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Experimental and Numerical Study of Rubber Intermixed Ballast System Subjected to Monotonic and Cyclic Loading

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Doctor of Philosophy

under the supervision of Dr. Yujie Qi and Distinguished Professor Buddhima Indraratna

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, *Chathuri Madhusanka Kulappu Arachchige* declare that this thesis, is submitted in fulfilment of the requirements for the award of *Doctor of Philosophy*, in the *School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

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LIST OF SYMBOLS

Letters

A	=	shift in the PSD curve after the test
A_L	=	area of the hysteresis loop
A_T	=	area of the triangle
B	=	area between the arbitrary boundary and the final PSD curve
a, b	=	Duncan and Chang model parameters
a_1, b_1	=	parameters associated with E_i
B_g	=	Marsal's breakage index
c	=	cohesion
C_c	=	coefficient of curvature
C_u	=	coefficient of uniformity
D	=	damping ratio
D_{max} , D_{min}	=	maximum and minimum particle size
D_r	=	relative density
d	=	dilatancy
E	=	secant modulus
E_i	=	initial tangent modulus
E_t	=	tangent modulus
E_{ur}	=	unloading modulus
E_{50}	=	secant modulus at 50% of the q_{peak}
E_d	=	strain energy density
$\hat{E}_d$	=	normalised strain energy density
E'_d	=	dissipated energy per cycle
e	=	void ratio
e_f	=	void ratio after the end of the test
e_i	=	void ratio at the beginning of the test
e_0	=	void ratio after the conditioning phase
F	=	Mohr-Coulomb failure envelope
f	=	frequency
F_s	=	shear yield function
G	=	specific gravity
G_B, G_R, G_s,	=	specific gravities of ballast, rubber, and RIBS respectively
G_f	=	specific gravity of fouling material
g	=	plastic potential
k_1, k_2	=	parameters associated with R_m

L	=	distance between two axles
M	=	mass
M_b	=	mass of ballast
M_c	=	critical state stress ratio
M_f	=	mass of fouling material
M_R	=	resilient modulus
m_s	=	mass of solids
N	=	number of cycles
P_4	=	percentage passing through 4.75 mm sieve (No 4)
P_{200}	=	percentage passing through 0.075 mm sieve (No 200)
p'	=	mean effective stress
q	=	deviator stress
q_{cyc}	=	cyclic deviator stress
$q_{cyc,max}$	=	maximum cyclic deviator stress
$q_{cyc,min}$	=	minimum cyclic deviator stress
q_f	=	deviator stress at failure
q_{peak}	=	peak deviator stress
q_{ult}	=	ultimate deviator stress
R_b	=	rubber content
R_f	=	ratio between q_f and q_{ult}
R_m	=	modification factor of hardening soil model
T	=	tonne
t	=	time
t_1, t_2	=	parameters associated with the permanent axial deformation model
U	=	distortional energy
V	=	train speed
V	=	total volume of the specimen
$V_{f'}$	=	volume of fouling material
V_{vb}	=	volume of voids
W_{ki}	=	percentage retained by weight in each sieve before test
W_{kf}	=	percentage retained by weight in each sieve after test

Greek letters

α, β	=	parameter associated with φ_p model
$\alpha_1, \alpha_2, \beta_1, \beta_2$	=	parameters associated with $k_1$and k_2
α', β'	=	parameter associated with distortional energy model
γ	=	shear strain
γ_d	=	dry unit weight
γ_f	=	shear strain up to the peak shear stress
γ_w	=	unit weight of water
γ^p	=	hardening parameter
$\dot{\gamma}^p$	=	rate of plastic shear strain
ε_1	=	Total permanent axial deformation
ε_1^e	=	elastic axial strain
ε_1^p	=	plastic axial strain
$\varepsilon_2^e, \varepsilon_3^e$	=	elastic lateral strains
$\varepsilon_a, \varepsilon_v, \varepsilon_r$	=	axial, volumetric and radial strains respectively
$\varepsilon_{a,1}$	=	axial deformation after first loading cycle
ε_i	=	axial deformation after monotonic conditioning phase
ε_q	=	deviator strain
ε_{rec}	=	recoverable strain
ε_v^p	=	plastic volumetric strain
$\dot{\varepsilon}_v^p$	=	rate of plastic volumetric strain
η	=	stress ratio
η_{peak}	=	peak deviator stress ratio
λ, μ	=	parameter associated with φ_p model
ν	=	poisson's ratio
σ	=	normal stress
σ_3'	=	effective confining pressure
τ	=	shear stress
φ	=	friction angle
φ_{cv}	=	critical state friction angle
$\varphi_{d=0}$	=	friction angle at phase transformation state
φ_{ef}	=	effective friction angle
φ_m	=	mobilised friction angle
φ_p	=	peak friction angle
ψ	=	dilation angle
ψ_m	=	mobilised dilation angle
ψ_p	=	dilation angle at peak stress ratio

Abbreviations

AC	=	Aggregate Crushing value
ARTC	=	Australian Rail Track Corporation
AREMA	=	American Railway Engineering and Maintenance of Way Association
BBI	=	Ballast Breakage Index
DAQ RIBS	=	Data Acquisition of RIBS Section
DAQ REF	=	Data Acquisition of Reference Section
DEM	=	Discrete Element Modeling
ELT	=	End-of-Life Tyres
FI	=	Fouling Index
FEM	=	Finite Element Modeling
IMRT	=	Iran Ministry of Roads and Transportation
LAA	=	Loss Angeles Abrasion value
LVDT	=	Linear Variable Differential Transducer
MDD	=	Maximum Dry Density
MGT	=	Million Gross Tons
NSW	=	New South Wales
PSD	=	Particle Size Distribution
PTZ	=	Pan-Tilt-Zoom
RC	=	Rubber Crumbs
RIBS	=	Rubber Intermixed Ballast System
R & D	=	Research and Development
T5	=	Traffic Classification T5
TDA	=	Tyre Derived Aggregates
TfNSW	=	Transport for New South Wales
USP	=	Under Sleeper Pads
VCI	=	Void Contamination Index
WA	=	Wet Attrition value

TABLE OF CONTENTS

CERTIFICATE OF ORIGINAL AUTHORSHIP i
ACKNOWLEDGEMENTS ii
LIST OF SYMBOLS iv
TABLE OF CONTENTS viii
LIST OF FIGURES xii
LIST OF TABLES xvi
LIST OF PUBLICATIONS xvii
ABSTRACT xix
1 INTRODUCTION 1
1.1 General Background 1
1.2 Research Motivation 5
1.3 Objectives and Scope 7
1.4 Thesis Outline 8
CHAPTER TWO 12
2 LITERATURE REVIEW 12
2.1 Introduction 12
2.2 End-of-Life Tyres (ELT) 13
2.2.1 Scrap Tyre Products 14
2.3 Ballast 15
2.3.1 Factors affecting ballast behaviour 16
2.3.2 Ballast fouling 17
2.4 Behaviour of Granular/Ballast Material under Monotonic Loading 19
2.5 Behaviour of Granular/Ballast Material under Cyclic Loading 24
2.6 Use of Elastic Tyre Aggregates in Railway Substructure 28
2.7 Constitutive Modelling 38

2.8 Field Testing for Mixtures of Ballast and Granular Rubber....41
2.9 Chapter Summary....42
CHAPTER THREE .... **Error! Bookmark not defined.**
3 MATERIALS AND TESTING PROGRAMME....44
3.1 Introduction....44
3.2 The Sizes of Rubber Granules....44
3.2.1 Particles prone to breakage....45
3.2.2 Shape of rubber particles....48
3.2.3 Criteria for assessing durability....50
3.3 Test Materials and Laboratory Test Plan....50
3.4 Sample Preparation and Test Setup....55
3.5 Monotonic Shearing....59
3.6 Cyclic Loading....60
3.7 Chapter Summary....61
CHAPTER FOUR .... **Error! Bookmark not defined.**
4 BEHAVIOUR OF RIBS MIXTURES UNDER MONOTONIC LOADING....63
4.1 Introduction....63
4.2 Stress-Strain Response....63
4.3 Dilatancy Behaviour....66
4.4 Modulus Degradation....70
4.5 Friction Angle and Dilation Angle....74
4.6 Ballast Breakage....80
4.7 Energy Absorption....83
4.7.1 Strain energy density....83
4.7.2 Effect of replaced rubber and distortional energy....86
4.8 Critical State Behaviour....88
4.9 Chapter Summary....91
CHAPTER FIVE .... **Error! Bookmark not defined.**
5 BEHAVIOUR OF RIBS MIXTURES UNDER CYCLIC LOADING....92

5.1 Introduction 92
5.2 Loading Procedure 93
5.3 Void Ratio 95
5.4 Permanent Deformation Behaviour 97
5.4.1 Axial strain 97
5.4.2 Volumetric strain 103
5.5 Resilient Modulus 105
5.6 Damping Ratio and Energy Dissipation Capacity 107
5.7 Ballast Degradation under Cyclic Loading 109
5.8 Chapter Summary 111
CHAPTER SIX 113
6 ASSESSING THE OPTIMAL RUBBER CONTENT 113
6.1 Introduction 113
6.2 Conventional Ballast as the Reference 114
6.3 Proposed Acceptance Criteria for RIBS 116
6.4 Optimising the Amount of Rubber 117
6.5 Justifying the Optimal $R_b\%$ in RIBS Mixture under Cyclic Loading 122
6.6 Drainage Potential 123
6.7 Initial Compaction Characteristics 124
6.8 Chapter Summary 125
CHAPTER SEVEN 127
7 CONSTITUTIVE MODELLING OF BALLAST-RUBBER MIXTURES 127
7.1 Introduction 127
7.2 Strain Softening/Hardening Model 128
7.2.1 Hardening soil model 129
7.2.2 Shear hardening 133
7.2.3 Flow rule and plastic potential 134
7.3 Model Validation 138
7.3.1 Model parameters and calibration 138

7.3.2 Model validation using test data ... 141
7.4 Model Limitations ... 146
7.5 Chapter Summary ... 146
CHAPTER EIGHT ... 147
8 PRACTICAL APPLICATIONS AND LIMITATIONS ... 147
8.1 Introduction ... 147
8.2 Practical Application of RIBS in a Trial Track ... 147
8.2.1 Design of track ... 148
8.2.2 Construction of track ... 153
8.2.3 Observations and considerations during construction ... 158
8.2.4 Monitoring and test outcomes ... 159
8.3 Limitations of RIBS ... 159
8.4 Chapter Summary ... 161
CHAPTER NINE ... **Error! Bookmark not defined.**
9 CONCLUSIONS AND RECOMMENDATIONS ... 162
9.1 Introduction ... 162
9.2 Geotechnical Characteristics of RIBS under Static Loading ... 162
9.3 The Response of RIBS under Cyclic Loading ... 164
9.4 Optimal Amount of Rubber in RIBS Mixtures ... 166
9.5 Constitutive Modelling ... 166
9.6 Practical Applications and Limitations ... 167
9.7 Recommendations for Future Works ... 169
REFERENCES ... 171
APPENDIX A: Calculation of Material Quantities for the Specimens ... 185
APPENDIX B: Design Calculations of RIBS Track ... 187

LIST OF FIGURES

Figure 2.1 The influence of confining pressure on the angle of internal friction (adopted from Indraratna et al., (1998)).......20

Figure 2.2 Ballast Breakage Index (Indraratna et al., 2005).......22

Figure 2.3 The effect of particle breakage, dilatancy and confining pressure on the friction angle of latite basalt, as investigated by Indraratna and Salim (2002).......23

Figure 2.4 Strain response under cyclic loading (adopted from Sun et al., 2016).......26

Figure 2.5 An example of the shakedown mechanism (adopted from Sun et al., 2016) 27

Figure 2.6 Definition of the resilient modulus, M_R.......27

Figure 2.7 Particle size distribution of ballast mixed with rubber that was used in the study by Sol-Sanchez et al., (2015).......30

Figure 2.8 Settlements and energy dissipation capacity (adopted from Sol-Sanchez et al., 2015).......31

Figure 2.9 Stiffness modulus and damping ratio with diverse % of TDA (data source Esmaeili et al., 2016).......32

Figure 2.10 Settlement of ballast with different R_b% under cyclic loading (after Fathali et al., 2016 and Sol-Sanchez et al., 2015).......33

Figure 2.11 Comparison of particle breakage for ballast with different R_b% (adopted from Fathali et al., 2016).......34

Figure 2.12 Rate of energy consumption against the rate of particle breakage (Adopted from Indraratna and Salim (2002).......40

Figure 3.1 Marsal's breakage index, ($B_g = \Delta Wk > 0$) for pure ballast (latite basalt)..46

Figure 3.2 Different size rubber granules.......49

Figure 3.3 Evaluation of best particle size for rubber granules.......49

Figure 3.4 Particle size distribution of RIBS and rubber granules.......52

Figure 3.5 Ballast material preparation (a) vibrating shaker, (b) washing, (c) drying, and (d) prepared ballast.......53

Figure 3.6 Ballast mixed with rubber, (a) conventional Ballast, (b) rubber granules, and (c) RIBS with R_b=5%.......54

Figure 3.7 Laboratory testing program.......55

Figure 3.8 Schematic illustration of the large-scale triaxial testing system (modified after Sun, 2015).......56

Figure 3.9 Sample preparation and test setup: (a) prepared RIBS material (R_b=5%), (b) 7mm membrane supported by two split moulds, (c) compacting the layers with a vibrating plate, (d) last layer of RIBS (R_b=5%), (e) prepared sample, (f) a sample is placed inside the outer cell chamber, and (g) setup of the large scale triaxial apparatus. 58

Figure 4.1 Effect of the rubber on: (a-c) deviator stress-axial strain curves; (d-f) volumetric-axial strain curves 64

Figure 4.2 Variation of deviatoric stress ratio with axial strain 68

Figure 4.3 (a–c) Dilation-stress ratio responses of RIBS under different effective confining pressures: (a) 10 kPa, (b) 30 kPa and (c) 60 kPa; (d) maximum dilatancy with rubber content...69

Figure 4.4 Hyperbolic approximation (after Duncan and Chang (1970)).......................70

Figure 4.5 Initial tangent modulus,E_i 71

Figure 4.6 (a) Secant modulus degradation of pure ballast and RIBS (σ_3' = 60 kPa); (b) secant modulus degradation of RIBS at $\eta peak$ against the rubber content....................73

Figure 4.7 Effect of the rubber on (a) effective friction angle (φ_{ef}), friction angle at $\eta peak$ (φ_p) (b) dilation angle ψ at η_{peak} 76

Figure 4.8 Effect of confining pressure (σ_3') on φ_p of pure ballast (R_b=0)....................77

Figure 4.9 (a) Effect of rubber content (R_b) on φ_p of RIBS (R_b >0) (b) Relationship of α/β with confining pressure, ($R_b > 0$) 78

Figure 4.10 Comparison of peak friction angle, φ_p from the current study with a previous study by Indraratna et al., (1998). 79

Figure 4.11 Influence of R_b on ballast breakage index (BBI) 81

Figure 4.12 Influence of R_b on Marsal's breakage index, B_g = $\Delta W_k > 0$......................82

Figure 4.13 Particles passed through 4.75 mm sieve (after the shearing test at $\sigma 3' = 30\ kPa$)..83

Figure 4.14 (a) Shear strain versus shear stress σ_3'= 10 kPa, and (b) normalised strain energy densities variation against the rubber content. 85

Figure 4.15 Incremental distortional energy (ΔU) 86

Figure 4.16 Distortional energy (U) due to R_b% replaced with the same size of ballast particles at a given deviator strain (ε_q^*) 87

Figure 4.17 The relationship of α' and β' in terms of R_b% for the specimens tested at (a) $\sigma_3' = 30\ kPa$ and (b) $\sigma_3' = 60\ kPa$ 88

Figure 4.18 Estimation of the critical state stress ratio employing the stress ratio and dilatancy 89

Figure 4.19 Estimation of the critical state stress ratio employing the stress ratio and volumetric strain....90

Figure 4.20 3D surface plot of the critical stress ratio, M_c 91

Figure 5.1 Vertical cyclic stresses, q_{cyc} transmitted to the ballast layer underneath the rail by 25 t axle load coal train with wagons (adopted from Indraratna et al., 2010) 93

Figure 5.2 Details of the loading procedure....95

Figure 5.3 Void ratio (e) of the specimens at the beginning of the test e_i, after the conditioning phase e_0 and at the end of the test e_f 96

Figure 5.4 Permanent axial deformation after the monotonic conditioning phase εi 97

Figure 5.5 (a-b) Axial strain response of RIBS mixtures under effective confining pressures: (a) 30 kPa (b) 60 kPa; (c-d) rate of axial strain variation of RIBS mixtures under effective confining pressures: (c) 30 kPa (d) 60 kPa 99

Figure 5.6 Empirical modelling for permanent axial deformation under cyclic loads .102

Figure 5.7 (a-b) Volumetric strains (dilation) of RIBS mixtures under effective confining pressures: (a) 30 kPa (b) 60 kPa; (c-d) volumetric strain rates with respect to number of cycles under effective confining pressures: (c) 30 kPa (d) 60 kPa 104

Figure 5.8 Variation of M_R of RIBS mixtures against the rubber content, $R_b\%$ 105

Figure 5.9 Variation of resilient modulus of RIBS mixtures against the number of cycles under effective confining pressures: (a) 30 kPa (b) 60 kPa 106

Figure 5.10 Definition of the damping ratio and the dissipated energy per cycle 108

Figure 5.11 (a-b) Variation of the damping ratio against the number of cycles under effective confining pressures: (a) 30 kPa, (b) 60 kPa; (c-d) variation of dissipation energy against the number of cycles under effective confining pressures: (c) 30 kPa, (d) 60 kPa 108

Figure 5.12 Influence of R_b on Ballast Breakage Index, BBI 110

Figure 5.13 Patterns of ballast breakage 111

Figure 6.1 Typical ballasted track cross-section....115

Figure 6.2 Effective friction angle of rubber -ballast mixtures....118

Figure 6.3 Optimisation of the rubber content according to the ballast breakage index and associated axial strain....119

Figure 6.4 Higher E/E_i at η_{peak} compared to the pure ballast....120

_Toc103895203Figure 6.5 Higher energy absorption in RIBS compared to pure ballast 121

_Toc103895204Figure 6.6 Optimisation of the rubber content according to the resilient modulus and energy dissipation per cycle 123

_Toc103895205Figure 7.1 Hyperbolic approximation for non-linear stress–strain relationship of soils 129

_Toc103895206Figure 7.2 Effect of the rubber content (R_b) on E_i/σ_3' : (a) data from the current study, and (b) data from Song et al., 2019 132

Figure 7.3 (a) The linear variation of $k1$ against R_b (b) The linear variation of $k2$ against σ_3' 137

Figure 7.4 Predicted E_i versus E_i from tests 139

Figure 7.5 Deviator stress-axial strain curves from the test results and model predictions for pure ballast and RIBS with different R_b contents: (a) σ_3' =10 kPa; (b) σ_3' =30 kPa; (c) σ_3' =60 kPa. 142

Figure 7.6 Deviator stress-axial strain curves from the test results and model predictions for pure ballast and rubber-ballast mixtures with different R_b contents (test data from: Song et al., 2019) (a) σ =50 kPa; (b) σ =100 kPa; (c) σ =150 kPa. 143

Figure 7.7 Volumetric strain-axial strain curves from the test results and model predictions for pure ballast and RIBS with different R_b contents: (a) σ_3' =10 kPa; (b) σ_3' =30 kPa; (c) σ_3' =60 kPa. 144

Figure 7.8 Volumetric strain- axial strain curves from the test results and model predictions for pure ballast and rubber-ballast mixtures with different R_b contents (test data from: Song et al., 2019): (a) σ =50 kPa; (b) σ =100 kPa; (c) σ =150 kPa. 145

Figure 8.1 Soil sampling refusal at proposed RIBS section of track 149

Figure 8.2 Plan view and cross-section of instrumentation 151

Figure 8.3 Mixing the ballast and rubber granules at the site (a) the materials before mixing, and (b) volumetric mixer while producing RIBS 153

Figure 8.4 Ground preparation (a) excavation starts from the centreline of the track, and (b) the drainage layer on top of the subgrade is separated by a non-woven geotextile 154

Figure 8.5 Particle size distribution of capping material 155

Figure 8.6 Non-destructive density testing for the capping layer 156

Figure 8.7 Data acquisition system 156

Figure 8.8 Stages of RIBS track construction 158

Figure 8.9 Particle size distribution of RIBS in the field trial 161

LIST OF TABLES

Table 2.1 The specific gravity of tyre derived aggregates 15

Table 2.2 Ballast grading requirements AS 2758.7(2015).. 17

Table 2.3 Fouling classification (Selig and Waters, 1994) 18

Table 2.4 Empirical models developed to determine the permanent axial strain after any number of cycles 25

Table 2.5 Summary of previous studies for ballast-rubber mixtures under cyclic loads 37

Table 3.1 Particle sizes most likely to break... 47

Table 3.2 Characteristics of Latite Basalt (after Indraratna et al., (1998)) 51

Table 3.3 Basic properties of RIBS 59

Table 3.4 Monotonic loading triaxial program 60

Table 3.5 Cyclic loading triaxial program 61

Table 4.1 Effective friction angle of pure ballast and RIBS 74

Table 5.1 Empirical parameters of the model for permanent axial deformation 103

Table 7.1 Model parameters used for the validation.. 140

Table 8.1 List of the instruments 152

LIST OF PUBLICATIONS

A. Journal Papers

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C. Awards

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ABSTRACT

Quarried natural rock aggregates are the most demanded type of railway ballast worldwide, attributed to their favourable physical, geotechnical and mechanical properties. After a certain period of operation and fatigue under repeated loading, degraded ballast requires replenishment with freshly quarried ballast, which is one of the most expensive items in track maintenance schemes. Given the current environmental issues, as well as the challenges in obtaining very large quantities of ballast, railway authorities have now looked for other alternatives.

This doctoral study promotes the concept of using rubber granules from waste tyres as elastic aggregates appropriately blended with traditional ballast aggregates for enhanced performance of rail tracks, i.e., a Rubber Intermixed Ballast Stratum (RIBS). During the course of this study, large-scale laboratory experiments were conducted to examine the geotechnical characteristics of RIBS under monotonic loads, and an acceptance criterion was established to determine the rubber content required to optimise the performancep. The outcomes demonstrate that the proximity of 10% rubber granules by weight in the blended assembly, can significantly reduce dilation, control the degradation of the deformation modulus as well as reduce the breakage of natural rock aggregates. However, much higher rubber contents (>15%) may overly reduce the shear strength of the granular mix and also induce relatively large initial settlements. More significantly, replacing the ballast size fraction with rubber particles ranging from 9.5 to 19 mm with similar

angularity is certainly advantageous as they also reduce the breakage of load-bearing coarse aggregates, thus effectively controlling ballast fouling.

The study was further extended to evaluate the characteristics of RIBS subjected to typical cyclic loads by conducting large-scale triaxial tests following a monotonic conditioning phase. The results indicate that irreversible rearrangement of grain configurations during the conditioning phase was pronounced in RIBS leading to a reduction in deformation during cyclic loading. It was also demonstrated that RIBS increases the energy absorption capacity and damping properties compared to fresh ballast, and reduces ballast breakage while maintaining an adequate resilient modulus. Moreover, a constitutive model for rubber-mixed ballast has been developed to explain fundamentally the stress-dilatancy behaviour of RIBS. In a practical perspective, the application of RIBS in real-life tracks is elucidated to encourage railway asset owners and R&D stakeholders to adopt and implement RIBS given its proven sound geotechnical and mechanical properties. Finally, salient considerations of track design and construction are discussed in relation to the use of RIBS while recognising its limitations.