

RBCT PHASE V EXPANSION PROJECT CASE STUDY AND FOCUS ON BELT FEEDER USING DEM (DISCRETE ELEMENT MODELLING)

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1. PROJECT INTRODUCTION

Richards Bay Coal Terminal (RBCT), based in KwaZulu-Natal, South Africa, handles coal exports to buyers globally. Its main shareholders are Anglo Operations Ltd, BHP Billiton Energy Coal South Africa, Xstrata Coal South Africa, Optimum Coal Holdings, Exxaro Coal (Pty) Ltd, Kangra Coal, Sasol Coal Mining, Total Coal South Africa, South Dunes Coal Terminal Company, Koorfontein Mines, Exxaro Mpumalanga Coal (Pty) Ltd and Common Users (Quattro).

The Phase V expansion project was partially funded by the South Dunes Coal Terminal Company. As is the case for all new users, a number of black empowered coal exporters were included which enabled them to become shareholders in RBCT. The main contractor on the project was responsible for detailed design, construction and commissioning of the expansion of the facility. The contract was structured as an EPC contract (Engineering Procurement and Construction).

2. SCOPE OF WORK

The project objective was to increase the annual capacity of the terminal from 72 million tonnes to 91 million tonnes, making it the largest single export coal terminal in the world. The scope of work included major civil works and bridges, construction of all the substations, a water management system, rail network upgrading, rail signalling, rail electrification, upgrading of electrical infrastructure, instrumentation, replacement of the terminal control system, an additional 60 wagon/hour tandem tippler for rail wagon offloading, a 6 000 tph bucket wheel stacker-reclaimer to service a new, additional 26 hectare stockpile area, and a complete conveyor system expansion.

3. PROJECT DURATION

The project was officially awarded in late 2006 and handed over to the client in April 2010.

4. KEY TECHNICAL FACTORS

4.1 General Design Criteria

Description	Data
Product Conveyed	Clean (Export) coal
Max. Particle Size	-50 mm, 95% (80 mm, max.)
Moisture Content	20% max
Bulk Density	
Power	800 kg/m ³
Volumetric	720 kg/m ³
Angle of Repose	27° - 48°
Material Surcharge angle	20°

Table 1. Design criteria

4.2 Conveyors

The conveyor portion of the project included the extension of a number of existing conveyors as well as various new conveyors totalling 3.8 km in length. Three of the pertinent conveyors which formed part of this expansion are discussed.

4.2.1 Conveyor CV610

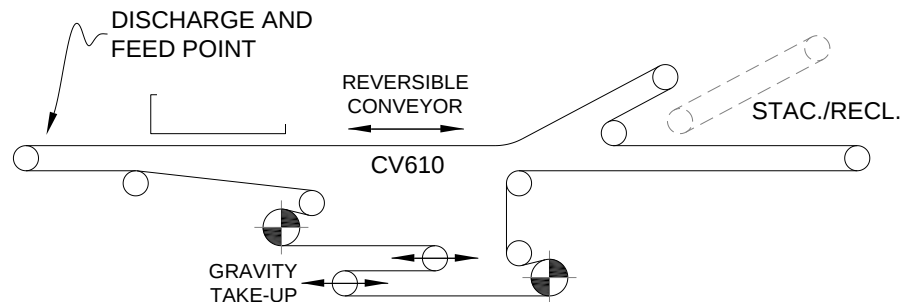


Figure 1. CV610 Diagram

Description	Data
Capacity	6,000 tph
Belt Width	1800 mm
Belt Speed	5.45 m/s
Length	1,644 m
Extension	-
Lift	7.7 m
Belt Type	1250 / 5 ply
Power	4x 375 kW

Table 2. CV610 Design specifications

Features:

- Reversible belt (take-up between drives (Figure 1))
- Tripper elevates belt during stacking mode
- Pivot feed chute
- Tail brake.

Lessons learnt:

- If the correct material properties in DEM simulations are uncertain but in the right 'ballpark' DEM still remains quite accurate for chute flow behaviour. It is a definitive tool which should be used in advance to optimise designs before manufacture, or to check designs for blockages before commissioning
- Idlers cannot be installed too long in advance as the idler supplier will not guarantee the bearings unless the idlers are all rotated on a regular basis.

Challenges:

- Pivot chute fed partly onto the belt transition area.



Figure 2. CV610 New stockyard conveyor

4.2.2 Conveyor CV623

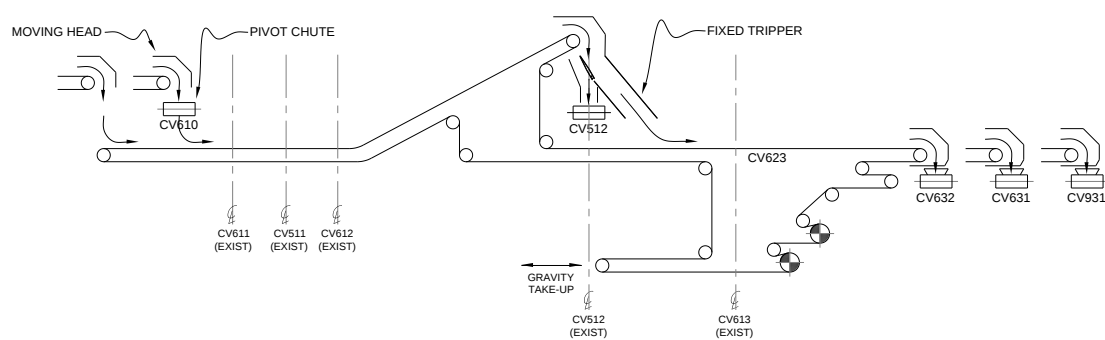


Figure 3. CV623 Diagram

Description	Data
Capacity	12,000 tph
Belt Width	2200 mm
Belt Speed	6.7 m/s
Length	625 m
Extension	-
Lift	6.5 m
Belt Type	ST 1250
Power	4x 485 kW

Table 3. CV623 Design specifications

Features:

- Maximum conveying capacity of 12 000 tph
- 6 000 tph feed rate interlocked with conveyor being fed
- Three-way moving head
- Complex transfer chute system feeding onto tail section.

- Fixed tripper
- Drives with flywheels installed to ensure smooth ramp-down for the immediate period after a conveyor trip
- Tail brake installed to prevent over filling of head chutes which engages gently after a stoppage in order not to counteract the aforementioned function of the flywheels.

Lessons learnt:

- Surges of material extracted from the feed chute and skirt box should be expected during conveyor start-up and can collide with intermediate chutes feeding onto the conveyor. Fine and moist material forms were higher than anticipated surcharge angles
- Depending on the distance between separate loading chutes, a continuous skirt plate is recommended to avoid spillage.

Challenges:

- To work closely with the client to plan and maintain commissioning schedules, especially on brown fields type projects where production is always a priority.



Figure 4. CV623 New stockyard spine conveyor transfer

4.2.3 Conveyor CV731

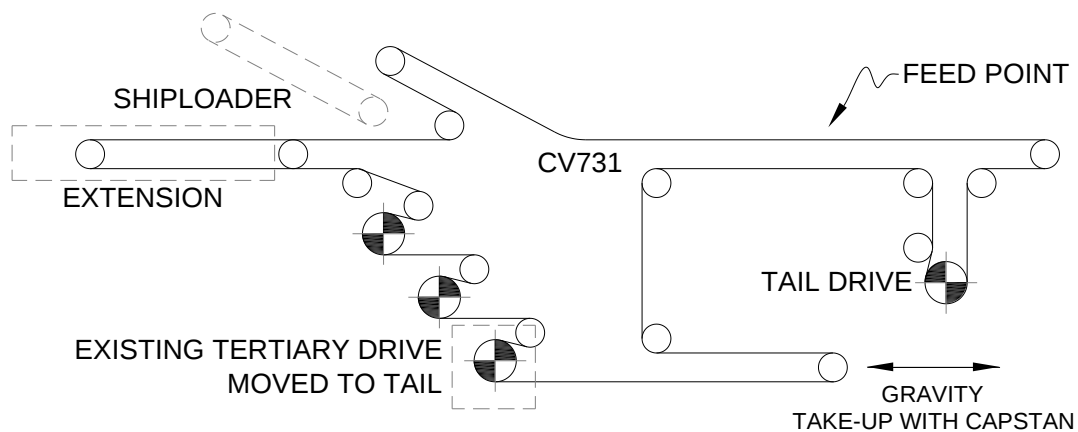


Figure 5. CV731 Diagram

Description	Data
Capacity	10,000 tph
Belt Width	2200 mm
Belt Speed	5.4 m/s
Length	1,206 m
Extension	120 m
Lift	8 m
Belt Type	1250 / 5 ply
Power	4x 450 kW

Table 4. CV731 Design specifications

Features:

- Tail drive installed (tertiary drive removed)
- Moveable tripper at shiploader
- Capstan winch.

Lessons learnt:

- The size of a fluid coupling cooler should be questioned as it may be too small depending on the permissible oil temperature after the number of consecutive conveyor start-ups required by the client specification.

Challenges:

- The existing conveyor did not comply to the stringent fluid coupling oil temperature specification before the extension. Extensive time and effort was spent on the start-up procedure, and to ensure that the oil temperature did not exceed the prescribed limit
- During the construction phase it was noticed that the conveyor steelwork levels on the wharf varied over time.



Figure 6. CV731 Wharf conveyor extension

5. DEM INTRODUCTION

The saying, 'garbage in, garbage out' is well known. The predicament in the industry is to accept that the outcome from any DEM (Discrete Element Modelling) simulation is functional, and that no standards currently exist for the determination of material input parameters required by DEM software.

To yield realistic results with flow simulations, some particle parameters may be used exactly as they are, and in other cases they have to be obtained experimentally by ensuring that the

particles in DEM behave, in practice, in the same way as the bulk solids. One or two actual particle parameters may have to be customised to increase the simulation speed due to software and hardware processing constraints.

The objective in this case was to establish acceptable DEM material input and interaction parameters for conveyor belt feeder loads. It could then also be used to verify and optimise future designs.

The procedure starts with the study of standard laboratory bulk solid flow material tests, and uses those tests as a reference to set up and perform relevant tests in the DEM software. It is necessary to ensure that the material input properties are proven to behave the same way as the bulk solids in practice. A typical laboratory report containing material properties for export quality coal was acquired, and the information was used to perform feeder load calculations.

The focus of the research was then transferred to a new conveyor belt feeder at RBCT which was installed to extract export coal from a hopper. Export coal is transported via rail from various coal mines across the country. A train of up to 200 wagons then arrives at RBCT, with each wagon containing approximately 84 tonnes of coal. By means of a tandem wagon tippler, the coal in two wagons is emptied into a split hopper. Belt feeders CV013 and CV014 then extract the coal from their individual hoppers. CV013 is identical to CV014. They feed the coal into a shared head chute which joins the coal stream from the two feeders, and feeds it via one chute onto conveyor CV015. There are five similar systems at RBCT including this installation. (Figures 7 to 11).

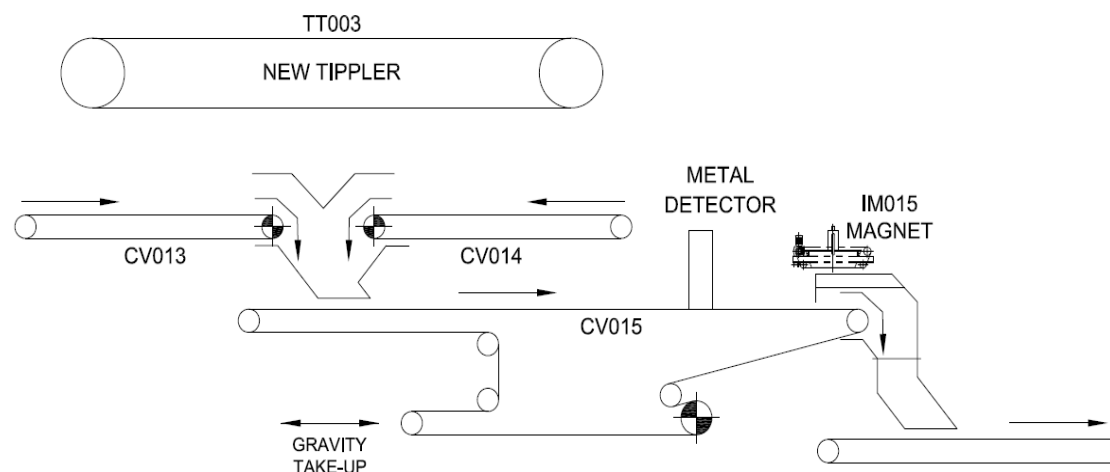


Figure 7. Process flow diagram



Figure 8. Train arriving at tippler



Figure 9. Wagons being tipped (tippler top view)



Figure 10. Wagons being tipped (tippler side view)



Figure 11. Empty wagons leaving tippler

The belt feeder was analysed on site to determine the actual horizontal shear force on start-up when the hopper is fully loaded. The feeder load calculations can then be verified using this information as well as to ascertain what shear resistance should be in the investigational DEM simulation.

In this investigation, the DEM software package called 'EDEM' was used which meant that there were three material properties and three material interaction inputs required.

Properties such as Poisson's ratio, the density (specific gravity) and the shear modulus are the material inputs. The coefficient of restitution, coefficient of static friction and coefficient of rolling friction are referred to as material interactions.

Poisson's ratio, the density, the shear modulus and the coefficient of restitution were employed in the simulation as fixed parameters. A full scale 3D model of the belt feeder and hopper system was generated to run the required experimental DEM simulations for the verification of the remaining material interaction properties, such as the coefficient of static friction and coefficient of rolling friction, to match the end results of the calculations and site data.

The basic knowledge that is required to understand the underlying factors affecting the bulk solid flow behaviour in DEM simulations will be discussed. Some DEM material tests and physical experiments were covered after a literature study. This report concludes with a discussion on the way forward as well as recommendations for future work.

6. DEM (DISCRETE ELEMENT MODELLING) SOFTWARE

Discrete Element Modelling software is designed for the simulation and analysis of bulk particulate solids handling and manufacturing operations, and allows for the importation and creation of geometrical models which interact with particles.

The software can generate particles through various means designated by the user. Before a simulation can start, all the material and geometry inputs including the interaction parameters need to be defined. Geometry dynamics can also be set up if required

DEM simulations can produce a wealth of valuable data [1] including:

- Internal behaviour of a granular bulk material interacting with machine surfaces
- Magnitude, frequency and distribution of collisions between system components
- Velocity and location of each particle
- Energy associated with impact, abrasion, cohesion and de-bonding of particles within a bulk
- Force chains and structural integrity of meta-particle structures.

The simulated particle interactions are analysed to obtain the design information. The results of a DEM simulation can be used for validating a prototype or for optimising new or existing designs.

6.1 Discrete Element Method

The discrete element method as utilised in the DEM software package is a numerical technique that computes the motion and interaction of large numbers of particles. The method was detailed in 1985 by Williams, Hocking and Mustoe [2] who generalised the finite element method.

The simulation contact model used in this case was the Hertz-Mindlin type which is used for all particle-particle and particle-geometry contact behaviour. The contact model is used to calculate all the particle contact forces existing between particles making contact. The model is based on the work of Mindlin [3]. The technical description of the contact model and the factors affecting the contact forces are shown below.

The contact mechanics can be considered as a 'spring-dashpot' configuration.

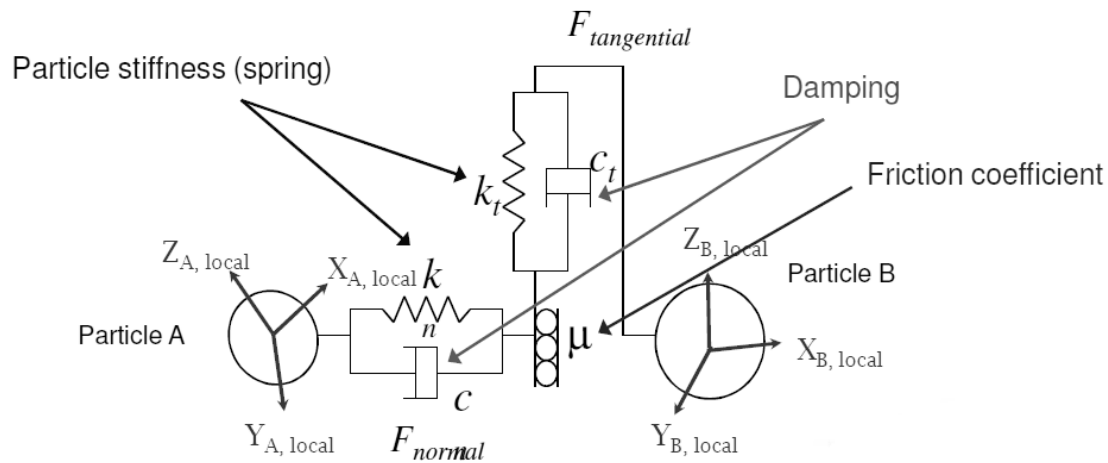


Figure 12. Typical contact model [4]

The normal force between particles is given by:

$$F_n = \frac{4}{3} Y \sqrt{R \delta_n^{\frac{3}{2}}}$$

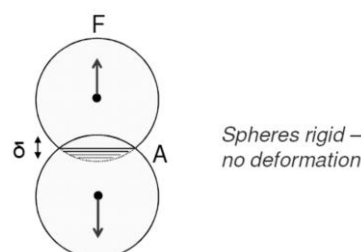
where

Y is the equivalent Young's modulus

R is the equivalent radius

δ_n is the normal overlap

Note: Contact force calculations are based on sphere overlaps; the selected contact model determines how force is applied [4]



The damping force between elements is given by:

$$F_n^d = -2 \sqrt{\frac{5}{6}} \beta \sqrt{S_n m} v_n^{\overline{rel}}$$

where

m is the equivalent mass

$v_n^{\overline{rel}}$ is the normal component of the relative velocity

The normal particle stiffness is given by:

$$S_n = 2 Y \sqrt{R \delta_n}$$

$$\beta = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}}$$

where

e is the coefficient of restitution

Tangential forces are based on tangential overlap

Tangential force is given by:

$$F_t = -S_t \delta_t$$

where

S_t is the tangential stiffness

δ_t is the tangential overlap

$$S_t = 8 G \sqrt{R \delta_n}$$

where

G is the equivalent shear modulus

Tangential damping is given by:

$$F_t^d = -2 \sqrt{\frac{5}{6}} \beta \sqrt{S_t m} v_t^{\overline{rel}}$$

where

$v_t^{\overline{rel}}$ is the relative tangential velocity

The tangential force is limited by Coulomb friction:

$$\mu_s F_n$$

where

μ_s is the coefficient of static friction

Rolling friction is accounted for by applying a torque to the contacting surfaces as follows:

$$\tau_i = -\mu_r F_n R_i \omega_i$$

where

μ_r is the coefficient of rolling friction

R_i is the distance of the contact point from the centre of mass of the object

ω_i is the unit angular velocity vector of the object at the contact point

The equations above directly relate the material properties that form part of this investigation to the mathematical simulation of contact forces. The Young's modulus is calculated from the program input parameters using the Poisson ratio and the shear modulus.

6.2 Bulk Solids Flow Influencing Factors

Bulk solid handling refers to the transfer of material from one location to another. The factors influencing the flow behaviour of material are investigated; these factors are divided into two subgroups:

- Extrinsic properties
- Intrinsic properties

Extrinsic properties are external effects on the bulk material such as the moisture content of the bulk material. The intrinsic properties which will be dealt with include the material shear modulus, coefficient of restitution, and the coefficient of static and rolling friction.

6.2.1 Moisture content

Coal was used in this investigation. Moisture is an important property of coal, as all coals are mined wet. Groundwater and other extraneous moisture is known as adventitious moisture and is readily evaporated. Moisture held within the coal itself is known as inherent moisture and is analysed quantitatively. Moisture in coal may occur in four possible forms [5].

- Surface moisture: water held on the surface of coal particles
- Hygroscopic moisture: water held by capillary action within the micro fractures of the material
- Decomposition moisture: water held in the coal's decomposed organic compounds
- Mineral moisture: water which comprises part of the crystal structure of hydrous silicates such as clays.

Total moisture is analysed by loss of mass between an untreated sample and the sample once analysed. This is achieved by any of the following [5] methods:

1. Heating the coal with toluene
2. Drying in a minimum free space oven at 150°C within a nitrogen atmosphere
3. Drying in air at 100°C to 105°C and relative loss of mass determined.

Inherent moisture is analysed similarly, though it may be done in a vacuum.

The effect of moisture on bulk solids in DEM is achieved by varying the cohesion between the particles. Cohesion can be applied to particle-particle and particle-geometry interactions, and involves an additional normal force during the contact. The primary reason for considering the moisture content of bulk material is linked to the effect that it has on the material handling properties. The moisture for this exercise would not be beneficial in a way that would contribute to the final results, but it does provide a benchmark for further studies.

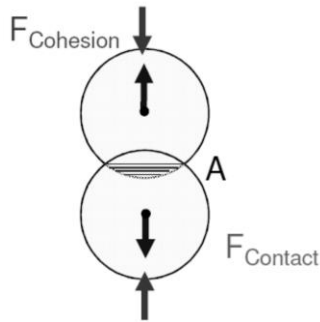
The additional normal force is given by:

$$F_N = kA$$

where

A is the overlap area (calculated from the normal overlap)

K is the energy density



The level of cohesion is increased by increasing the energy density, and can be determined in DEM by simple trial and error.

6.2.2 Coefficient of static friction and rolling friction

The coefficient of static friction [6] is defined as the ratio of the static friction force to the normal force of an element on a surface.

The static friction force, F , can be defined by the following equation:

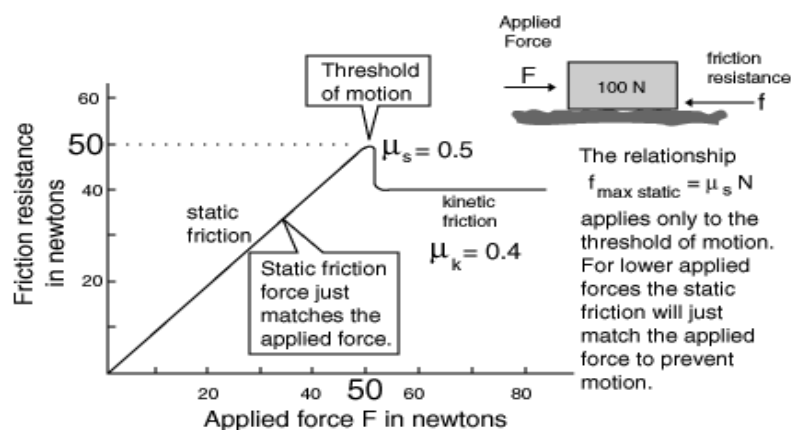
$$F = \mu_s N$$

where

N is the normal force of the object in newtons.

If a body is lying in the horizontal plane, a horizontal force exceeding that of the static friction force would need to be applied before the body starts moving. The coefficient of static friction is largely dependent on the material interaction and the surface finish at the point of contact. In this investigation, the static friction coefficient is determined for particle-particle interaction (coal-on-coal) and particle-wall interaction (coal-on-steel).

The coefficient of rolling friction is determined in exactly the same manner as that of the static friction coefficient. The coefficient is tested with relative ease for spherical particles, but the testing becomes problematic for the coefficient determination of arbitrarily shaped particles. The computing power requirements for a DEM simulation increase dramatically for non-spherical particles; this leads to the concept of adjusting the coefficient of rolling friction for a spherical particle to simulate that of one which is arbitrarily shaped.



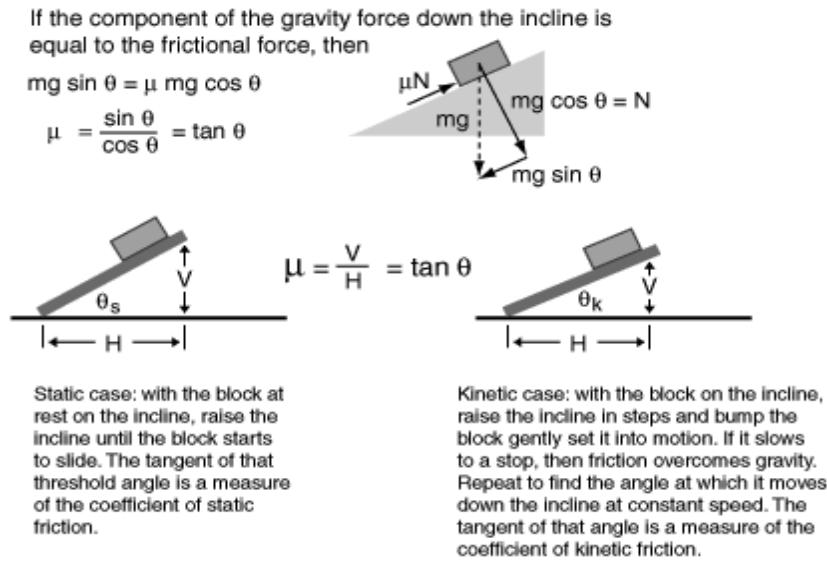


Figure 13. Illustration of static and kinetic friction

6.2.3 Poisson's ratio

Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force. Tensile deformation is considered positive and compressive deformation is considered negative. Virtually all common materials become narrower in cross-section when they are stretched.

The reason why, in the continuum view, is that most materials resist a change in volume as determined by the bulk modulus K , more than they resist a change in shape, as determined by the shear modulus, G . Poisson's effect is caused by slight movements between molecules and the stretching of molecular bonds within the material lattice to accommodate the stress. When the bonds elongate in the stress direction, they shorten in the other directions.

Material	Poisson's ratio
Isotropic upper limit	0.5
Rubber	0.48 ~0.5
Lead	0.44
Saturated Clay	0.4 - 0.5
Ice	0.33
Clay	0.3 - 0.45
Stainless Steel	0.3 - 0.31
Steel	0.27 - 0.3
Cast Iron	0.21 - 0.26
Sand	0.2 - 0.45
Concrete	0.2
Isotropic lower limit	-1

Table 5. Typical values for Poisson's ratio [7]

6.2.4 Shear modulus

The shear modulus is the ratio of a material's shear stress to the material shear strain if isotropic materials are considered. This is similar to Young's modulus which is the ratio of normal stress to normal strain.

The shear modulus is related to Young's modulus with the following equation [8]:

$$E = 2G(1 + \nu)$$

where

G is the shear modulus

ν is Poisson's ratio.

This equation only holds for isotropic material. As coal is not an isotropic material [9] this equation is used to approximate the shear modulus if the average Young's modulus and Poisson's ratio is known.

Material	Typical values for shear modulus (GPa) (at room temperature)
Diamond	478
Sapphire	175
Steel	79.3
Copper	44.7
Titanium	41.4
Glass	26.2
Aluminium	25.5
Polyethylene	0.117
Rubber	0.0006

Table 6. Typical values for shear modulus [10]

6.2.5 Coefficient of restitution

The coefficient of restitution (COR) is a ratio of the kinetic energy of a body before and after a collision which is derived from the conservation of momentum. The actual ratio depends on the material type, particle geometry and the relative velocities of particles at impact [11]. Experimental observations have been made where the restitution coefficient decreases with an increase in the normal component of the impact velocity.

An object with a COR of 1 collides elastically, while an object with a COR of 0 will collide in-elastically, effectively 'sticking' to the object it collides with, not bouncing at all.

7. LABORATORY BULK SOLID FLOW MATERIAL ANALYSIS

It is important to understand the physical laboratory bulk solids flow analysis methods before embarking on any experimental DEM test work.

The Jenike type shear tester with standard size shear cell (diameter {D} = 93 mm) is used in the tests to determine the flow properties of materials [12,13].

The sample is crushed and screened down to -4 mm depending on the lump sizes received, according to the DIN specification [14] which states the following for shear accuracy:

'The bin diameter must amount to at least 20 times the value of the largest grain diameter of the bulk material and must not be lesser than 40 times the value of the mean particle size. The height H, of the compressed specimen must lie between 0.3D and 0.4D.'

The following liner plates were used in the laboratory tests discussed hereafter. (Figure 14).

- Stainless Steel 316
- 3CR12
- Mild Steel
- VRN 400
- Smooth Ceramic Tile
- Tivar-88



Figure 14. Liner plates tested

7.1.1 Bulk density test

The specific gravity (SG) of the material is also required as an input to EDEM. By packing all the particles into a certain volume, the bulk density in DEM software is automatically created. The SG of materials is relatively well known and available in the industry.

The laboratory needs to test for the bulk density due to the variation of lump sizes and particle distribution in any sample.

The procedure is to fill the shear cell material freely without compaction. The surplus material is then carefully removed level with the shear cell. The spillage is cleaned; then the remaining material contained in the shear cell is weighed. The bulk density can now be calculated according to the volume of the shear cell. (Figure 15).



Figure 15. Bulk density test procedure

7.1.2 Shear test

The Jenike shear tester includes a circular cross-sectional shear cell which is located on the frame of the machine and the load applying parts, both in vertical (normal load) and horizontal (shear load) directions. Normal load is applied to the system shear cell by means of a gravity vertical loading system (weight hanger). The shearing action is also augmented by means of an electro-mechanically driven loading stem. This system moves the loading stem horizontally at a rate of approximately 2.5 mm/min. The shear force is measured with a load cell and indicated on a PC program recorder. The shear cell is illustrated schematically in Figure 16, and consists of a base (1), a shearing ring on the base (2) and a shearing lid (3) with a loading bracket (4) and a pin (5) attached to it. Vertical load is applied to the lid by means of a weight hanger (6) with standard weights (7) on it. A horizontal force is applied to the bracket by a mechanically driven measuring stem (8). The results of shear tests are generally expressed in terms of stresses. As the cells are loaded by weights and the recorder gives force values, the corresponding stress value is calculated by considering the cross-sectional area of shear cell.

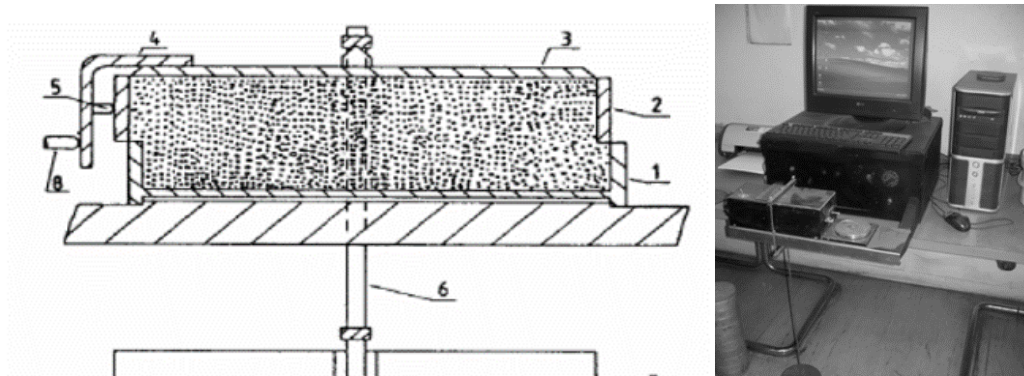


Figure 16. Schematic diagram and photo of a Jenike shear cell

The particle-wall (liner) shear is determined similarly to the particle-particle shear stated above. The only difference is that the base (1) is replaced with a liner plate sample.

7.1.3 Compressibility test

The compressibility tester is used to determine the effect of consolidating pressure upon the density of a material. Essentially the tester consists of a 63.5 mm diameter by 19 mm deep cell which is filled with a sample of material. A lid is placed on top on the sample. Loads are applied to the lid by means of a weight carrier and the compression of the sample is measured with a dial gauge. The lid on top of the sample is given one twist after each increment increase of vertical load applied, before the dial gauge reading is taken. Therefore, by knowing the mass of the sample, the volume of the sample and the vertical loads applied, the relationship between the bulk density and the consolidation can be determined. See arrangement in Figure 17.



Figure17. Compressibility test

The angle of friction for material in chutes and hoppers is measured using the coefficient of friction tester. (Figure 18).

The sample of liner is placed on the tester, and a ring is placed on top of the liner plate. Weights are placed on top of the material for a period of 15 seconds, and then removed. The friction tester is then lifted and the angle of sliding can be established. The weights on top of the material are in accordance with the impact forces acting on the chutes.



Figure 18. Friction test procedure

8. FEEDER LOAD CALCULATIONS AND COMPARISON

In this section the horizontal shear load of the belt feeder is determined theoretically by comparing two calculation methods with data obtained from laboratory tests for export coal.

8.1 Belt Feeder Design Data

Description	Data
Conveyor Number	CV013 / CV014
Conveyor Length	16 m (nom.)
Conveyor Lift	0 m
Conveyor Capacity	3 000 tph
Belt Width	2 500 mm
Belt Speed	0.67 m/s (nom.)
Belt	EP1250/5 Ply - 10 top + 3.5 bottom
Drive Unit	Helical bevel - base mounted
Drive Power	1x 110 kW
Fluid Coupling	Voith 487 TSS
Carry Idler Frames	Retractable type
Take-up	Horizontal screw type take-up

Table 7. Belt feeder design data

8.2 Hopper Parameters and Material Properties

The general belt feeder and hopper parameters are taken from the original design drawings, and the material properties are taken from an actual laboratory report [15]:

Belt feeder speed	v	=	0.7	m/s
Feeder inclination	θ	=	0	°
Hopper length	L_h	=	8.72	m
Hopper height	H_h	=	8.10	m
Diameter or width of hopper	D	=	10.2	m
Gravity	g	=	9.81	m/s ²
Bulk density (in hopper)	ρ_e	=	900	kg/m ³
Bulk specific weight	γ	=	8826	N/m ³
Angle of repose	Φ_r	=	38	°
Wall friction angle (of hopper liners)	Φ_w	=	46	°
Effective angle of internal friction	δ	=	57	°

Release angle	ψ	=	4.85	°
Hopper half-angle	α	=	30	°
Front width	B_F	=	0.95	m
Width between skirts	B_S	=	1.75	m
Height of material in contact with vertical hopper walls	H	=	0.5	m
Bin pressure ratio	K_j	=	0.40	

8.3 Conveyor Resistances

The belt conveyor resistances may be calculated using ISO 5048 and DIN 22101.

Hence: Σ Resistances = 45.82 kN

8.4 Horizontal Shear Resistance

The calculation methods and information herein are derived from international standards, publications and supplier catalogues to calculate the material load on the feeder. The horizontal shear resistance is checked by comparing two calculation methods.

8.4.1 Calculation Method 1 [16]

Horizontal shear resistance:

$$T_{shear} = \frac{1000}{3} \times \mu \times B_S \times L_h \times \rho_e \times H_h \times g$$

where

μ is the belt friction [use 0.4 for coal]

B_S is the width of hopper bottom or skirt width (m)

L_h is the length of the hopper bottom (m)

ρ_e is the material bulk density in the hopper (kg/m³)

H_h is the height of the hopper (m) [$H_h \leq 3B_S$]

8.4.2 Calculation Method 2 [17,18]

Effective surcharge head:

$$H_s = \frac{D \tan \phi_r}{2}$$

$$h_s = \frac{H_s}{m_s + 2}$$

where

H_s is the actual surcharge head.

m_s is material surcharge factor [0 = Rectangular / 1 = Conical Surcharge].

Effective radius:

$$R = \frac{D}{2(1 + m_c)}$$

where

m_c is the bin factor [0 = Rectangular / 1 = Square or Circular].

Hopper surcharge pressure:

$$p_s = \frac{\gamma R}{K_j \tan \varphi_w} \left[1 - e^{-K_j \tan \varphi_w \frac{H}{R}} \right] + h_s e^{-K_j \tan \varphi_w \frac{H}{R}}$$

Flow load equations:

$$\eta = \frac{1}{2} \left[\varphi_w + \sin^{-1} \left(\frac{\sin \varphi_w}{\sin \delta} \right) \right]$$

$$k_{hf} = \frac{2 (1 + \sin \delta \cos 2\eta)}{2 - \sin \delta (1 + \cos 2\{\alpha + \eta\})}$$

$$j = (m + 1) \left\{ k_{hf} \left(1 + \frac{\tan \varphi_w}{\tan \alpha} \right) - 1 \right\}$$

where

m is the hopper factor [0 = Plane-Flow/1 = Conical Hopper].

Pressure multiplier:

$$k_{Fm} = \frac{1 + \sin \delta}{1 - \sin \delta \cos 2(\alpha + \eta)}$$

Vertical Design Pressure:

$$p_{vod} = k_{Fm} \left\{ \frac{\gamma B_F}{2(j-1) \tan \alpha} + \left[p_s - \frac{\gamma D}{2(j-1) \tan \alpha} \right] \left[\frac{B_F}{D} \right]^j \right\}$$

Non-dimensional surcharge factor:

$$q_f = \left(\frac{\pi}{4} \right)^m \frac{p_{vod}}{\gamma B}$$

Vertical load (flow condition):

$$V_f = q_f \gamma L_h^{(1-m)} B_F^{(2+m)}$$

Coefficient of internal friction on shear plane:

$$\mu_s = \sin \delta$$

Equivalent Friction:

$$\mu_E = \frac{\mu_s \cos \psi - \sin \psi}{\cos(\theta + \psi) + \mu_s \sin(\theta + \psi)}$$

Shear resistance:

$$F_f = \mu_E * V_f$$

8.4.3 Calculation result summary

The feeder loads were calculated for hopper flow conditions based only on the operating procedures at RBCT. The summary of the results of the two methods follows:

	Method	Flow
M.1	Bridgestone	94.31 kN
M.2	A.W. Roberts / AS3774	81.24 kN
	M.2 Selected:	81.24 kN
	Safety Factor	1.15
	Total:	93.43 kN

Table 8. Calculation method comparison

The results are relatively close, but the preference is to work with calculation method 2 [17,18] with a safety factor of 15% added.

8.5 Total Resistance and Power Requirement

The total resistance and installed motor power is calculated by adding all the preceding conveyor resistances together, including the shear resistance, as follows:

$$\begin{aligned}
 &P_{\text{Installed}} && \text{Power Calculation} \\
 &F_{e_{\text{max}}} = F_{\text{Conveyor Resistance}} + F_{\text{Shear}} \\
 &F_{e_{\text{max}}} = 45.82 \text{ kN} + 93.43 \text{ kN} \\
 &\text{Maximum Force:} \\
 &F_{e_{\text{max}}} = \boxed{139.25} \text{ kN} \\
 &\text{Power (Absorbed):} \\
 &P_a && = F_e \times v \\
 &P_a && = \boxed{97.5} \text{ kW} \quad \text{incl. Material shear resistance} \\
 &\text{Efficiency:} \\
 &\eta_1 && = 96.0 \quad \% \quad \text{Fluid coupling} \\
 &\eta_2 && = 97.0 \quad \% \quad \text{Gearbox} \\
 &\text{Efficiency:} \\
 &\eta_1 \times \eta_2 = \eta_T && = \boxed{93} \% \\
 &\text{Power (due to Efficiency):} \\
 &P_m && = P_a / \eta \\
 &P_m && = \boxed{104.8} \text{ kW} \\
 &\text{Power (Installed):} \\
 &P_{\text{Installed}} && = \boxed{110} \text{ kW} \quad \text{Drive unit at Head End}
 \end{aligned}$$

9. SITE DATA

9.1 On-site Alterations to Hopper Required

During the commissioning phase of the belt feeders it was discovered that the feeders were not performing in accordance with their required design capacity of 3 000 tph each.

The reason for this was then investigated. This made it necessary to take physical dimensions by getting into the chute and on top of the belt feeder to measure the new hopper as it was installed, to compare to the design drawings. Dimensions were also taken from the existing belt feeders and hoppers on site that were achieving their capacity.

9.1.1 Measured existing Tippler 5 data

Description	Dimensions
Conveyor Number	CV404
Conveyor Capacity	3093 tph
Bulk Density	860 kg/m³
Belt Speed	0.8 m/s
Height - Hopper front to Top of Belt	0.885 m
Width - Hopper Outlet inside Liners	0.885 m
Height - Hopper Sides to Top of Belt	0.615 m
Width - Skirt plates inside Liners	1.950 m

Table 9. Tippler 5 measurements



Figure 19. CV404 hopper inside

9.1.2 Measured new Tippler 3 data

Description	Dimensions
Conveyor Number	CV013/CV014
Conveyor Capacity	2374 tph
Bulk Density	860 kg/m ³
Motor Speed	1493 rpm
Gearbox Ratio	91.57
Pulley Speed	16.31 rpm
Pulley Diameter	820 mm
Belt Speed	0.7 m/s
Height - Hopper front to Top of Belt	0.790 m
Width - Hopper Outlet inside Liners	0.890 m
Height - Hopper sides to Top of Belt	0.615 m
Width - Skirt plates inside Liners	1.765 m

Table 10. Tippler 3 measurements

It could then be seen that there was a major difference between the existing and new arrangements.



Figure 20. CV013 hopper inside

9.2 Proposed Modifications to Tippler 3 / CV013 and CV014 Hoppers

By determining the area which was required to achieve the desired capacity, and comparing it to the area extrapolated from the site measurements; the following recommendations were made:

- The hopper to be cut level with the bottom of the hopper support, from the front edge of the hopper backwards by a minimum distance of 1 250 mm
- The front opening needed to be increased by a minimum of 200 mm
- The shear gate required be modification by a further 200 mm, and replaced back into position.

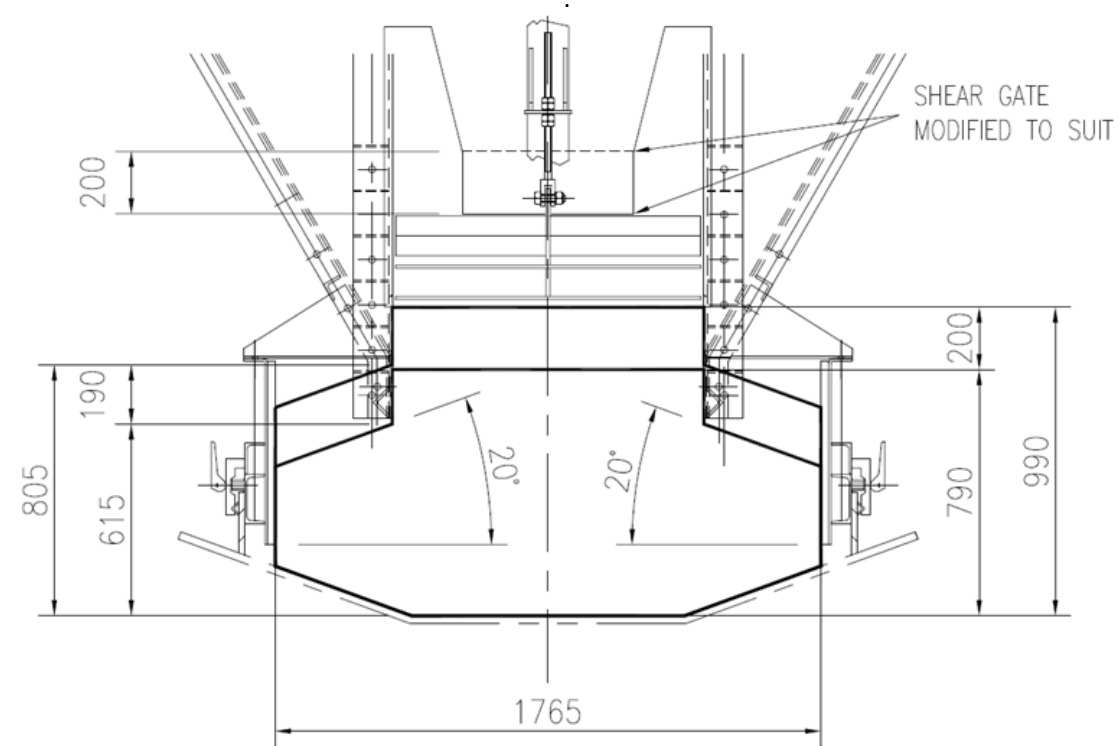


Figure 21. Proposed hopper modifications

9.3 Alterations Completed

Commissioning commenced and the nominal capacity of 3 000 tph was achieved after the alterations (Table 11).

Description	Dimensions
Conveyor Number	CV14
Height - Hopper front to Top of Belt	0.990 m (+200 mm)
Height - Hopper sides to Top of Belt	0.805 m (+190 mm)
Conveyor Capacity (Achieved).	2995 tph

Table 11. Data after modification of new hoppers

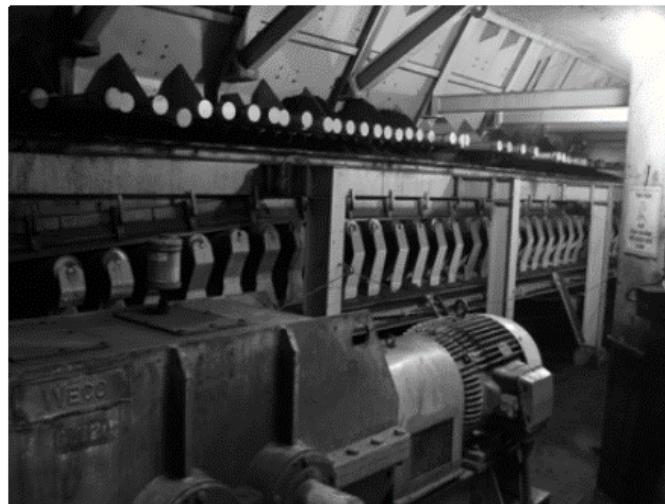


Figure 22. The feeder installation below ground level

9.4 Feeder Load Obtained From Site

The motor current on the 110 kW drive was recorded on site for the 'empty running' condition to determine the actual total resistance of the mechanical components, as well as the 'start-up condition', to determine the maximum horizontal shear force in the system by subtracting the 'empty running condition' from the 'start-up condition'. The horizontal shear force encompasses the shear between coal and coal, coal and rubber belting, and coal and hopper liners.

The following calculation shows the actual resistance of the mechanical components and total horizontal shear force in the system:

$$Power(kW) = \frac{\sqrt{3} \times V \times I \times \cos\phi}{1000}$$

where

V is the Voltage (Volts)

I is the Current (Amps)

cosφ is the Power Factor

Site Info:

Capacity	=	2995	Tph
Bulk Density	=	0.86	T/m ³
Belt Speed	=	0.7	m/s
Start-up Current	=	132	Amps
Empty Running	=	45	Amps

Calculation:

Voltage	=	525	Volts
Power Factor	=	0.85	@ 90% of Full Load

Start-up Power	=	102.60	kW
Empty Running	=	34.98	kW

Fluid Coupling Eff.	=	97.0	%
Gearbox Efficiency	=	97.0	%
Total System Eff.	=	94.1	%

Total Force	=	137.91	kN	Start-up
Total Force	=	47.01	kN	Empty Running

Hor. Shear Force	=	90.89	kN	Start-up
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10. DEM CALIBRATION

The aim is to accurately determine the particle-particle and particle-geometry interactions and material properties in DEM by running experimental simulations to match the shear force recorded on site.

One of the first steps is to understand and evaluate the parameters required by DEM to perform simulations. The particle-particle interaction parameters, as mentioned in the software, are as follows: Poisson's ratio, shear modulus, density, coefficient of restitution, coefficient of static friction and coefficient of rolling friction.

The software provides a database of material and the appropriate material properties which can be utilised. Although these properties are included with the software, depending on the application and the material of interest, it is best to reassess the accuracy of these input parameters. Arbitrary interaction properties are given which are not representative of the material and focus is placed on the physical determination of these parameters to better represent the bulk material.

The course of investigation starts with a brief evaluation of the standard material properties provided in DEM. Next, the actual material properties are established. Reference is made to published data to validate assumptions: these assumptions are paired with the necessary logical argument to reinforce the developing methodology of accurately representing bulk material in DEM.

10.1 Selection of Material Input Properties and Interactions

Coal material properties generally have a large variation due to the non-isentropic nature of the material. One coal study indicates a shear modulus ranging from 800 MPa to 2 400 MPa, and a Poisson's ratio ranging from 0.1 to 0.3 [19]. The decision was made to work with steel liners (VRN steel) in all the DEM simulations, partly due to the fact that the steel liner friction is comparable to that of ceramic liners, depending on the smoothness of the steel and surface roughness of ceramic liners. Steel liners with a very high Brinell hardness such as VRN are more commonly used in the mining industry.

The following material properties were selected:

Material Properties	Coal	Steel	Rubber
Poisson's Ratio	0.2 [19]	0.3 [8]	0.48 [7]
Shear Modulus [Pa]	2e+9 [19]	7.7e+10 [8]	6e+5 [10]
Density [kg/m ³]	1357 [20]	7850 [8]	1700 [8]

Table 12. Feeder simulation material properties

10.2 DEM Experiments for Material Interactions

10.2.1 Coefficient of restitution

The coefficient of restitution can also be found by taking the square root of the ratio of the height of one bounce, to that of the preceding bounce i.e. $COR = (\text{rebound height}/\text{drop height})^{0.5}$.

A simple DEM test can be performed by assigning an interaction value to Base 'A' and corresponding Particle 'A', as well as to Base 'B' and the corresponding Particle 'B' as depicted in Figure 23. This compares the effect of the interaction input values - by this means testing and adjusting the values to ensure that it behaves correctly and attains an appropriate value.

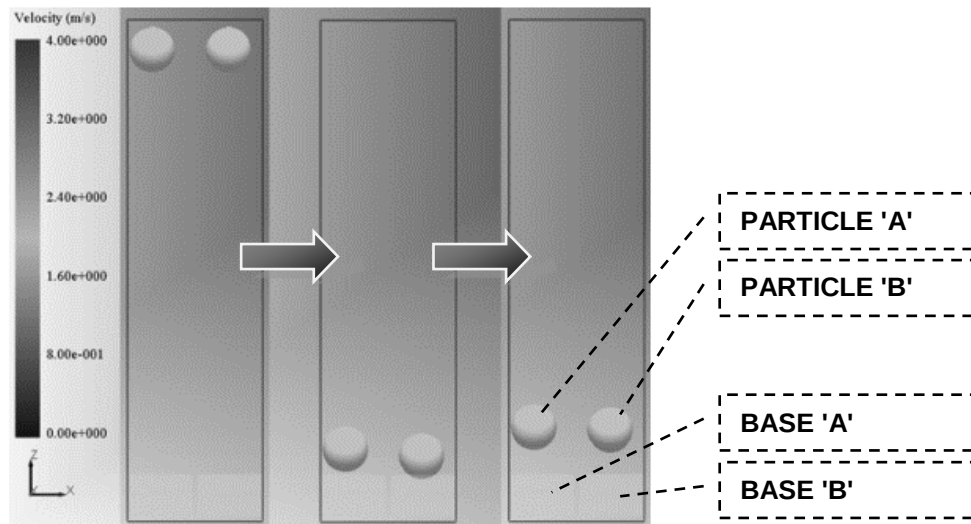


Figure 23. DEM coefficient of restitution test

The following values were selected by performing the test in Figure. 23.

Material Interactions	Coal-Coal	Coal-Steel	Coal-Rubber
Coefficient of Restitution	0.25	0.22	0.27

Table 13. Material interaction determined

10.2.2 Static and rolling coefficient of friction test

The DEM test in Figure 24 may be used to determine the coefficient of static friction, and the coefficient of rolling friction. This is achieved by feeding the material onto a surface, then lifting up the surface from a horizontal position. The assigned interaction values can then be tested and refined to ensure that the material slides down the surface at the desired angle to the horizontal (Figure 1).

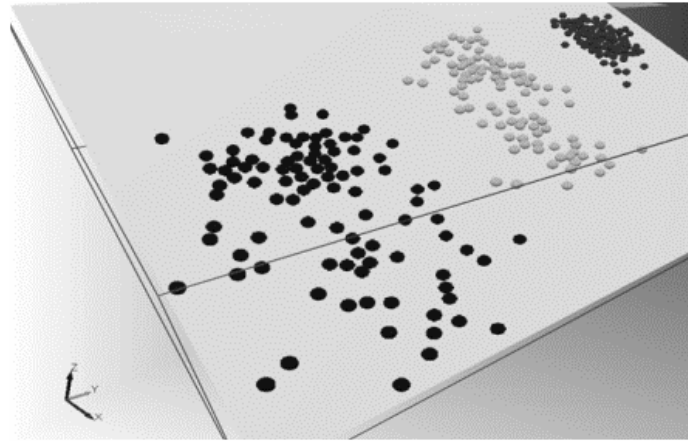


Figure 24. Static and rolling coefficient of friction test

In this instance, the coefficient of static and rolling friction were not determined by using this method, but determined by fine-tuning the values of the material interactions within the main simulation.

10.2.3 EDEM simulation time step

The time step formula in EDEM is as follows:

$$T_R = \frac{\pi R \left(\frac{\rho}{G} \right)^{\frac{1}{2}}}{(0.1631\nu + 0.8766)}$$

The time step in EDEM is therefore affected by the following material properties:

- R = Particle radius
- ρ = Density
- G = Shear modulus
- ν = Poisson's ratio

The material properties affect the time step in such a way:

- R ▲ Higher value = Bigger time step
- ρ ▲ Higher value = Bigger time step
- G ▼ Lower value = Bigger time step
- ν ▼ Lower value = Bigger time step

Note: Bigger time step = Shorter simulation time

It is imperative to optimise the simulation time step as much as possible due to the fact that it can take hours, and sometimes days, for larger simulations. It can be stated that the shear modulus has a significant impact on the simulation speed. The density of the particles is generally kept unchanged to ensure that the simulation results are accurate. Poisson's ratio is also kept as authentic as possible because it does not have a significant effect on the

simulation speed. The particle radius may however, be adjusted to an acceptable maximum size to increase the time step.

A time step of 20% or less is advised by the software supplier to ensure a stable simulation, otherwise the particles may behave somewhat erratically and deliver inaccurate results.

10.2.4 Time step optimisation

10.2.4.1 Shear modulus vs. coefficient of restitution

Current time step value:

T_R	=	100%	0.00011
T_R	=	20%	0.00002

R	Particle radius	0.04	m
ρ	Density	1350	kg/m ³
G	Shear modulus	2,000,000,000	Pa
ν	Poisson's ratio	0.2	

It has been noted in DEM that there is a correlation between the shear modulus and the coefficient of restitution. The adjustment of the coefficient of restitution is vital to attain more accurate results in terms of silo wall loads and material shear, when the shear modulus has been adjusted for time step optimisation.

A simple DEM experiment is proposed to determine the consequent coefficient of restitution interaction values in relation to the adjusted shear modulus.

The proposed test consists of a composite particle which is not submissive to rolling but shear only. Only three components form part of the experiment: a vertical plate, horizontal plate and a composite particle. The vertical plate then pushes the particle to shear across the horizontal plate. (Figure 25).

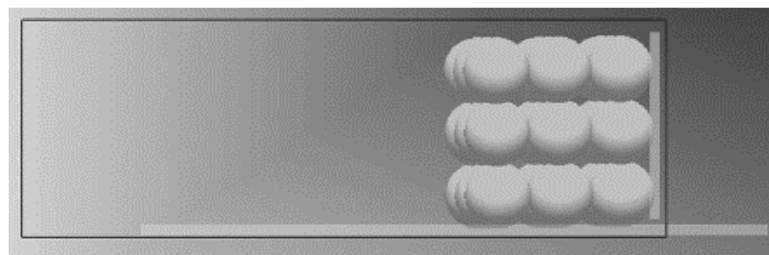


Figure 25. DEM shear modulus vs. coefficient of restitution experiment

The actual shear modulus with the corresponding coefficient of restitution can be tested in a relatively short time because the simulation essentially contains only one particle.

After a number of simulations are run containing the actual values, the trial runs with the optimised shear modulus and corresponding coefficient of restitution can be tested.

Optimised time step value:

T_R	=	100%	0.00011
T_R	=	10%	0.00051

R	Particle radius	0.04	m
ρ	Density	1350	kg/m ³
G	Shear modulus	1,000,000	Pa
ν	Poisson's ratio	0.2	

10.3 Revised Material Input Properties and Interactions

The revised material input properties and interactions due to the optimised time step are:

Material Properties	Coal	Steel	Rubber
Poisson's Ratio	0.2	0.3	0.48
Shear Modulus [Pa]	1e+6	7.7e+10	1e+6
Density [kg/m ³]	1357	7850	1700

Table 14. Feeder simulation material properties

Note: The shear modulus for rubber was also revised because the lowest possible shear modulus input value in EDEM is 1e+6 Pa.

Material Interactions	Coal-Coal	Coal-Steel	Coal-Rubber
Coefficient of Restitution	0.6	0.22	0.27

Table 15. Feeder simulation material interactions

10.4 DEM Simulations on Actual Belt Feeder and Hopper Arrangement

A full scale model of the belt feeder and 'site modified' hopper arrangement (Section 7.2) was prepared for insertion into the DEM software package (Figure 26).

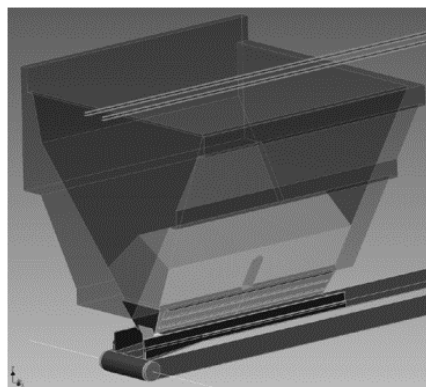


Figure 26. Illustration of full scale model

Numerous simulations were run to achieve the correct horizontal shear force by adjusting the material interactions of the coefficient of static friction, and the coefficient of rolling friction.

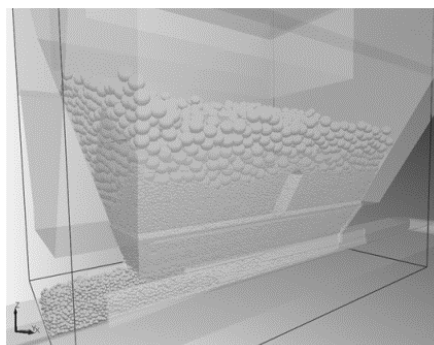


Figure 27. DEM hopper filled with material

In the following illustration, (Figure 28) the shear plane can clearly be observed. It shows the stationary material on the feeder. The feeder is then started and accelerates up to full speed within 4 seconds, from 10 s – 14 s.

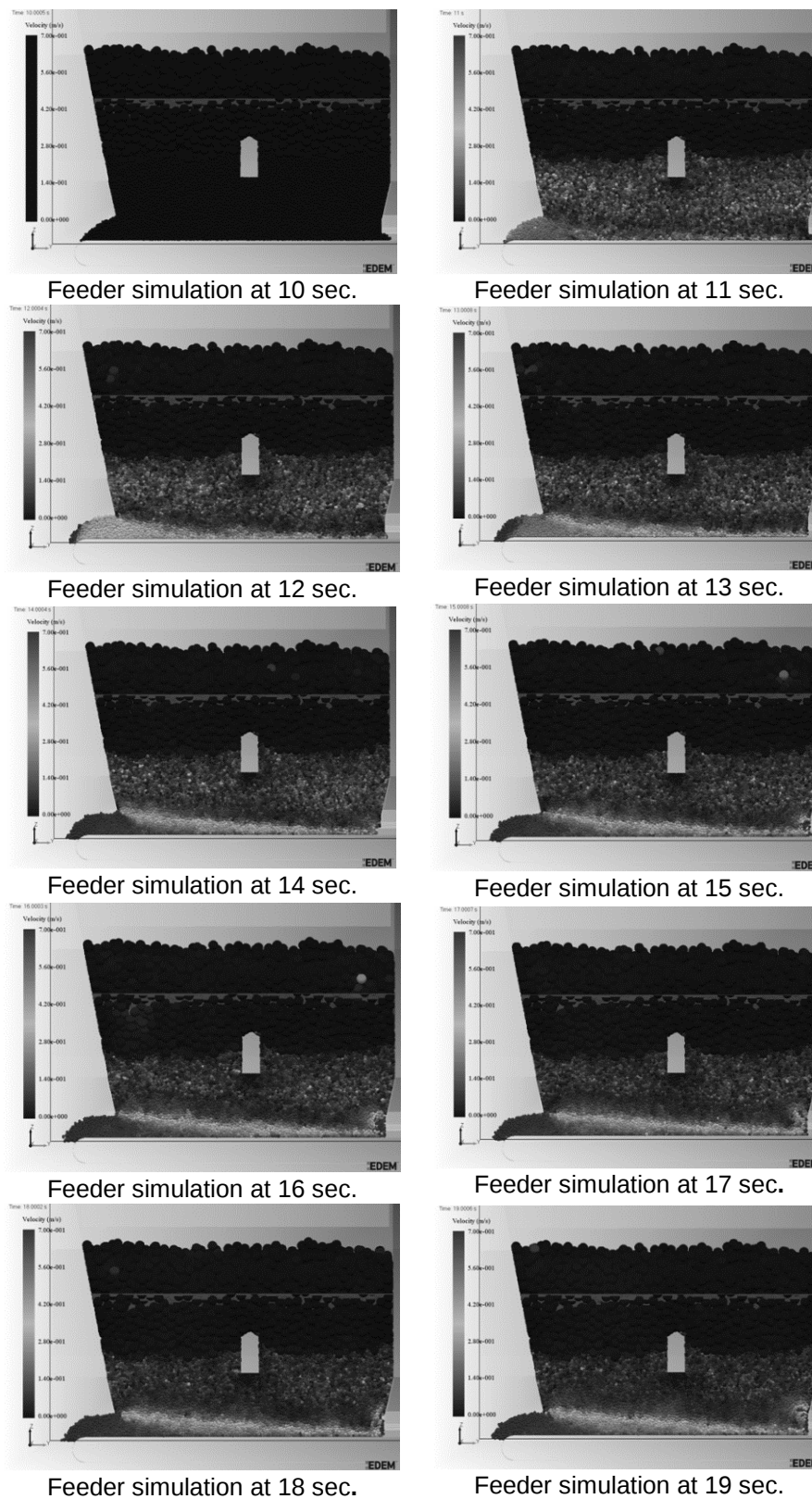


Figure 28. Simulation progression

Figure 29 shows that the horizontal shear force of the coal-coal, coal-steel liners and coal-rubber conveyor belt interactions are accurately achieved at 96.03 kN.

Note: Larger particles were inserted into the hopper on top of the smaller particles to provide the required material mass in the system and at the same time increased the simulation speed because of the larger particle diameter.

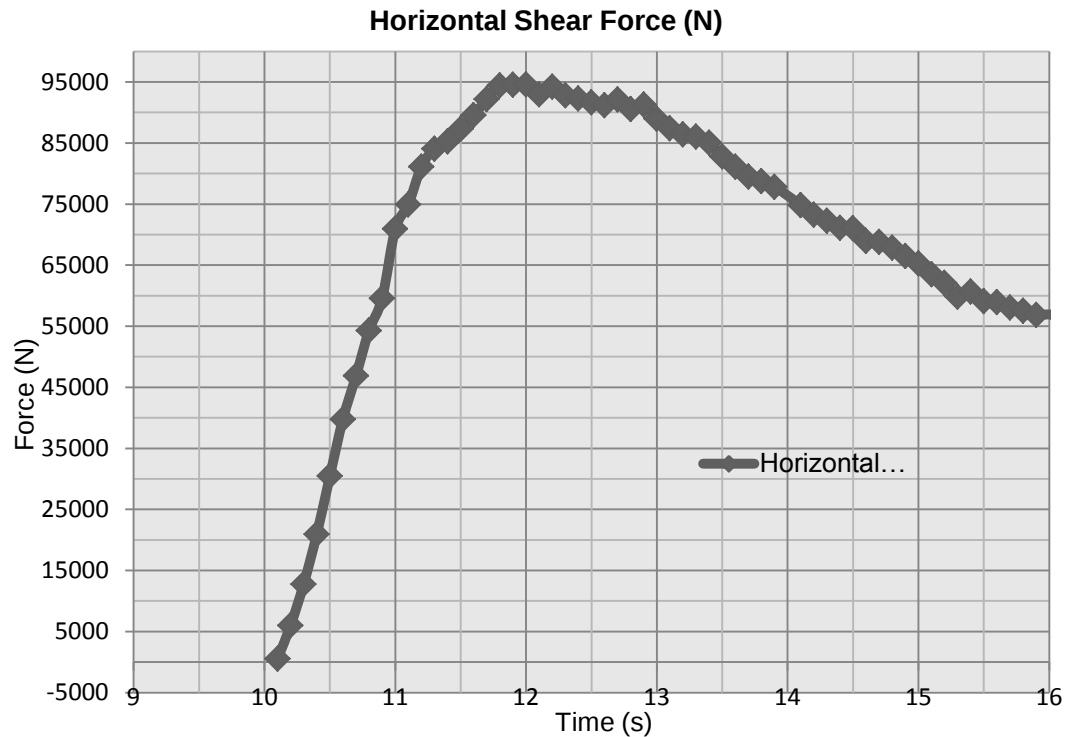


Figure 29. Horizontal shear force graph

After achieving the correct horizontal shear force which compares with the actual site shear resistance, it is possible to declare the accurate coefficient of static friction and the coefficient of rolling friction material interactions.

11. SUMMARY AND FINDINGS

The calculation domain surrounding the geometry and particles, which is used to calculate the interactions, is generally adjusted to be as small as possible, since this affects the speed of each simulation. It is important to note that the final simulation was run at a 10% time step, and that a finer mesh for the conveyor belt model was constructed to ensure that none of the elements made contact with the part of the belt that protruded past the limits of the calculation domain.

The domain is divided up into small grid cells - the size of the grid cells also affect the simulation speed. The optimal recommended size of the grid cell is two times the smallest particle radius.

Description	Calculation	Site	DEM
Sum of Conveyor Resistances [kN]	45.82	46.53	-
Horizontal Shear Force [kN]	93.43	90.89	94.59
Total Feeder Resistance [kN]	139.25	137.42	-

Table 16. Summary of feeder resistances

It is recommended that representative composite particles are used in all DEM simulations to produce the interlocking, shearing effect of actual particles instead of using spherical particles with increased friction values (Figure 30).

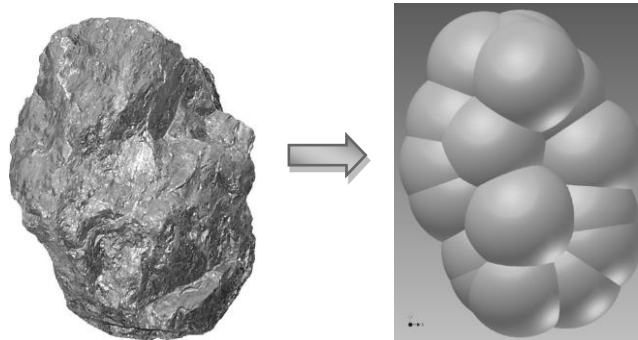


Figure 30. Representative composite particle

12. CONCLUSION

The advantage of working with a 'scale model' for research as done in this case on site is because it reduces the error margin tremendously. It provides actual results and enhanced accuracy because the efficiencies within the system are known.

This paper shows the procedure to determine the required bulk material parameters required for DEM simulations. Representing the bulk material using the parameters as required by DEM software is a tedious process that consists of many physical experiments that can result in error. Refining this method can result in a viable procedure used to represent the bulk material as required by DEM.

The results obtained from the feeder simulation can be used for other similar simulations required, such as handling clean coal with steel or ceramic liners in power stations, mines feeding clean coal to Eskom and other coal export terminals around the world.

Note that the high value of the coefficient of restitution is however not ideal, and should not be used to simulate transfer chutes and conveyors having material profile plates.

13. FUTURE WORK

Future tests can be performed by simulating the bulk solids flow and Jenike shear tests as done in the laboratory, but due to simulation and CPU processor speed this is not yet feasible. It would take an estimated period of 30 days to carry out a similar laboratory test (Figure 33). It would be ideal to match the DEM simulations to the laboratory test results, then to transfer those material input values and interactions into the software, which would include external effects on the bulk material such as moisture content.

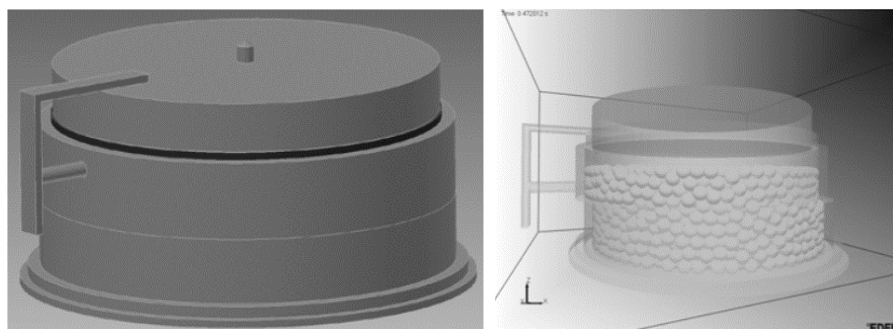


Figure 31. Jenike shear tester model and DEM experiment

Laboratory testing equipment may also be developed specifically to obtain DEM input parameters.

REFERENCES

- [1] DEM Solutions. EDEM 2.3 Getting Started with EDEM (Quickstart Guide). 2010. EDEM. Revision 1C.
- [2] Williams, J, Hocking, G and Mustoe, G. The Theoretical Basis of the Discrete Element Method. 1985.
- [3] DEM Solutions. EDEM 2.3 User Guide. 2010. EDEM. Revision 2C.
- [4] EDEM 2.1 DEM Solutions Training: EDEM Contact Models - Introduction to contact models and material properties. 2010. EDEM. Revision 2.1/3.
- [5] Coal assay. Wikipedia, The Free Encyclopedia. [Online] 17 May 2011. http://en.wikipedia.org/w/index.php?title=Coal_assay&oldid=429540060.
- [6] Halliday, Resnic and Walker. Fundamentals of Physics. 7th Edition. NJ: John Wiley & Sons Inc., 2005.
- [7] Poisson's ratio. Wikipedia, The Free Encyclopedia. [Online] 14 June 2011. http://en.wikipedia.org/w/index.php?title=Poisson%27s_ratio&oldid=434250440.
- [8] The Southern African Institute of Steel Construction. South African Steel Construction Handbook (Limit States Design). Johannesburg: CTP Book Printers, 1997 Third Edition.
- [9] Wang, G, et al. An analytical model of the mechanical properties of bulk coal under confined stress. 2007.
- [10] Shear modulus. Wikipedia, The Free Encyclopedia. [Online] 1 June 2011. http://en.wikipedia.org/w/index.php?title=Shear_modulus&oldid=432026307.
- [11] Stevens, A B. Comparison of soft-sphere models to measurements of collision properties. Powder Technology. 2005, pp. 99-109.
- [12] Institution of Chemical Engineers. Standard Shear Testing Technique for Particulate Solids using the Jenike Shear Cell. UK: (European Federation of Chemical Engineering), 1989.
- [13] ASTM International. Standard Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Cell. 2000. ASTM D6128-00.
- [14] DIN Standard. Actions on Structures Part 6: Design Loads for Buildings and Loads in Silo Bins. 2005. DIN 1055-6:2005-03.
- [15] Bulk Solids Flow SA cc. Bulk Solids Flow Report, Wouter A.H. Deijns. s.l.: Supplied courtesy of Anglo Coal, 2001. BSF340B.
- [16] Bridgestone Corporation. Conveyor Belt Design Manual. Chuo-ku, Tokyo, Japan: s.n., (n.d.).
- [17] Roberts, Alan W. Feeder Interfacing, Loads and Power Focusing on Belt and Apron Feeders. Feeding of Bulk Solids. The University of Newcastle: Centre for Bulk Solids and Particulate Technologies, Chapter 7.
- [18] Australian Standard. Loads on Bulk Solids Containers. 1996. AS 3774. 1996.
- [19] Karacan, C. Ozgen. Elastic and Shear Moduli of Coal Measure Rocks derived from Basic Well Logs Using Fractal Statistics and Radial Basis Functions. Disaster Prevention and Response Branch, Pittsburgh Research Laboratory. Pittsburgh, USA : s.n., 2010.
- [20] The South African Coal Processing Society. Coal Preparation in South Africa. Pietermaritzburg : Natal Witness Commercial Printers, 2002.
- [21] Effects of moisture content on some physical properties of lentil seeds. M, Amin, M, Hossain and K, Roy. 2004, Journal of Food Engineering, pp. 83–87.
- [22] Callister, J, William D. Materials Science and Engineering an Introduction. 6th Edition. NJ : John Wiley & Sons Inc., 2003.
- [23] ASTM International. Annual Book of ASTM Standards: Standard Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Cell. 2001. Vol. 04.08.
- [24] International Standards Organisation. Continuous mechanical handling equipment - Belt conveyors with carrying idlers - Calculation of operating power and tensile forces. 1989. ISO 5048:1989.
- [25] Dunlop Catalogue. Dunlop Belting Products: Conveyor Belt Selection. 2000. B2.
- [26] Melco Catalogue. Melco Conveyor Equipment. January 2006.
- [27] Apron Feeder Design and Hopper Interaction. Bailey, Warren. (n.d.).

- [28] DIN Standard. Continuous Mechanical Handling Equipment - Belt Conveyors with Carrying Idlers - Calculation of Operating Power and Tensile Forces. 1989. DIN 5049:1989.
- [29] Robinson, GK, Sinnott, MD and Cleary, PW. Summary of Results of ACARP Project on Cross-Belt Cutters. Victoria, Australia: The Journal of The Southern African Institute of Mining and Metallurgy, June 2010, Vol. 110, pp. 331-338.

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