IDENTIFICATION, CHARACTERISATION AND MODELLING OF DYNAMIC

ADHESION FOR OPTIMISED TRANSFER SYSTEM DESIGN

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Ву

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STATEMENT OF ORIGINALITY

I hereby certify that the work embodied in the thesis is my own work, conducted under normal supervision. The thesis contains no material which has been accepted, or is being examined, for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968 and any approved embargo.

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ABSTRACT

The depletion of favourable bulk material deposits in relation to their handleability is prompting the industry to consider mining material that may have comparatively less favourable flow properties. Typically found beneath the water-table, less favourable bulk materials frequently exhibit an increased clay and moisture content, leading to Wet and Sticky Material (WSM) and problematic behaviours regarding handleability. WSMs can have a significant impact in the materials handling stream due to the expensive downtime of processing equipment, which is attributed to the complex inter-particle and boundary adhesion mechanisms found within the bulk material. To better understand the characteristics of WSMs, new theoretical models are required and consequently developed within the scope of this research.

For the identification of a WSM, a comprehensive study was undertaken where revised testing methods have been developed to attain quantifiable measurements for the problematic characteristics of bulk materials. The wall adhesion and inter-particle adhesion tests were developed and adapted for iron ore from existing methods that are typically used for fine powders. These tests have been performed in conjunction with a sweep of traditional flow property tests which were conducted on three iron ore samples. The three iron ore samples have been supplied from the Pilbara region of Western Australia and include; Upper Channel Iron Deposit (UCID), Lower Channel Iron Deposit (LCID) and the Denatured Zone (found between the UCID and LCID layers). The threshold moisture content for problematic behaviours were identified, where, Denatured was identified as the most problematic in relation to the adhesive strength it exhibits.

To further understand the adhesive properties of the iron ore samples, a revised methodology for the estimation of bulk material adhesion determined from the extrapolation of the Instantaneous Yield Locus (IYL) produced from Jenike direct shear testing was undertaken. The predicted adhesion values from this methodology are compared to experimental measurements using an inter-particle adhesion tester where good correlation was found. Once the adhesive properties of each iron ore sample were identified, a theoretical model was developed and validated experimentally to define the dynamic adhesion of the bulk material samples. The developed model was able to predict the geometrical constraints where the identification of the effective angle at which the shear failure equates to a zero-bond depth was found for three typical wall liners used in industry.

Following the identification of the dynamic adhesion geometrical constraints, it was observed by the author that the natural agglomeration of the iron ore samples assisted in the flow of the material through transfer systems. Additionally, it was also observed that the formed agglomerates reduced the amount of dust generated during transportation. An investigation was undertaken on the effects of agglomeration on the materials handling sector where the benefits of reduced build-up and a reduction of dust generation was shown. It was found that for an equivalent Run-of-Mine (ROM) iron ore moisture content, there was a significant reduction for the amount of build-up that commonly leads to potential blockages in industry.

The final aspect of the presented research is the utilisation of numerical simulations for the prediction of problematic behaviours found in industrial systems. The characteristics of WSMs can be computationally expensive to model and with the development of the Discrete Element Method (DEM) in conjunction with the advancement in computational power over the past decade, it is now more feasible to model WSMs in DEM simulations. Three cohesion models capable of replicating WSMs are investigated where the potential to replicate problematic bulk material behaviours and computational solve times are analysed. The models used include; the Simplified Johnson-Kendall-Roberts (SJKR) model, Easo Liquid Bridging model and the Edinburgh Elasto-Plastic Adhesion (EEPA) model.

In this study, the coupling of the SJKR and Easo Liquid Bridging models is proposed and used to predict problematic bulk material behaviour. Additionally, a calibration procedure is developed and undertaken where the parameters for each cohesion model are discussed in detail. A series of calibration simulations with systematic parameter variation was undertaken to define a set of calibration matrices. The developed calibration matrices resulted in the selection of a unique parameter setting, which can be used for the simulation of on-site applications to optimise plant geometry and other operational parameters. Finally, numerical modelling validation was undertaken using a lab scale vertical impact testing facility where good correlation between experimental and simulation results was found.

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NOMENCLATURE

ROMAN SYMBOLS

Α	contact area of adhesion partners	m ²
A_a	area of material stream at exit to "flow-round" zone	m ²
A_p	area of material stream at entrance to "flow-round" zone	m²
a	contact radius of particles in contact	m
A_{cont}	contact area between two particles	m ²
a _{IKR}	contact radius of particles in contact	m
A_{ws}	contact area of wall liner sample	m²
b	intersection point on shear stress axis	Ра
b_w	bulk material stream width	m
C	scaling factor	-
C _h	bulk material cohesion	Ра
Ĉ	resultant force vector for kinetic wall friction tester	Ν
C_{IDST}	cohesion determined using Jenike direct shear tester	Ра
C_n	correction factor for hardness indenter shape	-
d	scaling factor	-
D	inter-particle distance	m
d_2	thickness of capillary liquid	m
d_{o}	liquid bridge rupture distance	m
d_n	diameter of particle	m
$d_{sp/sp}$	interaction of two spheres in contact	m
e	coefficient of restitution	-
E^*	equivalent particle Young's modulus	Ра
F_A	adhesive force	Ν
F _{ad}	adhesive force acting between particles	Ν
F _c	capillary force	Ν
F _{CP}	particle cohesion force	Ν
F_D	frictional drag force	Ν
f_{hys}	sum of hysteretic spring force	Ν
F _{IPA}	inter-particle adhesion force	Ν
F _{normal}	force acting in normal direction	Ν
F_n	external normal force acting on particle	Ν
f_n	normal force acting on particle for EEPA model	Ν
f_{nd}	normal damping force	Ν
f_o	pull-off force	Ν
F_{PO}	pull-off force required to separate two contacting particles	Ν
F _{SJKR}	force required to separate two contacting particles	Ν
$F_{sp/pl}$	capillary force for particle-to-wall contact	Ν
$F_{sp/sp}$	capillary force for particle-to-particle contact	Ν
$F_{tangential}$	force acting in tangential direction	Ν
F_{viscN}	viscous force normal component	Ν
F_{viscT}	viscous force tangential component	Ν
F _{WA}	wall adhesion force	Ν
g	acceleration due to gravity	m/s²
h	adjusted bulk material stream drop height	m
Н	horizontal force component for kinetic wall friction tester	Ν
h_a	thickness of material stream at exit to "flow-round" zone	m
h_b	bulk material burden height	m

H _b	build-up height	m
h _{crit}	critical build-up height where build-up stops	m
h_i	build-up height as defined in Figure 4.10	m
H _{lb}	minimum distance of liquid bridge	m
h_o	initial bulk material stream drop height	m
h_p	thickness of material stream at entrance to "flow-round" zone	m
$\dot{h_s}$	height of rock-box transfer	mm
k_1	initial loading stiffness	N/m
k_2	unloading/loading stiffness	N/m
$\bar{K_a}$	adhesive handleability ranking	-
k _{adh}	adhesive stiffness	N/m
K _c	cohesive handleability ranking	-
K _f	flowability ranking	-
K_n	Hertzian normal stiffness	N/m
k_n	stiffness in normal direction	N/m
k_t	stiffness in tangential direction	N/m
Ĺ	length of roughness measurement	mm
Lo	initial thickness of bulk material stream	m
L_n^{o}	length of indentation along its axis	mm
L	thickness of bulk material stream	m
m	shear index	-
'n	mass flow rate	kg/s
<i>m</i> _{out}	mass flow rate after impact	kg/s
m^*	equivalent particle mass	kg
m_1	residual mass from dynamic adhesion testing	kg
m_{after}	final mass of filter bag and dust	g
m_{haa}	initial mass of filter bag	g
m_{cone}	mass of empty cone	g
Mp	draw down remaining mass	kg
m _{drained}	final mass of drained sample	g
m_{full}	mass of cone filled with sample	g
$M_{\rm S}$	shear box remaining mass	kg
m _{sample}	mass of sample in tumble drum	g
M_{W}	build-up remaining mass	kg
masshulk	mass of bulk material sample	g
$mass_{total}$	mass of bulk material particle	g
n	shear index	-
Ν	normal force	Ν
n_n	power value for force overlap relationship	-
P_{HK}	applied load for Knoop hardness measurement	kgf
R	radius of particle centre to contact point	m
R^*	equivalent particle radii	m
r_1	radius of steel surfaces	m
R_1	radius of particle	m
R_2	radius of particle	m
R_a	centre line average roughness	μm
R_b	radius of material burden centroid	m
R _h	radius of head pulley	m
R _{OZ}	mean radius of material stream curvature	m
R_p	radius of particle	m
r_P	radius of major Mohr stress circle	Ра

R _t	centroid radius of element	m
r_T	radius of major Mohr stress circle	Ра
R_q	root mean square roughness	μm
S	separation distance between particles	m
Т	tensile strength determined using tensile tester	Ра
t	element thickness	m
t _{bc}	belt carry back element thickness	m
\vec{u}	normal vector from particle centre to contact point	-
ν	velocity of mass element	m/s
v_a	thickness of material stream at exit to "flow-round" zone	m/s
v_p	thickness of material stream at entrance to "flow-round" zone	m/s
V	vertical force component for kinetic wall friction tester	Ν
V_b	belt velocity	m/s
V _{bond}	volume of liquid bridge	m³
V_d	discharge velocity	m/s
V_{lb}	volume of liquid bridge	m³
v_n	particle normal relative velocity	m/s
$v_n \overrightarrow{rel}$	normal component of relative velocity	m/s
V _{slc}	surficial liquid volume to solids volume	%
V _{sLi}	particle i surface liquid volume	m³
V_{sLj}	particle j surface liquid volume	m³
v_t	particle tangential relative velocity	m/s
<i>volume_{particle}</i>	volume of bulk material particle	m³
volume _{total}	volume of bulk density testing apparatus	m³
v _{out}	stream velocity off build-up	m/s
W _d	width of rock-box transfer dynamic zone	mm
W _S	width of rock-box transfer static zone	mm
W_{Tot}	total energy of liquid bridge	J
x	power value for adhesion branch	-
<i>x</i> _{c1}	distance from centre to edge of liquid bridge	m
<i>x</i> _{c2}	distance from centre to edge of liquid bridge	m

GREEK SYMBOLS

α	stress angle acting on arbitrary plane	0
α_b	conveyor inclination angle	0
α_c	liquid bridge embracing angle	o
α_d	discharge angle	0
α_i	angle of impact plate	o
α_p	angle of material stream inflow to impact plate	o
β	damping coefficient	-
β_o	ore surface angle	o
β_p	impact plate inclination angle	0
β_{wall}	wall liner angle	0
γ	liquid surface tension	N/m
γ_b	bulk material specific weight	kN/m³
Ύd	dynamic shear angle determined from rock-box transfer	0
γ_n	coefficient of critical damping in normal direction	-
γ_s	static shear angle determined from rock-box transfer	o
γ_t	coefficient of critical damping in tangential direction	-
ΔA	element contact area	m²
ΔA_h	stream element contact area	m²
ΔA_{IPA}	element contact area between inter-particle bonds	m²
ΔA_{WA}	element contact area between element and belt surface	m²
ΔA_t	belt carry back element contact area	m²
ΔF_c	centrifugal force	N
ΔG	gravitational force	Ν
Δh_i	incremental change in build-up height	m
Δm	element mass	kg
Δr	change in radius	m
$\Delta \gamma$	contact surface energy	N/m
δ	effective angle of internal friction	0
δ_1	half filling angle	8
δ_2	half filling angle	0
δ_{JKR}	particle overlap for JKR contact model	m
δ_{min}	particle overlap where minimum hysteretic force occurs	m
δ_n	particle overlap in normal direction	m
δ_p	plastic particle overlap	m
δ_{po}	plastic overlap	m
Е	voidage acting between particles	-
ε _c	admissible relative deviation value	%
ε_D	shear angle determined using draw down test	0
\mathcal{E}_{r}	co-efficient of restitution	-
ε _s	shear angle determined using shear box test	0
θ	total inclination angle	0
θ_a	Horizontal angle of material stream inflow to impact plate	0
θ_c	liquid bridge contact angle	0
θ_{eff}	effective contact angle between particles I and J	Ū.
μ	coefficient of friction	-
μ_f	viscosity of fluid	m²/s
μ_k	kinematic surface friction	-
μ_p	particle-to-particle friction	-
μ_r	particle rolling friction	-

μ_s	particle sliding friction	-
μ_{st}	static surface friction	-
$ ho_{bulk}$	bulk density of bulk material sample	kg/m³
$ ho_{particle}$	particle solids density of bulk material sample	kg/m³
σ	normal stress	Ра
σ_1	major principal stress	Ра
σ_{1c}	nominated consolidation pressure	Ра
σ_2	minor principal stress	Ра
σ_{lpha}	acting normal stress	Ра
σ_a	adhesive stress	Ра
σ_{ao}	adhesive strength	Ра
$\sigma_{a(lin)}$	adhesive stress linear prediction	Ра
$\sigma_{a(par)}$	adhesive stress parabolic prediction	Ра
σ_{ave}	average principal stress	Ра
σ_c	unconfined yield strength	Ра
σ_{co}	cohesive strength	Ра
σ_{IPA}	inter-particle adhesion stress	Ра
σ_n	normal stress for kinetic wall friction tester	Ра
σ_P	pre-consolidation normal stress	Ра
σ_s	shear stress for kinetic wall friction tester	Ра
σ_{ST}	liquid surface tension	N/m
σ_t	tensile adhesive strength	Ра
σ_T	normal stress component connecting IYL and major Mohr circle	Ра
σ_w	normal stress to the wall	Ра
σ_{wa}	tensile strength from wall adhesion tester	Ра
σ_{WA}	wall adhesion stress	Ра
τ	shear stress	Ра
$ au_{lpha}$	acting shear stress	Ра
$ au_k$	kinematic shear stress	Ра
$ au_o$	cohesive stress	Ра
$ au_P$	pre-consolidation shear stress	Ра
$ au_s$	static shear stress	Ра
$ au_T$	shear stress component connecting IYL and major Mohr circle	Ра
τ_w	shear stress at the wall	Ра
τ_{wa}	cohesive stress at the wall	Ра
φ	planing angle for kinetic wall friction tester	0
φ_f	angle co-ordinate of flow round zone	0
φ_{imp}	impingement angle	0
φ_t	angle of internal friction	0
φ_w	wall friction angle	o
Ω_{AED}	adhesion energy density	J/m³
Ω_{CED}	cohesion energy density	J/m³
ω_D	angle of repose determined using draw down test	o

ABBREVIATIONS

AED	Adhesion Energy Density
AOR	Angle of Repose
AR	Adhesive Handleability Ranking
BIF	Banded Iron-Formation
CED	Cohesion Energy Density
CID	Channel Iron Deposit
CLA	Centre Line Average
COR	Coefficient of Restitution
CPU	Central Processing Unit
CR	Cohesive Handleability Ranking
DEM	Discrete Element Method
DEMC	Dust Extinction Moisture Content
DMT	Derjaguin-Muller-Toporov
EEPA	Edinburgh Elasto-Plastic Adhesion
EYL	Effective Yield Locus
GPU	Graphics Processing Unit
нк	Knoop Hardness
IOA	Iron Ore A
IOB	Iron Ore B
IOC	Iron Ore C
IYL	Instantaneous Yield Locus
JKR	Johnson-Kendall-Roberts
LAMMPS	Large-scale Atomic/Molecular Massively
	Parallel Simulator
LCID	Lower Channel Iron Deposit
LIGGGHTS	LAMMPS Improved for General Granular
	and Granular Heat Transfer Simulations
MC	Moisture Content
PF	Particle Sliding Friction
PFA	Powder Flow Analyser
PSD	Particle Size Distribution
RF	Particle Rolling Friction
RMS	Root Mean Square
ROM	Run-of-Mine
RSD	Rotary Sample Divider
SDMC	Saturated Drained Moisture Content
SJKR	Simplified Johnson-Kendall-Roberts
ST	Surface Tension
UCID	Upper Channel Iron Deposit
WSBCT	Warren Spring-Bradford Cohesion Tester
WSM	Wet and Sticky Material
WYL	Wall Yield Locus
XRF	X-Ray Fluorescence

PUBLICATIONS

The following publications have been produced during the time of the PhD candidature:

JOURNAL

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CONFERENCE

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