of a Suitable Crack Growth Law, *Association of Asphalt paving Technologists*, 70, pp. 206–241.

Zhang, D., Huang, X. and Zhao, Y. (2012) ‘Investigation of the shape, size, angularity and surface texture properties of coarse aggregates’, *Construction and Building Materials*, 34, pp. 330–336. doi: 10.1016/j.conbuildmat.2012.02.096.

Zhang, J. *et al.* (2017) ‘Moisture damage evaluation of aggregate–bitumen bonds with the respect of moisture absorption, tensile strength and failure surface’, *Road Materials and Pavement Design*, 18(4), pp. 833–848. doi: 10.1080/14680629.2017.1286441.

Zhang, Y. *et al.* (2018) ‘Impacts of air-void structures on the rutting tests of asphalt concrete based on discretized emulation’, *Construction and Building Materials*, 166, pp. 334–344. doi: 10.1016/j.conbuildmat.2018.01.141.

Zhang, Y., Luo, R. and Lytton, R. L. (2011) ‘Microstructure-Based Inherent Anisotropy of Asphalt Mixtures’, *Journal of Materials in Civil Engineering*, 23(10), pp. 1473–1482. doi: 10.1061/(ASCE)MT.1943-5533.0000325.

Zheng, M. *et al.* (2015) ‘Comparison and analysis on heat reflective coating for asphalt pavement based on cooling effect and anti-skid performance’, *Construction and Building Materials*, 93, pp. 1197–1205. doi: 10.1016/j.conbuildmat.2015.04.043.

Zhu, H. *et al.* (2007) ‘Influence of polyester fibre on the performance of asphalt mixes’, *SATC 2007 - 26th Annual Southern African Transport Conference: The Challenges of Implementing Policy*, (2), pp. 708–715.

Appendix

