THE INFLUENCE OF STEEL CORD CONVEYOR BELT DIMENSIONS ON INDENTATION ROLLING RESISTANCE PERFORMANCE

Paul Munzenberger[1], Craig Wheeler[2]

[1]TUNRA Bulk Solids Materials Handling Research Associates

[2]The University of Newcastle, Australia

INTRODUCTION

For some time, long conveyors have utilized conveyor belts with low rolling resistance bottom covers; the low rolling resistance cover properties help to lower the conveyor's overall system resistance which is a key benefit that allows a conveyor designer to modify the conveyor's specifications to achieve a more profitable design. Low rolling resistance conveyor belts obviously reduce the drive requirements of a given conveyor, as well as the power consumption, but they can also be used to reduce the belt strength requirements, increase the throughput for a given power input or each benefit may be traded off against the others to achieve any particular balance that is required for a proposed design.

Much effort has been expended to develop new cover compounds for use in Low rolling resistance conveyor belts. Other ideas like the effects of secondary reinforcements on reducing indentation rolling resistance have also been experimentally investigated, but one area of steel cord conveyor belt design that has not been considered, for exploitation to achieve more gains in indentation rolling resistance performance, is the dimensions of the conveyor belt's elements. To say that no elements of a conveyor belt have been considered is not true: extensive work of both a theoretical and experimental nature has been conducted to determine the effect of bottom cover thickness on indentation rolling resistance and it is widely known that thinner bottom covers are conducive to good indentation rolling resistance performance. However, previous efforts have been limited to determining the influence of the bottom cover's thickness on indentation rolling resistance as, up until now, no model has existed that could be used to assess the influence of other elements of the conveyor belt; and, experimentally, it is costly to produce the required number of steel cord conveyor belts and the machinery that is large enough to measure the indentation rolling resistance of steel cord conveyor belt is rare. But, what of the other elements of the conveyor belt? How does a wider cord spacing or thicker steel cords affect indentation rolling resistance? Or, what influence does the thickness of the top cover have?

A recent advancement in the field of theoretical analysis of conveyor belt indentation rolling resistance is the development, by the Author, of a true three dimensional finite element analysis model of the indentation rolling resistance problem that can be used to directly study the effects of the size of various elements of a steel cord conveyor belt. This paper aims to show the results of an investigation into how the indentation rolling resistance is changed by modifying the size and location of individual conveyor belt components.

THE THREE DIMENSIONAL FINITE ELEMENT ANALYSIS INDENTATION ROLLING RESISTANCE MODEL

The three dimensional finite element analysis indentation rolling resistance model is the latest iteration of a family of indentation rolling resistance models that begins with Wheeler's two dimensional model (Wheeler, 2003), which was a modified version of the model published by Lynch (Lynch, 1969); Munzenberger (Wheeler & Munzenberger, 2012) further modified the method by taking Wheeler's model and adjusting the viscoelastic calculations so that commercial finite element analysis software could be used to carry out the solving of the model's stiffness matrix. This change had the advantage of being fast to generate results: with efficient commercial solvers, and of being able to view the model's solution in the software's post processing environment where the deformed shape could be viewed and other information like contact length and rubber strains could be easily measured. Following on, a new two dimensional indentation rolling resistance model was programmed that was similar to the previous iteration but replaced the poorly performing constant strain triangle finite elements – that were used in all previous models – with the more realistically performing bilinear rectangle element. The new element type improved the accuracy of the indentation rolling resistance predictions but at the expense of longer solution times that were a result of the mathematical complexities of the new element type. The latest indentation rolling resistance model is the three dimensional model (Munzenberger, 2017), it incorporates many of the features of the two previous indentation rolling resistance models but adds the third dimension and a new element type known as a trilinear brick which is the three dimensional equivalent of the bilinear rectangle.

A view of the three dimensional indentation rolling resistance model is shown in Figure 0.1. The model is shown with twice the calculated deformations applied, which makes the contact area more visible, and with each element shown in its component colours so that the cord and the bottom and top covers are distinguishable. In making use of the commercial finite element analysis software's post processing environment, the same model is shown in Figure 0.2 with vertical strain contours applied.

A three dimensional indentation rolling resistance simulation is slow to run, and because of this, only the minimum possible amount of conveyor belt is modelled. In Figure 0.1 it can be seen that, while the full thickness of the conveyor belt is modelled, only a section beginning at the cord centre line and finishing at the midpoint of the space between the cords is included. Modelling this small amount of conveyor belt reduces the solution time for one data point of a small conveyor belt model (something like an ST1000) to around eight hours. The length of the model is defined by the user, with longer models being preferred; however, to avoid significant increases to the solution times, only enough of the model is represented to capture the extent of the strained areas introduced by the contact deformations and model lengths of around 120 mm are normal. At the beginning of a simulation, each un-deformed element represents a cube with a side length of 0.5 mm.

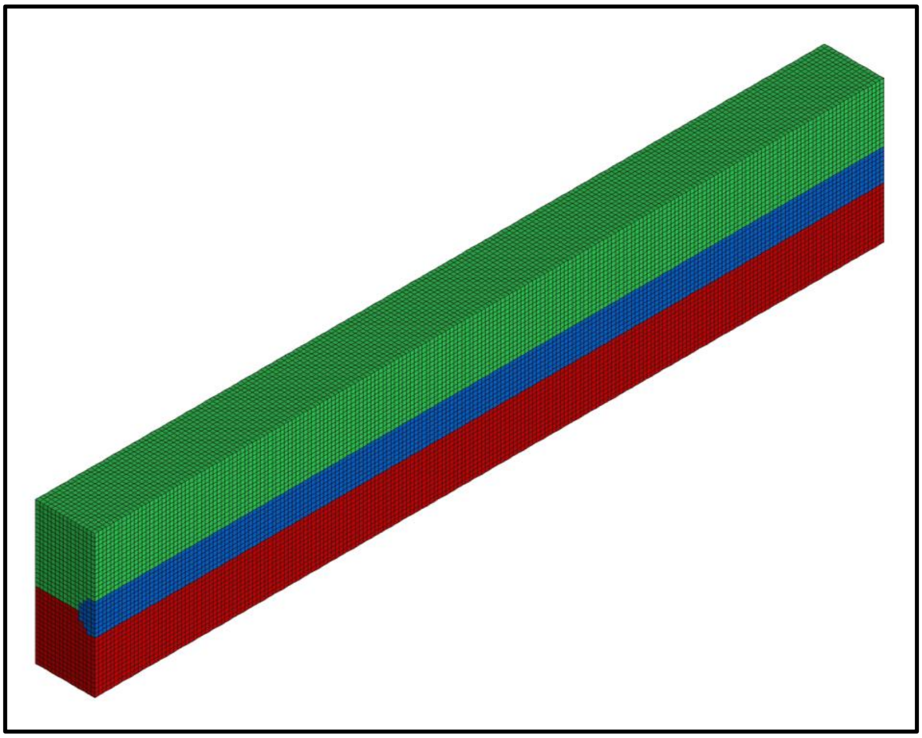


Figure 0.1 A view of a three dimensional indentation rolling resistance model

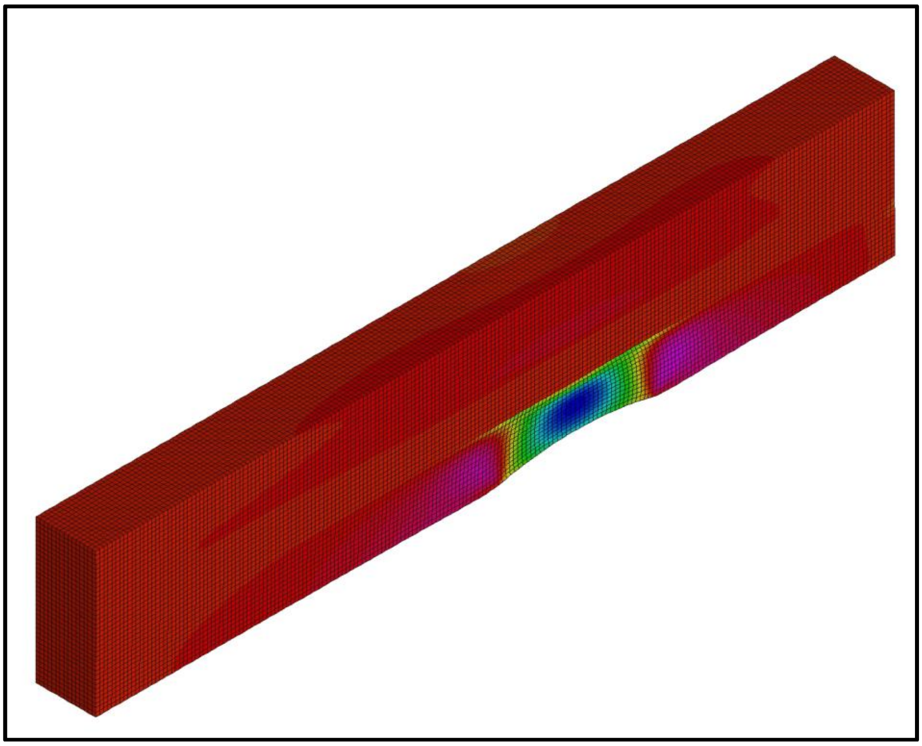


Figure 0.2 The model from Figure 0.1 shown with strain contours superimposed on the elements

Two simplifications of the belt model can also be seen in Figure 0.1: it will be noted that the cord insulation rubber is not modelled by a separate group of elements and that the cord cross section is represented by an arrangement of cubes which only approximates the round shape of a cord. There is no insulation rubber represented in the model primarily because there are usually no material properties available for entry into the model; instead, the region of the insulation rubber is divided into two sections with the lower half using the same material properties as the bottom cover rubber while the upper half uses the same material properties as the top cover. The unusual cross section shape of the cord is necessary to avoid the need for odd shaped rubber elements around the cable, which would require individual mathematical calculations to be programmed for them, and is further justified by the fact that the cords used in conveyor belt do not, in reality, have a round cross section. Further to this, no attempt has been made to bestow the cord elements with similar properties to steel cord, and the cord is instead modelled as being made from solid steel; this approximation is reasonable since the cord is not required to be flexible in the model, as the conveyor belt is modelled as always being flat, and the cross sectional properties of an actual cord are not to dissimilar to solid steel in that they are both significantly stiffer than rubber.

The three dimensional indentation rolling resistance model can be programmed with any desired cross section (to a tolerance of 0.5 mm) and allows the user to specify the cord diameter and pitch, the top and bottom cover thicknesses and also the idler diameter.

COMPARISON OF SIMULATION PREDICTIONS AND EXPERIMENTAL RESULTS

The need to prove that the three dimensional indentation rolling resistance model is accurate could be avoided by presenting the various predictions as a percentage change from a reference conveyor belt design; however, this paper will be presenting its predictions in terms of the expected, or absolute, indentation rolling resistance performance of a conveyor belt manufactured with the same dimensions as the reference model. In order to prove that the presented predictions bear some resemblance to reality, it is necessary to prove that some of the model predictions match a related set of experimental results.

Experimental measurements for the indentation rolling resistance of a low rolling resistance conveyor belt were conducted on the University of Newcastle's large indentation rolling resistance test facility which is shown in Figure 0.3. The relevant belt details and test parameters are given in Table 1 and Table 2 respectively. The indentation rolling resistance test machine uses the belt flex method devised by Spaans (Spaans, 1978) to apply the vertical load (F_V) to the test idler and, as such, the measurements that are obtained from the machine are the sum of the test belt's indentation rolling resistance and its flexure resistance. Since, for the experiment and simulation comparison, only the indentation rolling resistance (F_{IRR}) results are of interest, they must be extracted from the combined results.

Rating:	ST1250
Bottom Cover Compound:	Low Rolling Resistance
Top Cover Compound:	DIN-X
Bottom Cover Thickness:	6.5 mm
Top Cover Thickness:	7.5 mm
Cord Diameter:	4.0 mm
Cord Pitch:	15.0 mm

Table 1 Low rolling resistance conveyor belt details

Temperature:	20 °C
Speed:	4 m/s
Idler Diameter:	6” (152 mm)
Belt Sag:	0.50, 0.75, 1.00 and 1.25 %
Belt Load Range:	1.0 – 5.0 kN/m

Table 2 Indentation rolling resistance test parameters

Figure 0.3 The University of Newcastle’s large indentation rolling resistance test machine inside its temperature controlled room (Munzenberger, 2017)

Separation of indentation rolling resistance and belt flexure measurements can be achieved with the conservative method outlined in Australian Standard AS1334.13 (Conveyor and Elevator Belting Commitee RU-002, 2017), however, for the comparison shown here an alternative method, which yields slightly more accurate results at the expense of a large increase in the amount of experimental and analytical work required (Munzenberger, 2017), was used. Essentially, what is a rather complex procedure, can be explained as follows: at the required belt speed and loads, belt resistance testing is carried out with the experimental setup adjusted so that the test belt is bent around the test idler by a large, though still realistic, amount; when the measurements are complete the belt flexure angle is reduced and more measurements are taken; this process is repeated until there is a set of measurements taken for four or more belt flexure angles. The belt flexure angles should approach zero degrees, but since testing at zero degrees is impossible – as the test belt tension cannot apply any additional vertical load to the test idler – the indentation rolling resistance results for zero degrees of belt flexure are calculated by extrapolating the measurements, collected at higher belt flexure angles, to zero degrees. In this way, indentation rolling resistance results that are free of any belt flexure resistance are obtained.

To complete the comparison of the experimental and simulation results, the test belt dimensions are entered into the three dimensional indentation rolling resistance model and, after several days, a set of predictions are obtained. A comparison of the extrapolated, zero degree belt flexure indentation rolling resistance results (labelled as “0 % Sag”) and the theoretical results (labelled as “FEA 2 %”) are given in Figure 0.4 where it can be seen that there is reasonable agreement between the experimental results and the theoretical predictions. Note that here the 0 % refers to the amount of simulated belt sag while the 2 % refers to the strain percentage of the finite element analysis material property inputs and is not related to the 0 % value in any way.

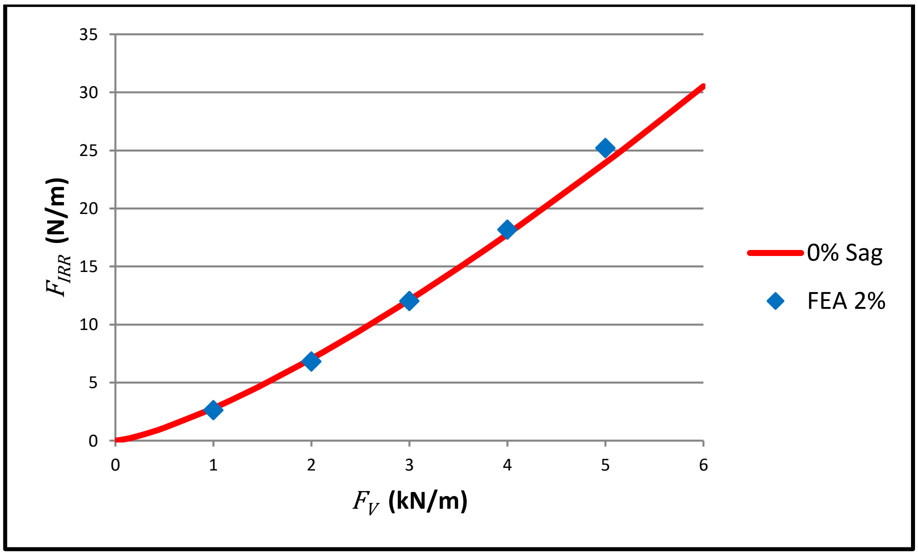


Figure 0.4 A comparison of low rolling resistance conveyor belt 0% sag experimental and three dimensional simulation results.

In Figure 0.4 and throughout this paper, indentation rolling resistance (F_{IRR}) results are presented in a graphical form against the vertical load (F_V); the vertical load is simply the force that is applied to the test idler while the indentation rolling resistance result is being measured.

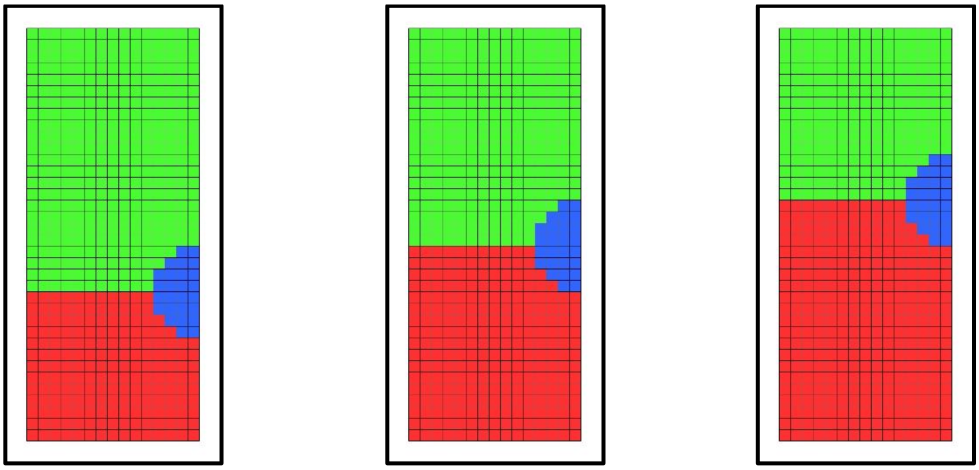
With the model – and its material properties – shown to be suitably accurate, it can now be used as the reference model for a series of indentation rolling resistance simulations that are designed to show the effects that different sized steel cord conveyor belt elements can have on the indentation rolling resistance performance. The model and results that were just presented will act as the reference model and will be included in every group of results that follows.

INDENTATION ROLLING RESULTS FOR CONVEYOR BELTS WITH DIFFERENT DIMENSIONS (MUNZENBERGER, 2017)

Now that the reliability of the three dimensional model is confirmed, it becomes possible to use it to make indentation rolling resistance predictions for conveyor belts manufactured using the same materials but with different element dimensions. In the following, indentation rolling resistance results for new models that are based on the reference model – presented in the previous section, but with modified dimensions, will be presented. Each model uses the same material properties as the reference model and simulates the same test conditions as listed in Table 2. For each element variation, a series of model cross sections will be shown that are intended to depict the dimension changes that are being modelled; the indentation rolling resistance results will then be given in two graphical forms: one being the results from the simulation and the second being the same set of results rearranged to clearly show the effect of the dimensional change on indentation rolling resistance predictions.

CORD HEIGHT

The first dimension that was studied for its effects on indentation rolling resistance was the position of the steel cord within the belt. Figure 0.5 shows how the finite element analysis model was varied to predict the effects of cord position; as shown by the three models, the cord position is modified while the overall model thickness is kept constant. This series of models acts similarly to models with changing bottom cover thickness, however, this is investigated later and only changing the cover thickness results in a thinner model. Here, the only dimension that is modified is the vertical location of the cord within the model hence the “cord centre height” labels rather than any reference to the cover thickness. The simulation results are shown in Figure 0.6 and are rearranged in Figure 0.7 to show the effect of the cord centre height dimension change more clearly. Unsurprisingly, the results given in Figure 0.7 show the predicted indentation rolling resistance is proportional to the vertical position of the cord, as is the thickness of the bottom cover which is probably responsible for a large part of the increase. The middle model shown in Figure 0.5 is the reference model that was used to produce the simulation results for the comparison in the previous section.



6.5 mm Cord Height 8.5 mm Cord Height 10.5 mm Cord Height

Figure 0.5 Model cross sections for different cord centre heights.

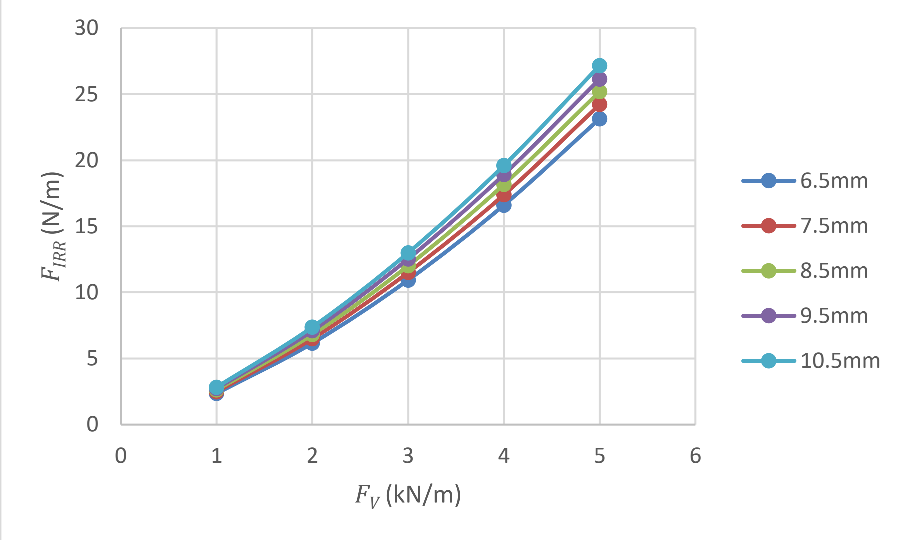


Figure 0.6 Indentation rolling resistance simulation results for different cord centre heights versus vertical load.

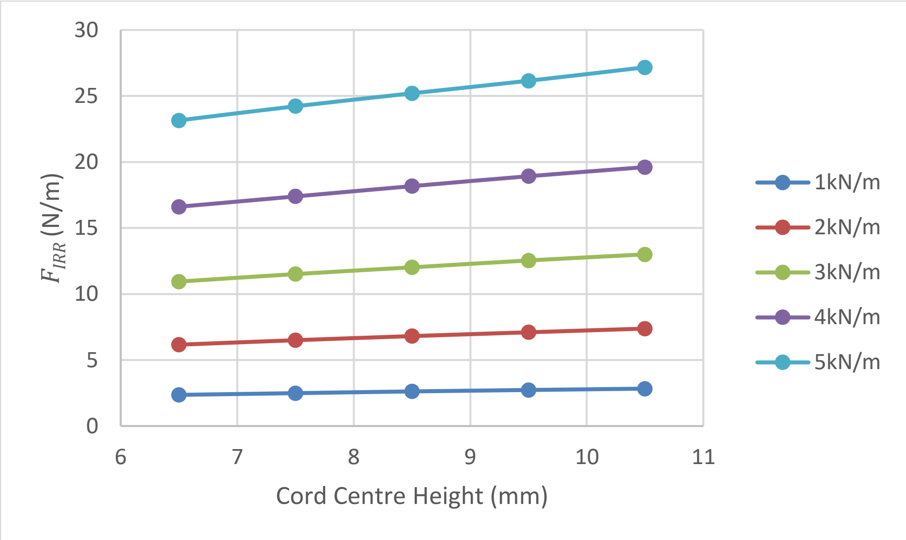
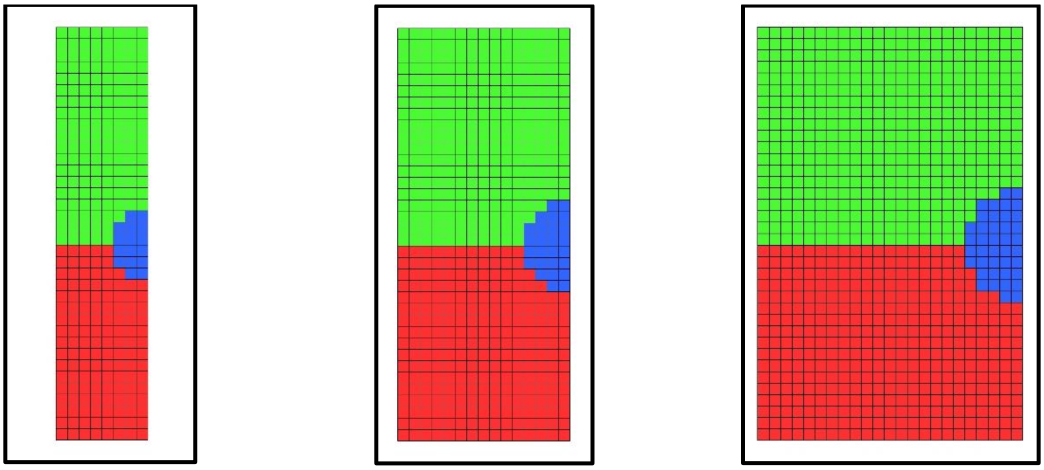


Figure 0.7 Rearranged indentation rolling resistance simulation results versus different cord centre heights.

CORD DIAMETER

In this series of simulations, the effect of different cord diameters on indentation rolling resistance predictions was investigated. Figure 0.8 shows the series of models used to study different cord diameters; the models show that the cord diameter is changing from left to right but they also show that the models are getting wider as the cord diameter increases. The increased model width is replicating the increasing cord pitch that would be needed to maintain the same belt strength, or cord area – based on the circular area rather than the modelled area – when using different diameter cords. Due to the resolution of the finite element analysis model, the desired model pitch to cord diameter ratio could not be maintained exactly and Figure 0.9 shows the per-metre width area achieved for each cord diameter investigated against the actual cord area of the original model. Although there is some error in the model dimensions they are considered to be adequate for their intended purpose.



3.0 mm Cord Diameter | 4.0 mm Cord Diameter | 5.0 mm Cord Diameter

Figure 0.8 Model cross sections for different cord diameters and constant cord area.

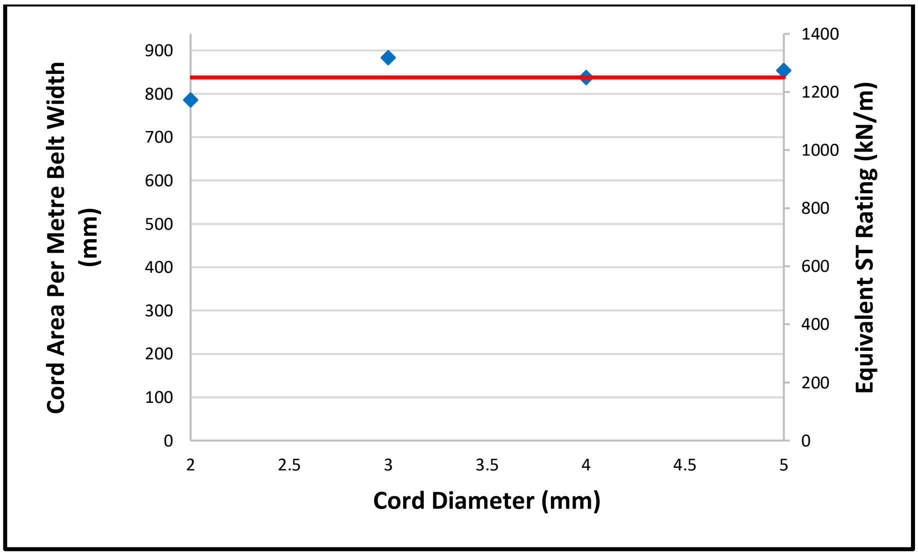


Figure 0.9 Actual area of the conveyor belt model – per metre, marked by the line, and the actual areas achieved for each cord diameter modelled marked by the points. The two vertical axes scales are equivalent and relate to all graphed data.

Figure 0.10 shows the simulation results and Figure 0.11 gives the same results to make the effect of different cord dimensions on indentation rolling resistance predictions clear. The results predict that indentation rolling resistance will rise for conveyor belts that use fewer large diameter cords to achieve their strength rating. This is possibly caused by the ability of the wider section of rubber between the thicker cables to deform more for a given load than the narrow section of rubber between the more numerous smaller diameter cables, thus allowing more rubber to become active in the generation of indentation rolling resistance.

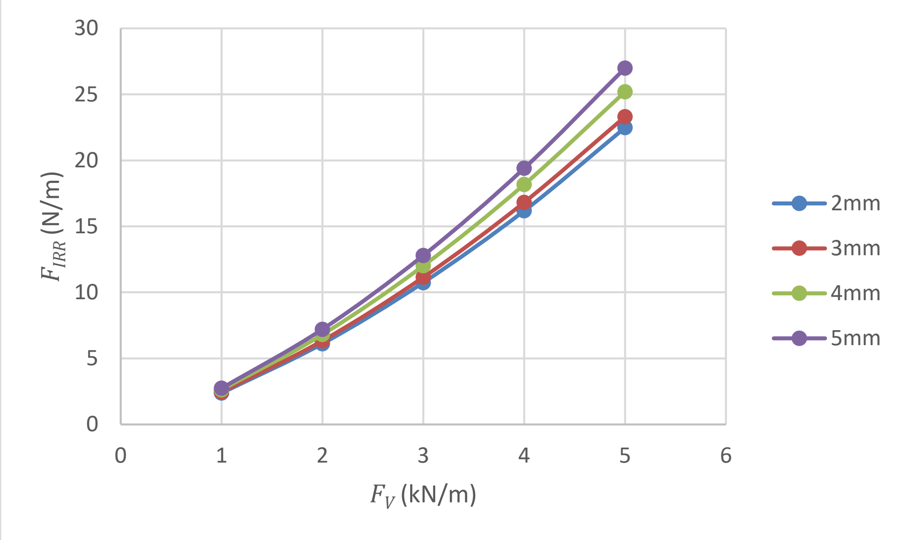


Figure 0.10 Indentation rolling resistance simulation results for different cord diameters and constant cord area versus vertical load.

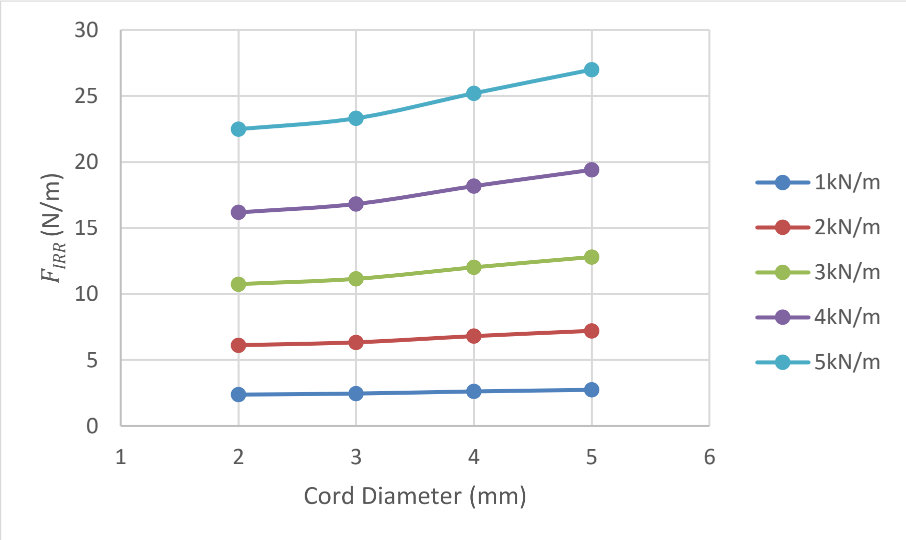


Figure 0.11 Indentation rolling resistance results versus cord diameters for constant cord area models.

CORD PITCH

Some of the models used to study the effect of cord pitch on indentation rolling resistance are shown in Figure 0.12. Cord pitches from the minimum possible pitch – with the cords touching each other – up to 19 mm were investigated. The simulations are similar to the models used to study the cord diameter, however, here, only the pitch is varied while the cord diameter is held constant so the strength of the conveyor belt being modelled is inversely proportional to the cord pitch.

The indentation rolling resistance simulation results for the varying cord pitches are given in Figure 0.13 and the rearranged predictions are shown in Figure 0.14. The results here are similar to those in Figure 0.11 and predict that for larger cord pitches the indentation rolling resistance will rise.

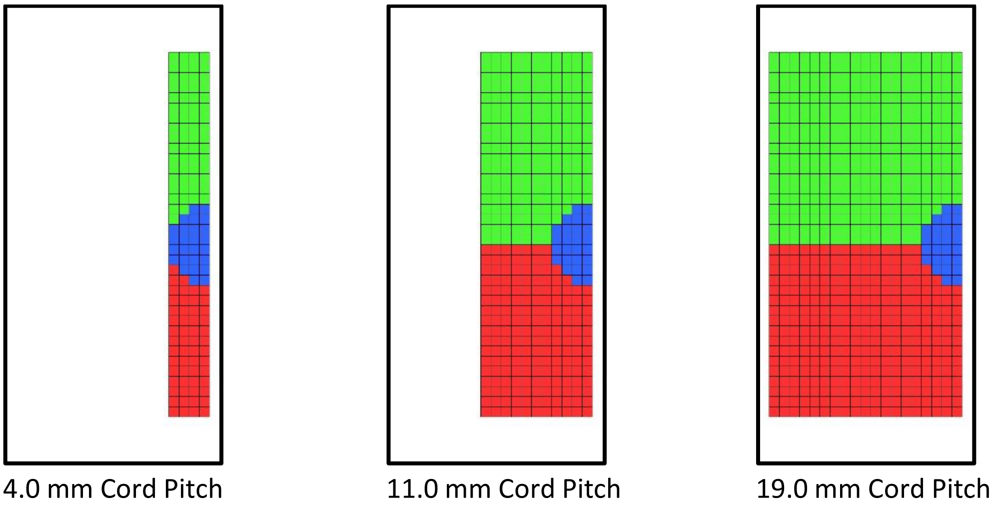


Figure 0.12 Model cross sections for different cord pitches.

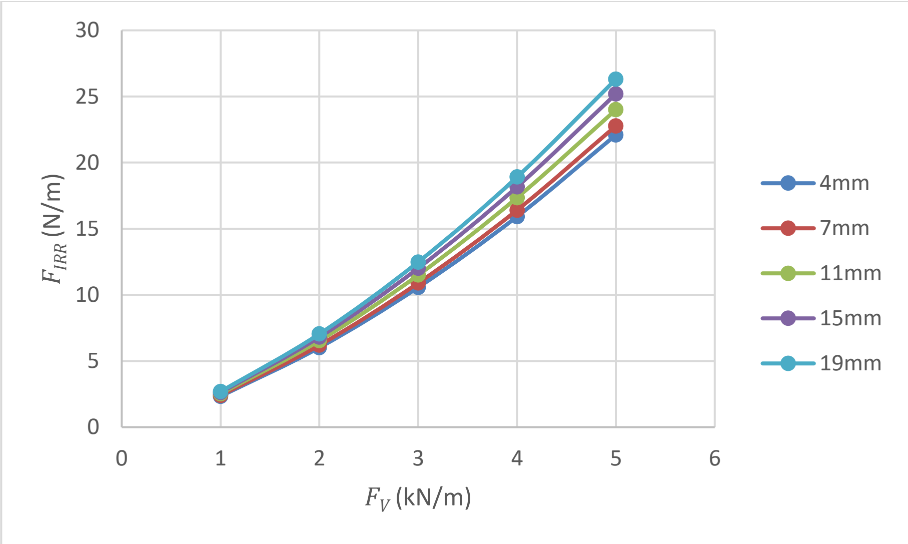


Figure 0.13 Indentation rolling resistance simulation results for different cord pitches versus vertical load

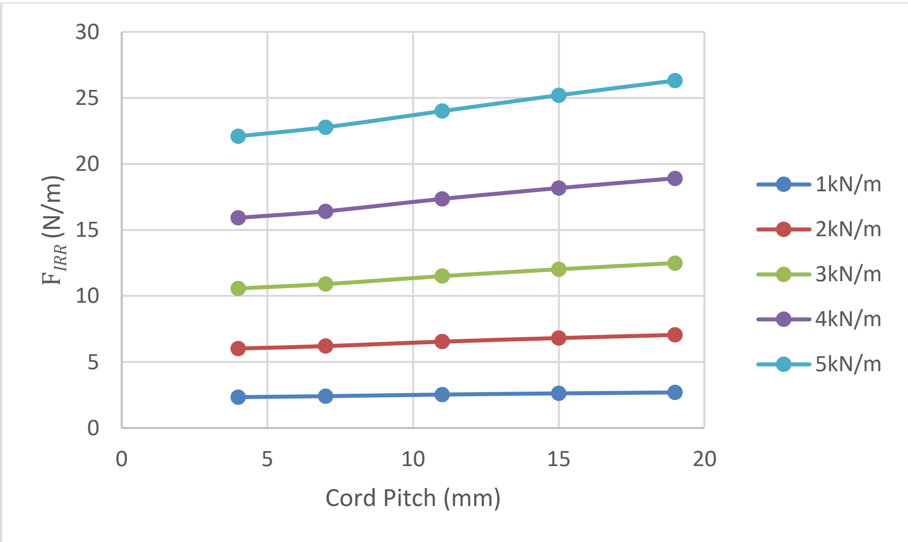
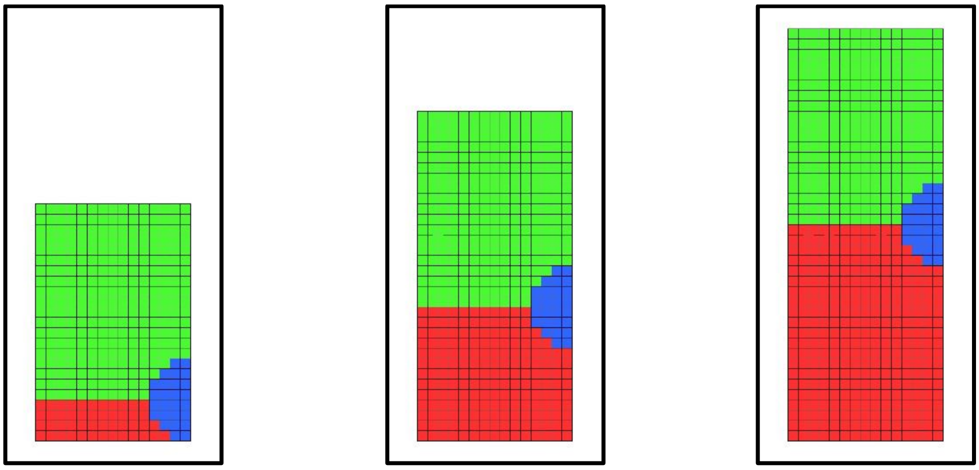


Figure 0.14 Indentation rolling resistance results versus different cord pitch.

BOTTOM COVER THICKNESS

Some of the models used to investigate the effects of bottom cover thickness on indentation rolling resistance are shown in Figure 0.15; the models show that as the bottom cover thickness is modified no other dimensions are changed, resulting in the overall model thickness changing by the same amount as the cover thickness. The bottom cover thickness indentation rolling resistance simulation results are shown in Figure 0.16, and Figure 0.17 shows the rearranged results which presents the effect of different bottom cover thicknesses more clearly. As with the results from Figure 0.7, the predictions are proportional to the cover thickness but here the trend is stronger, most likely due to the overall thickness of the belt model changing as well.



0.0 mm Bottom Cover   4.5 mm Bottom Cover   8.5 mm Bottom Cover

Figure 0.15 Model cross sections for different bottom cover thicknesses

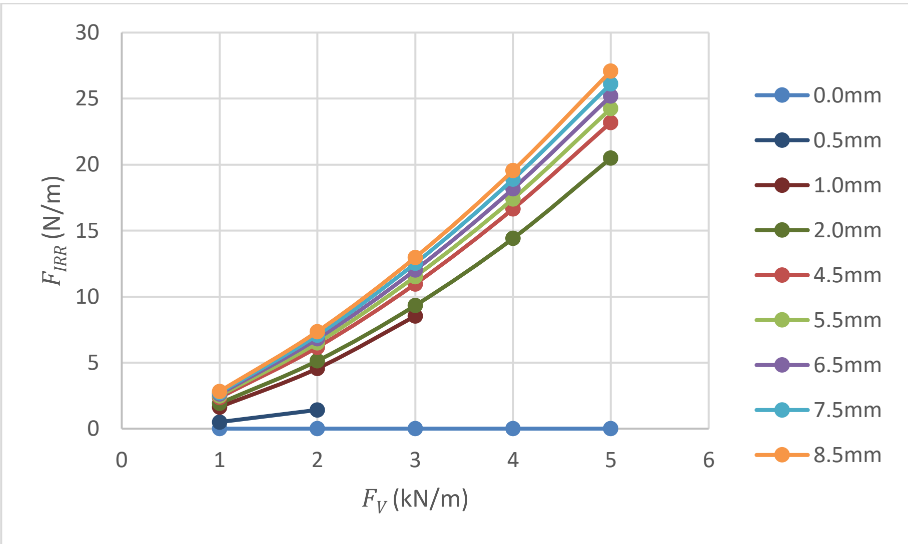


Figure 0.16 Indentation rolling resistance predictions for different bottom cover thicknesses versus vertical load

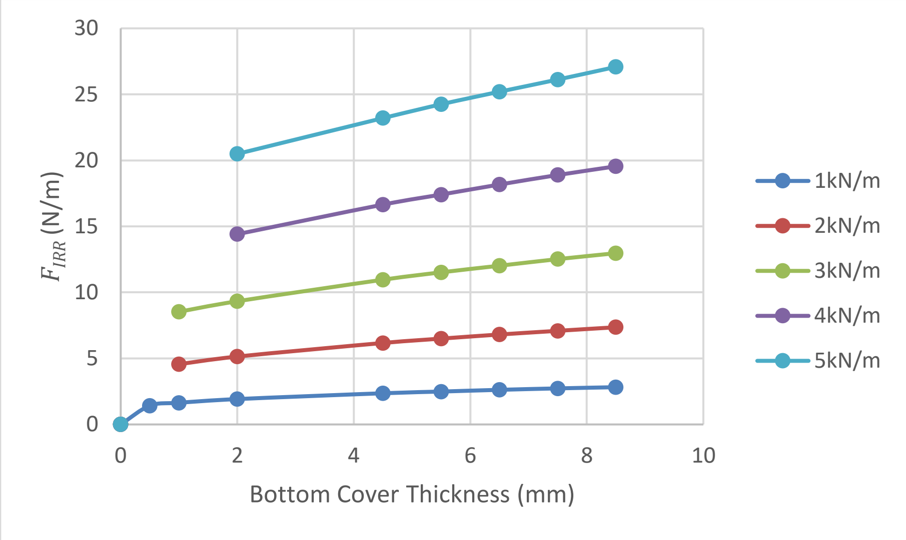


Figure 0.17 Indentation rolling resistance results versus different bottom cover thickness

The simulation showed that for a bottom cover thickness of 0 mm there would be zero indentation rolling resistance regardless of the applied load: this result was expected as the entire load is carried through the cord part of the model which has no viscoelastic properties. The data for the 0.5 mm and 1.0 mm bottom cover thicknesses is incomplete because of inaccurate predictions that were caused by the lack of element layers between the cord and the bottom of the model which lead to large strain gradients in those elements and, from there, a failure of the solution to converge.

TOP COVER THICKNESS

The final set of indentation rolling resistance simulation models is shown in Figure 0.18. They were used to study the effect of different top cover thicknesses on indentation rolling resistance. Care must be taken here to note that *the effect of different top cover thicknesses* does not refer to the indentation rolling resistance performance of the conveyor belt if its orientation was inverted – as it could be on the return belt of a belt conveyor but rather the effect of the top cover thickness on the indentation rolling resistance of the conveyor belt in its upright orientation, rolling on its bottom cover. The simulation results are shown in Figure 0.19 and are rearranged in Figure 0.20 to more clearly show the effect of top cover thickness on indentation rolling resistance. The predictions show that for top cover thicknesses in the normal range above 5 mm there should be little difference in indentation rolling resistance performance; while at lower thicknesses the indentation rolling resistance can be expected to rise. The rise in the indentation rolling resistance of thin top covers seems to stem from the lack of sufficient top cover material to stabilize the rubber in the areas between the cords thus permitting more movement there. Unlike what was experienced with the bottom cover thickness simulations, these models experienced no difficulties with thin top covers as this section of the model is an area of low strain and small numbers of elements could easily cope with the small strain gradients found there.

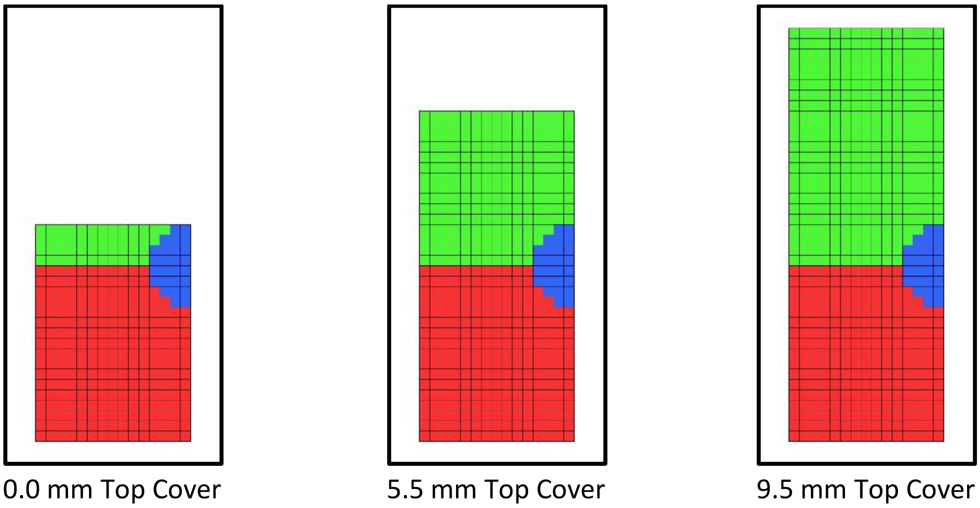


Figure 0.18 Model cross sections for different top cover thicknesses

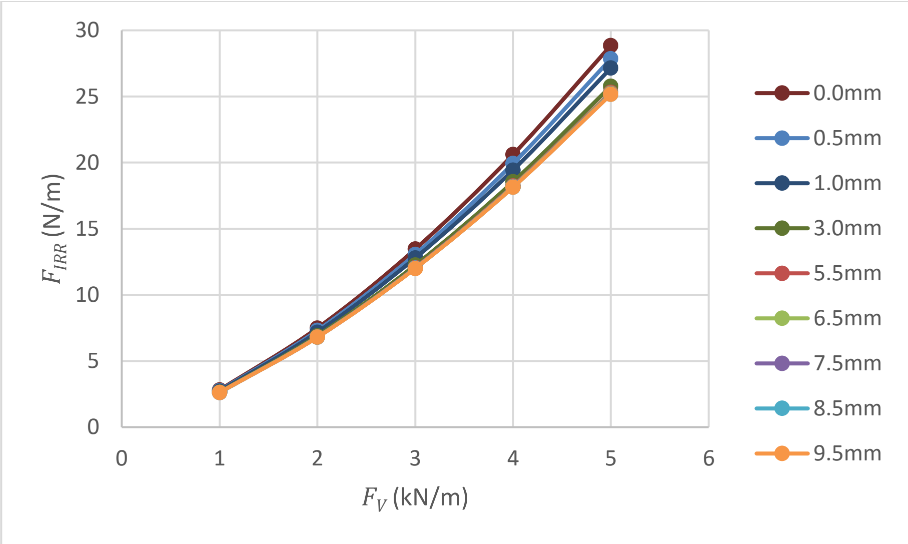


Figure 0.19 Indentation rolling resistance simulation results for different top cover thicknesses versus vertical load

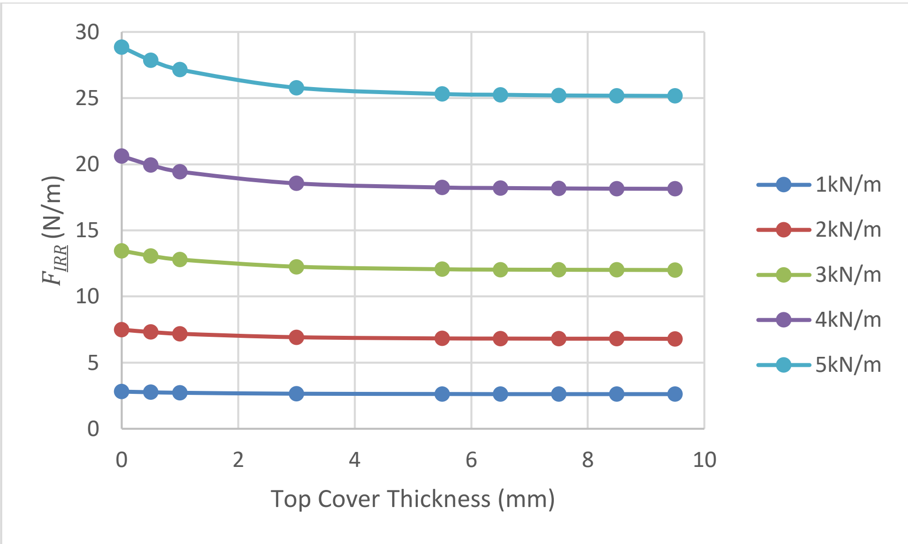


Figure 0.20 Indentation rolling resistance results versus different top cover thicknesses

CONCLUSION

A true three dimensional indentation rolling resistance model for the prediction of conveyor belt indentation rolling resistance has been produced and has been shown to make good predictions by way of comparison with experimental results. The model has then been used to show the effect that each element of a steel cord conveyor belt has on its indentation rolling resistance performance. The predictions shown agree with the previously proven property that thinner conveyor belt bottom covers tend to improve indentation rolling resistance properties but they have also shown that the size of the gap between the steel cords is an important consideration when designing low rolling resistance conveyor belts. The three dimensional model has also predicted that the top cover has an influence on the indentation rolling resistance of the conveyor belt (which is rolling on its bottom cover) with thinner top covers predicted to increase the overall indentation rolling resistance performance. Hopefully in the future, conveyor belt designers will be able to take this information, build upon it, and create a new generation of low rolling resistance conveyor belts based not only on high performance rubbers but also by incorporating smart design as well.

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ABOUT THE AUTHOR

PAUL MUNZENBERGER

Paul Munzenberger is research and consulting engineer at TUNRA Bulk Solids. He completed an apprenticeship as a Fitter Machinist in early 2001, and spent several years involved in the maintenance and repair of belt conveyors, and other associated coal handling equipment. He completed his Bachelor's Degree in Mechanical Engineering at the University of Newcastle in 2007; whereupon, he assumed his position with TUNRA Bulk Solids. Whilst working For TUNRA Bulk Solids, he commenced a PhD in Mechanical Engineering in the field of belt conveying technology which was completed in 2017. Paul's areas of interest are belt conveying and finite element analysis.

DR PAUL MUNZENBERGER
TUNRA Bulk Solids
The University of Newcastle
University Drive
Callaghan NSW 2308 AUSTRALIA
Telephone: (+61 2)4033 9012
Email: Paul.Munzenberger@newcastle.edu.au

CRAIG WHEELER

Dr Craig Wheeler is an Associate Professor in the School of Engineering at the University of Newcastle, Australia and Associate Director of TUNRA Bulk Solids. He worked as a mechanical engineer for BHP Billiton for eleven years and then as a research fellow at the Centre for Bulk Solids and Particulate Technologies for four years. He was appointed as an academic in the Discipline of Mechanical Engineering in 2000.

A/Prof Craig Wheeler
Centre for Bulk Solids and Particulate Technologies
School of Engineering, The University of Newcastle
University Drive, Callaghan NSW 2308 Australia
Telephone: (+61 2) 4033 9037
Email: Craig.Wheeler@newcastle.edu.au