IDENTIFICATION, CHARACTERISATION AND MODELLING OF DYNAMIC ADHESION FOR OPTIMISED TRANSFER SYSTEM DESIGN

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By

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DOCTOR OF PHILOSOPHY

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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

A	*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*	m^2
a	*contact radius of particles in contact*	m
A_{cont}	*contact area between two particles*	m^2
a_{JKR}	*contact radius of particles in contact*	m
A_{ws}	*contact area of wall liner sample*	m^2
b	*intersection point on shear stress axis*	Pa
b_w	*bulk material stream width*	m
c	*scaling factor*	-
c_b	*bulk material cohesion*	Pa
C	*resultant force vector for kinetic wall friction tester*	N
C_{JDST}	*cohesion determined using Jenike direct shear tester*	Pa
C_p	*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_p	*diameter of particle*	m
$d_{sp/sp}$	*interaction of two spheres in contact*	m
e	*coefficient of restitution*	-
E^*	*equivalent particle Young’s modulus*	Pa
F_A	*adhesive force*	N
F_{ad}	*adhesive force acting between particles*	N
F_c	*capillary force*	N
F_{CP}	*particle cohesion force*	N
F_D	*frictional drag force*	N
f_{hys}	*sum of hysteretic spring force*	N
F_{IPA}	*inter-particle adhesion force*	N
F_{normal}	*force acting in normal direction*	N
F_n	*external normal force acting on particle*	N
f_n	*normal force acting on particle for EEPA model*	N
f_{nd}	*normal damping force*	N
f_o	*pull-off force*	N
F_{PO}	*pull-off force required to separate two contacting particles*	N
F_{SJKR}	*force required to separate two contacting particles*	N
$F_{sp/pl}$	*capillary force for particle-to-wall contact*	N
$F_{sp/sp}$	*capillary force for particle-to-particle contact*	N
$F_{tangential}$	*force acting in tangential direction*	N
F_{viscN}	*viscous force normal component*	N
F_{viscT}	*viscous force tangential component*	N
F_{WA}	*wall adhesion force*	N
g	*acceleration due to gravity*	m/s^2
h	*adjusted bulk material stream drop height*	m
H	*horizontal force component for kinetic wall friction tester*	N
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
h_s	*height of rock-box transfer*	mm
k_1	*initial loading stiffness*	N/m
k_2	*unloading/loading stiffness*	N/m
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
L	*length of roughness measurement*	mm
L_o	*initial thickness of bulk material stream*	m
L_p	*length of indentation along its axis*	mm
L_s	*thickness of bulk material stream*	m
m	*shear index*	-
$\dot{m}$	*mass flow rate*	kg/s
$\dot{m}_{out}$	*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_{bag}	*initial mass of filter bag*	g
m_{cone}	*mass of empty cone*	g
M_D	*draw down remaining mass*	kg
$m_{drained}$	*final mass of drained sample*	g
m_{full}	*mass of cone filled with sample*	g
M_S	*shear box remaining mass*	kg
m_{sample}	*mass of sample in tumble drum*	g
M_W	*build-up remaining mass*	kg
$mass_{bulk}$	*mass of bulk material sample*	g
$mass_{total}$	*mass of bulk material particle*	g
n	*shear index*	-
N	*normal force*	N
n_p	*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*	Pa

R_t	*centroid radius of element*	m
r_T	*radius of major Mohr stress circle*	Pa
R_q	*root mean square roughness*	µm
S	*separation distance between particles*	m
T	*tensile strength determined using tensile tester*	Pa
t	*element thickness*	m
t_{bc}	*belt carry back element thickness*	m
$\vec{u}$	*normal vector from particle centre to contact point*	-
v	*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*	N
V_b	*belt velocity*	m/s
V_{bond}	*volume of liquid bridge*	m^3
V_d	*discharge velocity*	m/s
V_{lb}	*volume of liquid bridge*	m^3
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*	m^3
V_{sLj}	*particle j surface liquid volume*	m^3
v_t	*particle tangential relative velocity*	m/s
$volume_{particle}$	*volume of bulk material particle*	m^3
$volume_{total}$	*volume of bulk density testing apparatus*	m^3
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*	-
x_{c1}	*distance from centre to edge of liquid bridge*	m
x_{c2}	*distance from centre to edge of liquid bridge*	m

GREEK SYMBOLS

α	*stress angle acting on arbitrary plane*	°
α_b	*conveyor inclination angle*	°
α_c	*liquid bridge embracing angle*	°
α_d	*discharge angle*	°
α_i	*angle of impact plate*	°
α_p	*angle of material stream inflow to impact plate*	°
β	*damping coefficient*	-
β_o	*ore surface angle*	°
β_p	*impact plate inclination angle*	°
β_{wall}	*wall liner angle*	°
γ	*liquid surface tension*	N/m
γ_b	*bulk material specific weight*	kN/m^3
γ_d	*dynamic shear angle determined from rock-box transfer*	°
γ_n	*coefficient of critical damping in normal direction*	-
γ_s	*static shear angle determined from rock-box transfer*	°
γ_t	*coefficient of critical damping in tangential direction*	-
ΔA	*element contact area*	m^2
ΔA_h	*stream element contact area*	m^2
ΔA_{IPA}	*element contact area between inter-particle bonds*	m^2
ΔA_{WA}	*element contact area between element and belt surface*	m^2
ΔA_t	*belt carry back element contact area*	m^2
ΔF_c	*centrifugal force*	N
ΔG	*gravitational force*	N
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*	°
δ_1	*half filling angle*	°
δ_2	*half filling angle*	°
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
ε	*voidage acting between particles*	-
ε_c	*admissible relative deviation value*	%
ε_D	*shear angle determined using draw down test*	°
ε_r	*co-efficient of restitution*	-
ε_S	*shear angle determined using shear box test*	°
θ	*total inclination angle*	°
θ_a	*Horizontal angle of material stream inflow to impact plate*	°
θ_c	*liquid bridge contact angle*	°
θ_{eff}	*effective contact angle between particles i and j*	°
μ	*coefficient of friction*	-
μ_f	*viscosity of fluid*	m^2/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*	-
ρ_{bulk}	*bulk density of bulk material sample*	kg/m^3
$\rho_{particle}$	*particle solids density of bulk material sample*	kg/m^3
σ	*normal stress*	Pa
σ_1	*major principal stress*	Pa
σ_{1c}	*nominated consolidation pressure*	Pa
σ_2	*minor principal stress*	Pa
σ_α	*acting normal stress*	Pa
σ_a	*adhesive stress*	Pa
σ_{ao}	*adhesive strength*	Pa
$\sigma_{a(lin)}$	*adhesive stress linear prediction*	Pa
$\sigma_{a(par)}$	*adhesive stress parabolic prediction*	Pa
σ_{ave}	*average principal stress*	Pa
σ_c	*unconfined yield strength*	Pa
σ_{co}	*cohesive strength*	Pa
σ_{IPA}	*inter-particle adhesion stress*	Pa
σ_n	*normal stress for kinetic wall friction tester*	Pa
σ_P	*pre-consolidation normal stress*	Pa
σ_s	*shear stress for kinetic wall friction tester*	Pa
σ_{ST}	*liquid surface tension*	N/m
σ_t	*tensile adhesive strength*	Pa
σ_T	*normal stress component connecting IYL and major Mohr circle*	Pa
σ_w	*normal stress to the wall*	Pa
σ_{wa}	*tensile strength from wall adhesion tester*	Pa
σ_{WA}	*wall adhesion stress*	Pa
τ	*shear stress*	Pa
τ_α	*acting shear stress*	Pa
τ_k	*kinematic shear stress*	Pa
τ_o	*cohesive stress*	Pa
τ_P	*pre-consolidation shear stress*	Pa
τ_s	*static shear stress*	Pa
τ_T	*shear stress component connecting IYL and major Mohr circle*	Pa
τ_w	*shear stress at the wall*	Pa
τ_{wa}	*cohesive stress at the wall*	Pa
φ	*planing angle for kinetic wall friction tester*	°
φ_f	*angle co-ordinate of flow round zone*	°
φ_{imp}	*impingement angle*	°
φ_t	*angle of internal friction*	°
φ_w	*wall friction angle*	°
Ω_{AED}	*adhesion energy density*	J/m^3
Ω_{CED}	*cohesion energy density*	J/m^3
ω_D	*angle of repose determined using draw down test*	°

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ABBREVIATIONS

AED	**A**dhesion **E**nergy **D**ensity
AOR	**A**ngle **o**f **R**epose
AR	**A**dhesive Handleability **R**anking
BIF	**B**anded **I**ron-**F**ormation
CED	**C**ohesion **E**nergy **D**ensity
CID	**C**hannel **I**ron **D**eposit
CLA	**C**entre **L**ine **A**verage
COR	**C**oefficient **o**f **R**estitution
CPU	**C**entral **P**rocessing **U**nit
CR	**C**ohesive Handleability **R**anking
DEM	**D**iscrete **E**lement **M**ethod
DEMC	**D**ust **E**xtinction **M**oisture **C**ontent
DMT	**D**erjaguin-**M**uller-**T**oporov
EEPA	**E**dinburgh **E**lasto-**P**lastic **A**dhesion
EYL	**E**ffective **Y**ield **L**ocus
GPU	**G**raphics **P**rocessing **U**nit
HK	**K**noop **H**ardness
IOA	**I**ron **O**re **A**
IOB	**I**ron **O**re **B**
IOC	**I**ron **O**re **C**
IYL	**I**nstantaneous **Y**ield **L**ocus
JKR	**J**ohnson-**K**endall-**R**oberts
LAMMPS	**L**arge-scale **A**tomic/**M**olecular **M**assively **P**arallel **S**imulator
LCID	**L**ower **C**hannel **I**ron **D**eposit
LIGGGHTS	**L**AMMPS **I**mproved for **G**eneral **G**ranular and **G**ranular **H**eat **T**ransfer **S**imulations
MC	**M**oisture **C**ontent
PF	**P**article Sliding **F**riction
PFA	**P**owder **F**low **A**nalyser
PSD	**P**article **S**ize **D**istribution
RF	Particle **R**olling **F**riction
RMS	**R**oot **M**ean **S**quare
ROM	**R**un-**o**f-**M**ine
RSD	**R**otary **S**ample **D**ivider
SDMC	**S**aturated **D**rained **M**oisture **C**ontent
SJKR	**S**implified **J**ohnson-**K**endall-**R**oberts
ST	**S**urface **T**ension
UCID	**U**pper **C**hannel **I**ron **D**eposit
WSBCT	**W**arren **S**pring-**B**radford **C**ohesion **T**ester
WSM	**W**et and **S**ticky **M**aterial
WYL	**W**all **Y**ield **L**ocus
XRF	**X**-**R**ay **F**luorescence

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PUBLICATIONS

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

JOURNAL

Carr, M. J., Roberts, A. W. and Wheeler, C. A., 2019. *A Revised Methodology for the Determination of Bulk Material Cohesion and Adhesion.* Advanced Powder Technology, Vol. 30, No. 10, pp. 2110-2116. (doi:10.1016/j.apt.2019.06.025)

CONFERENCE

Carr, M., Roberts, A. and Wheeler, C., 2018. *A Revised Methodology for Cohesion and Adhesion Analysis of Bulk Materials.* In: Proceedings 9th International Conference for Conveying and Handling of Particulate Solids - CHoPS 2018. London, United Kingdom.

Carr, M., Wheeler, C., Williams, K., Katterfeld, A., Elphick, G., Nettleton, K. and Chen, W., 2018. *Discrete Element Modelling of Problematic Bulk Solids onto Impact Plates.* In: Proceedings 9th International Conference for Conveying and Handling of Particulate Solids - CHoPS 2018. London, United Kingdom.

Carr, M., Plinke, J., Williams, K., Roberts, A. and Chen, W. 2017. *Determination of the Handleability Index of Adhesive Bulk Materials.* In: Proceedings AusIMM (6th Ed.), Iron Ore 2017 Conference Proceedings. Australasian Institute of Mining and Metallurgy (AusIMM), Perth, Australia.

Carr, M., Williams, K., Chen, W., Hayter, B., Roberts, A. and Wheeler, C., 2017. *The Dynamic Adhesion of Wet and Sticky Iron Ores onto Impact Plates*. In: Proceedings AusIMM (6th Ed.), Iron Ore 2017 Conference Proceedings. Australasian Institute of Mining and Metallurgy (AusIMM), Perth, Australia.

Carr, M. J., Chen, W., Williams, K. and Katterfeld, A., 2016. *Comparative Investigation on Modelling Wet and Sticky Material Behaviours with a Simplified JKR Cohesion Model and Liquid Bridging Cohesion Model in DEM.* In: Proceedings 12th International Conference on Bulk Solids Material Storage, Handling and Transport (ICBMH), Darwin, Australia.