Journal of Applied Polymer Science

# The Influence of Viscoelastic Property Measurements on the Predicted Rolling Resistance of Belt Conveyors

**Jayne I. O'Shea, Craig A. Wheeler, Paul J. Munzenberger, Daniel G. Ausling**
TUNRA Bulk Solids, The University of Newcastle, University Drive, Callaghan, New South Wales 2308, Australia
Correspondence to: J. I. O'Shea (E-mail: Jayne.Oshea@uon.edu.au)

**ABSTRACT:** This article discusses how determining the viscoelastic properties of the cover material of a conveyor belt, using different rheological test modes, can result in significant differences in properties for the same material and testing conditions. The viscoelastic properties are applied to two mathematical models used to predict and compare the indentation rolling resistance performance of two rubber compounds. This article demonstrates how inaccuracies in the testing of the viscoelastic properties could result in a material with higher indentation rolling resistance properties being selected for a conveying system, making the power consumption of the system larger than necessary. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40755.

**KEYWORDS:** applications; mechanical properties; properties and characterization; viscosity and viscoelasticity

Received 6 February 2014; accepted 24 March 2014
**DOI: 10.1002/app.40755**

## INTRODUCTION

Belt conveyors are one of the most economically viable ways of transporting bulk materials. A great importance has been put on efficient design as the demand for faster belt speeds and longer conveying distances increases. Research by Hager and Hintz established that ~60% of energy consumption in long horizontal overland conveying systems is from the indentation of the belt bottom cover as it passes over the idler rolls, due to the weight of the belt and bulk material.[1]

Being such a large component of the total energy of a system, much research has been performed in reducing the indentation energy loss, with particular advancements being made by belt manufacturers in developing low rolling resistance rubber compounds. Such compounds have been used on the overland conveyor belts at Channar in Western Australia and on the longest single flight overland conveyor in the world located at Curragh North in Queensland. The energy saved by using these low rolling resistance compounds resulted in a significant reduction in both capital and operating costs compared to conventionally designed systems as described in Nordell and Steven.[2,3]

Despite the already considerable developments made in low rolling resistance compounds, further research has the potential to improve the technology significantly. During the initial stages of compound development, belt manufacturers compare the rolling resistance performance of different compounds used for the bottom cover using analytical models. The use of analytical models when designing conveyor systems is becoming more prevalent as engineer and client awareness increases on how lowering rolling resistance can significantly reduce the power of a system and therefore lowers capital and life cycle costs. Nordell provided a number of case studies comparing power requirements predicted using a viscoelastic rheological method to actual measured power requirements of overland conveying systems, highlighting the cost savings with a well-designed system.[4]

Rolling resistance is dependent on a number of system parameters, the main ones are: idler roll diameter, belt loading, belt cover thickness and the viscoelastic material properties of the bottom belt cover. Viscoelastic material properties are typically tested using a dynamic mechanical analyzer (DMA) or rheometric solids analyzer (RSA). These properties are also dependent on the operating conditions of the system including temperature, belt speed and belt load, which can make determining the material properties in conditions close to real quite difficult.

Different rheological test methods and equipment can be used to determine viscoelastic properties of rubber compounds; including strain, frequency, temperature and time sweeps performed under tension, compression, shear or torsion. Lodewijks describes the different tests, highlighting the lack of a standardized test method when applying the properties to belt conveying.[5] Lodewijks discussed the accuracy of theoretical models used to predict the indentation rolling resistance of a system, concluding that the performance of compounds can only be compared when testing is done on one specific rheometer for one set of operating conditions, as the results are greatly dependent on test procedure and analysis techniques.[5]

This article will apply material viscoelastic properties determined using various modes of dynamic testing to two analytical models and compare the predictions to actual measurements of rolling resistance taken from tests performed on the same rubber compound on a purpose built test facility located at the University of Newcastle.

## JONKERS INDENTATION ROLLING RESISTANCE MODEL

A commonly used rolling resistance model is that developed by Jonkers.[6] The equation derived by Jonkers for the horizontal force, $F_j$ due to the indentation rolling resistance is

$$F_j=\left(\frac{W^4h}{E'D^2}\right)^{\frac{1}{3}}\frac{\pi}{2}\tan(\delta)\left[\frac{(\pi+2\delta)\cos(\delta)}{4\sqrt{1+\sin(\delta)}}\right]^{\frac{4}{3}}\ (N/m) \qquad (1)$$

where $W$ is the vertical load per unit width of belt from the weight of the material and belt, $h$ is the bottom cover thickness of the belt, $D$ is the idler roll diameter and material properties $E'$ and $\delta$ are the storage modulus and loss angle of the bottom cover of the belt, respectively.

Jonkers equation overestimates the rolling resistance because it is derived from a simplistic model of viscoelasticity. The limitations of Jonkers equation are discussed in detail by Lodewijks, Wheeler, Rudolphi and Qui and Chai.[7–10] Jonkers calculated the energy absorbed by the belt backing material as it travels over one idler roll. The viscoelastic behavior of the belt backing material is modeled as a Winkler foundation, which is a simplified one-dimensional deformation model, assuming no shear deformation. A linear relationship is assumed between load and indentation depth, even though the load/deformation response for most rubber compounds is only linear at very low strains. The idler roll is modeled as a rigid cylinder and the belt indentation profile is assumed to be symmetrical about the centerline of the idler roll; however, at typical operating speeds, the indentation profile tends to be more asymmetrical.

Much research has gone into developing more accurate indentation models using Jonkers model as a basis; however, Jonkers equation is still the most commonly used model for a quick comparison of rubber compounds because of its direct relationship between energy loss and dynamic material properties, where rolling resistance is proportional to $\tan\delta/E'^{(1/3)}$.

Because of its popularity and ease of application, Jonkers model will be used as one of the analytical models in this article to demonstrate the variation of predictions using material properties from different modes of testing.

## QC-N INDENTATION ROLLING RESISTANCE MODEL

The QC-N model was developed as a theoretically more accurate indentation rolling resistance model than Jonkers oversimplified model.[10] Similar to Jonkers, master curve rubber data can be applied directly to the model, unlike the analytical models developed by Lodewijks and Rudolphi and Reicks which require Maxwell–Weichert parameters to represent the viscoelastic properties of the rubber.[7,11]

Like other one-dimensional models, the QC-N model assumes the belt behaves as a Winkler foundation passing over a rigid idler. The contact profile is assumed to be a half-sinusoidal function. A 'transient term' is included in the model to account for the contact stresses transient response to the indentation deformation, which is neglected by other one-dimensional models.

The equation derived for the horizontal force, $F_Q$ due to the indentation rolling resistance is

$$F_Q=\sin\delta D_Q(\pi/4)^{4/3}\left(h/\bar{G}R^2\right)^{1/3}W^{4/3}\ (N/m) \qquad (2)$$

where $W$ is the vertical load per unit width of belt from the weight of the material and belt, $h$ is the bottom cover thickness of the belt, $R$ is the idler roll radius and material property $\delta$ is the loss angle of the bottom cover of the belt.[10] $\bar{G}$ is given by eq. (3), $D_Q$ is a dimensionless function described by eq. (4) and $A(\alpha)$ is a function which is a factor of $D_Q$, defined by eq. (5).

$$\bar{G}=\sqrt{G'(\omega)^2+G''(\omega)^2} \qquad (3)$$

$G'$ and $G''$ are the shear elastic modulus and shear loss modulus of the master curve, respectively.

$$D_Q=\left\{(1/2)\sin\alpha^*[A(\alpha^*)-\cos\alpha^*]+\left(\frac{1}{4}\right)[2\alpha^*+\sin(2\alpha^*)]-\int_0^{\alpha^*}A(\alpha)\cos\alpha\, d\alpha\right\}\left\{\cos\delta-\cos(\alpha^*+\delta)-\sin\delta\int_0^{\alpha^*}A(\alpha)\,d\alpha\right\}^{-4/3} \qquad (4)$$

$$A(\alpha)=0.6520\exp(-\alpha/0.4843)-0.0544\alpha+0.3480 \qquad (5)$$

Phase angle $\alpha=\omega t$, with $\omega$ being the frequency and t being time. $\alpha^*$ is described by eq. (6), where $b/a$ is the ratio of the distance between the point of maximum indentation and the idler-belt contact trailing edge to the distance between the point of maximum indentation and the idler-belt leading edge.

$$\alpha^*=(\pi/2)[1+b/a] \qquad (6)$$

Although the QC-N model is not as simple to implement as Jonkers equation, it does show that there is a direct relationship between energy loss and dynamic material properties, where rolling resistance is proportional to $\sin\delta/\bar{G}^{(1/3)}$. This can be used for a quick comparison of rubber compounds.

## MATERIAL TESTING

The materials viscoelastic properties used for the aforementioned rolling resistance models are tested by applying an oscillating mechanical deformation to a sample and measuring the resultant stress, replicating the stress response of a belt being deformed as it moves over an idler roll on a conveying system.

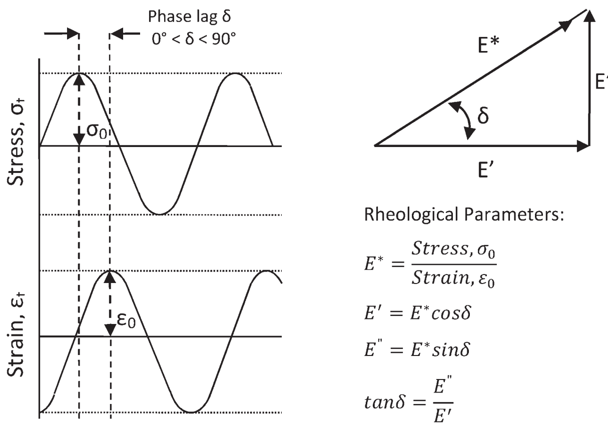


**Figure 1.** Viscoelastic behavior.

The stress response of a viscoelastic material will be out-of-phase with the applied strain. From the results of these tests an elastic modulus $E'$, a loss modulus $E''$ and phase angle $\delta$ can be calculated, see Figure 1.

An RSA-G2 solids analyzer was used for testing the viscoelastic properties of the rubber compounds in this article. The RSA-G2 has an axial force adjustment feature that was utilized during

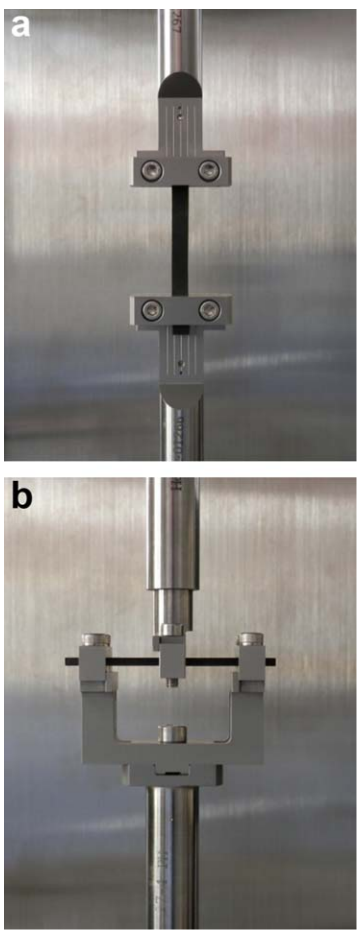


**Figure 2.** RSA G2 solids analyzer: (a) tension clamp and (b) dual cantilever clamp. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

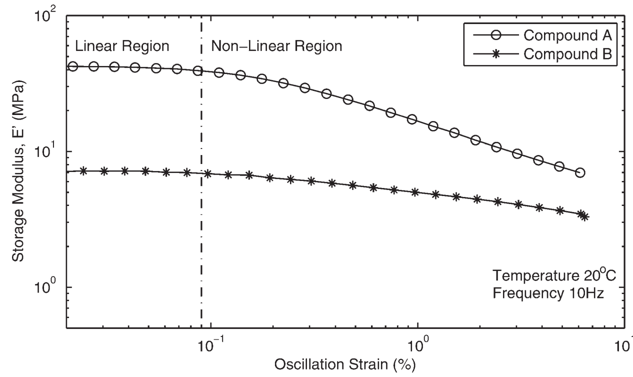


**Figure 3.** Strain sweep.

testing. This feature senses volumetric changes in a sample from changes in temperature and adjusts the clamp position accordingly to ensure the actual force is kept constant.

Three dynamic test modes were performed on each material. A strain sweep was performed at a single temperature and frequency, using the tension clamp pictured in Figure 2(a), to determine the linear viscoelastic region. At low strains, the elastic modulus is independent of strain and for strain values greater than 0.09% for the compounds shown in Figure 3, the modulus begins decreasing and the behavior is nonlinear. Larger oscillating strains have a much greater effect on the dynamic properties of compound A in Figure 3.

The second mode of testing performed on each material was a temperature ramp, as shown in Figure 4. A temperature ramp performed with a linear heating rate is used to determine the temperature dependence of a sample at one frequency and strain amplitude; it is one of the most sensitive techniques for identifying the glass transition temperature. The sudden decline in the storage modulus and corresponding peak in tan$\delta$ is where the glass transition temperature occurs. A temperature ramp performed at 10 Hz, with a 2% oscillating strain amplitude is one of the most common dynamic experiments used for a quick comparison of the viscoelastic properties of materials.

The maximum testable frequency for the RSA-G2 is 100 Hz, because inertia effects of the clamp become significant as frequency increases. However, with larger strain amplitudes,

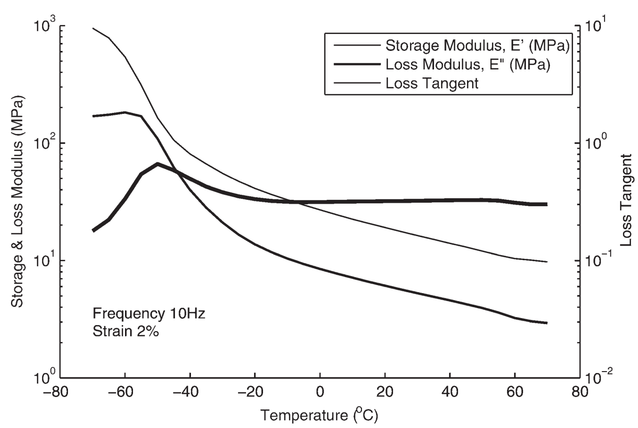


**Figure 4.** Temperature ramp.

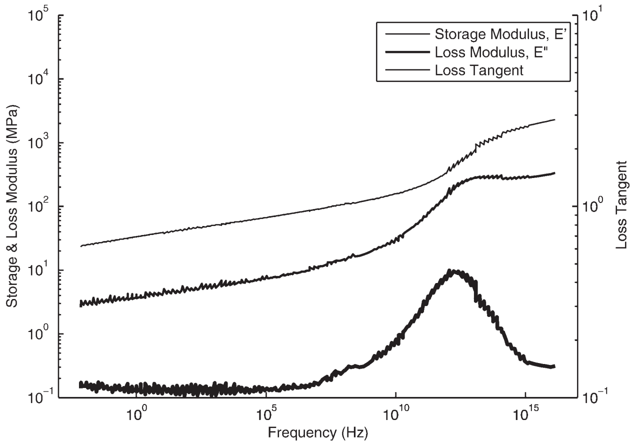


**Figure 5.** Master curve from time–temperature superposition.

inertia effects can influence the results at frequencies as low as 15 Hz. The deformation rate of the bottom cover of a conveyor belt due to the idler rolls normally ranges from 50 to 1000 Hz, which is outside of the RSA-G2 testable range. To determine the viscoelastic properties at these equivalent frequencies time–temperature superposition principles can be employed.

Data to perform time-temperature superposition is obtained by performing a temperature and frequency sweep on a sample. This test involves holding the temperature and strain constant while varying the frequency, the temperature is then stepped up in increments and held at the new temperature for a period of time to ensure a uniform temperature throughout the material before the frequency sweep is performed again. Master curves of the storage modulus, loss modulus, and tan$\delta$ data are derived from time–temperature sweeps where temperature and frequency are related through the Williams Landel Ferry transfer equation:

$$\log(a_T) = -C_1(T-T_o)/[C_2+(T-T_o)] \tag{7}$$

where $a_T$ is the frequency shift factor, $T$ is the temperature, $T_0$ is the reference temperature and $C_1$ and $C_2$ are material constants.

Figure 5 shows a master curve developed from time–temperature superposition. Master curve data can be used in indentation rolling resistance models. Three time–temperature sweeps were performed on each of the materials in this article, one in the linear strain region and two in the nonlinear strain region.

## INDENTATION ROLLING RESISTANCE TEST FACILITY

The indentation rolling resistance of the belt compounds studied in this article was measured on a purpose built test facility; see Wheeler and Munzenberger for a detailed description of the measurement rig.[12] The test facility is designed to measure rolling resistance for a range of idler roll diameters, belt speeds, vertical loads and belt compounds. The entire test facility is located within a temperature control room, thus testing can be performed over a range of temperatures.

The facility includes a measurement system shown in Figure 6. The measurement apparatus has strategically positioned load cells, which simultaneously measure the vertical load, horizontal load, and rim drag on the measurement idler roll. Rim drag is the force required to rotate the bearings and seals of the idler roll, it is subtracted from the total horizontal force when calculating the rolling resistance. The belt flexure is also measured and subtracted from the total horizontal force as separate component.

The vertical load is imposed on the belt by two "hold down rolls" and the tail end belt pulley. As can be seen in Figure 7, two "hold down rolls" are positioned on the carry side of the belt equal distances from the measurement roll. The rolls are pushed down on the top of the belt until the belt is deflected enough to give an equivalent sag ratio of a nominated value. The conveyor belts tested in this article are all steel cord reinforced; meaning the load being applied to the measurement idler roll is directly through the steel cables. The vertical load on the belt is varied by changing the belt tension by moving the tail pulley.

## TEMPERATURE-DEPENDENT PERFORMANCE OF COMPOUNDS

Belt conveyor rubber compounds used in overland conveying systems are typically made from 40% of styrene-butadiene rubber and 60% of natural rubber. Other components can be added to alter the properties specific to the needs of the belt for operating conditions, with exact ratios depending on the requirements for the belt conveying system.[13] Two rubber compounds were analyzed in this article. Compound A is a standard belt rubber used for typical belt conveyor systems and compound B is a low rolling resistance compound for temperatures greater than 10°C (as will be seen in the following section).

The temperature dependence of the indentation rolling resistance for the two rubber compounds was estimated and measured for analysis. The system parameters used for testing and calculation were as follows:

Idler roll diameter, $D = 178$ mm.

Simulated belt load, $W = 2000$ N/m.

Idler pitch 2.5 m.

Belt width, $b_w = 400$ mm.

Simulated belt sag, 1%.

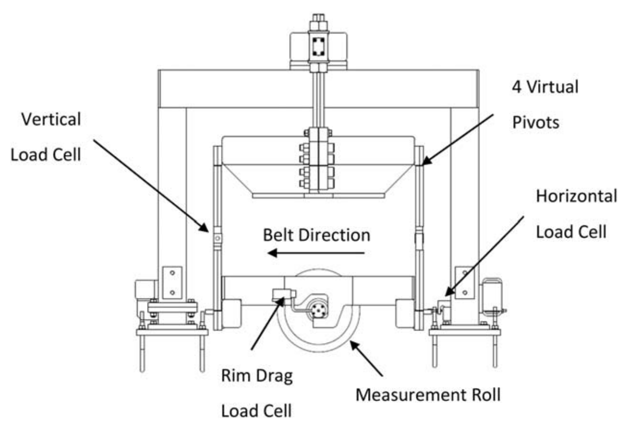


**Figure 6.** Measurement apparatus on indentation rolling resistance test facility.

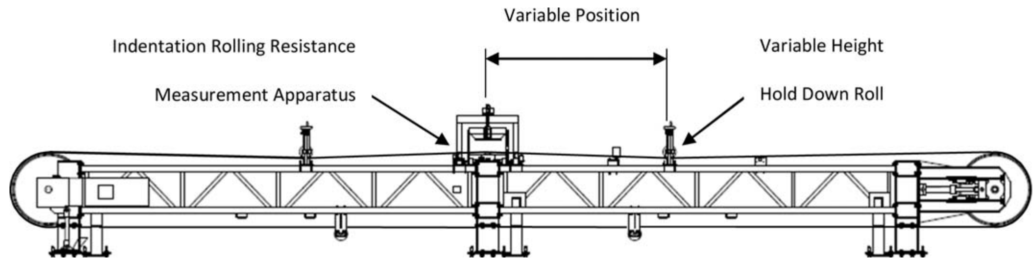


**Figure 7.** Belt path induced by "hold down rolls."

Belt speed, $v = 4$ m/s.

Belt test temperatures, $T = -20$, $-10$, 0, 10, 20, 30, 40, and 50°C.

Belt bottom cover thickness, $h = 8.5$ mm.

The "apparent" bottom cover thickness was used for calculation, which is equal to the bottom cover thickness plus half the cord diameter.[14] In order to compare the effect of material properties only on the rolling resistance, the experimentally measured results were normalized by factor $\left(\frac{Wh}{D^2}\right)^{1/3}$ and compared to the normalized Jonkers equation and QC-N model.

The experimentally measured rolling resistance factor (RRF) is shown in Figure 8. The measured rim drag and belt flexure resistance were removed from the experimental results.

The results show that for the experimental temperature range, the indentation rolling resistance (IRR) for compound A is constant and for compound B there is a decrease in IRR as temperature increases. For the test conditions described above, compound A performs better for temperatures between −20°C and 7.5°C and compound B performs better for temperatures above 7.5°C.

The first test mode used to measure the material properties for Jonkers equation and the QC-N model was a temperature ramp where the temperature was increased at a rate of 5°/min. Figure 9 shows the calculated RRF from a temperature ramp performed with a 2% strain amplitude applied at 10 Hz. For this test mode, both models over predict the IRR. The magnitude of the RRF determined by the QC-N model is closer to that of the experimental findings then using Jonkers equation. Jonkers equation predicts a cross-over temperature of −13.5°C for the two compounds and the QC-N model predicts a cross-over temperature of −17°C, both well below the experimental cross-over temperature of 7.5°C.

During a temperature ramp, the temperature is increased at a steady rate, making it questionable whether the temperature throughout the sample would be even, especially for thicker samples. Not allowing the whole sample to reach a constant temperature could result in errors in the measurement of viscoelastic properties and therefore errors in the calculation of rolling resistance. This was investigated by performing a temperature sweep as the second test mode used to measure the properties on the two compounds and examining the difference.

The strain amplitude and oscillating frequency were held constant at 2% and 10 Hz, respectively, while the temperature was increased in 10°C increments. The sample was held constant at each temperature for 5 min to ensure the temperature throughout the sample was even before measuring the properties. Figure 10 shows that the RRF calculated using temperature sweep material properties gives similar approximations to the experimental values found using the temperature ramp data for the particular sample size and tension clamp used. Once again, both models over predict the RRF using this material data, with the QC-N model giving a closer prediction than Jonkers equation.

As previously mentioned, the material properties are greatly dependent on the operating conditions. Compounds are often compared using tests performed with a 2% strain amplitude, when in reality the compressive strain of the bottom cover of the belt will depend on belt load, idler roll diameter, bottom

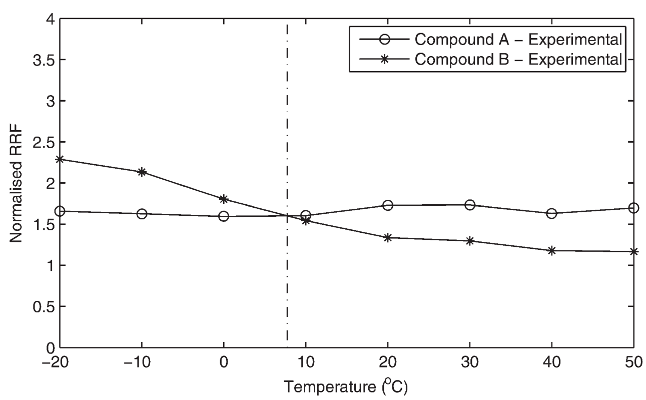


**Figure 8.** Normalized IRR versus temperature, measured experimentally.

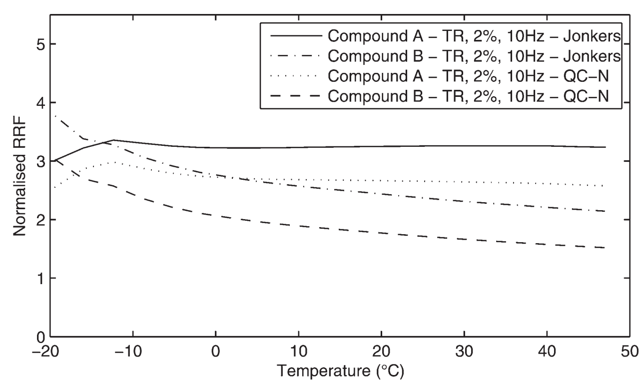


**Figure 9.** Normalized IRR versus temperature. Material properties taken from a temperature ramp (TR), with a 5°C/min ramp rate, performed at 10 Hz with 2% strain amplitude, using a tension clamp.

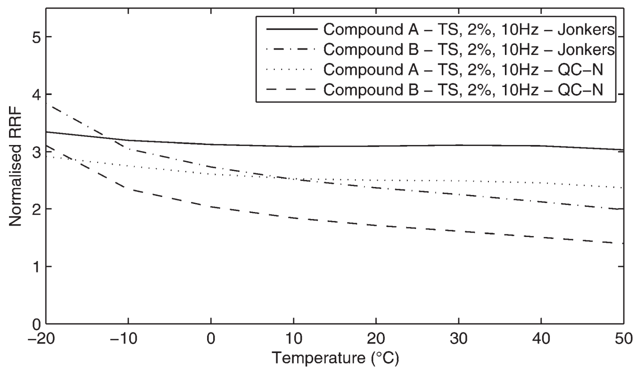


**Figure 10.** Normalized IRR versus temperature. Material properties taken from a temperature sweep (TS) performed at 10 Hz with 2% strain amplitude using a tension clamp.

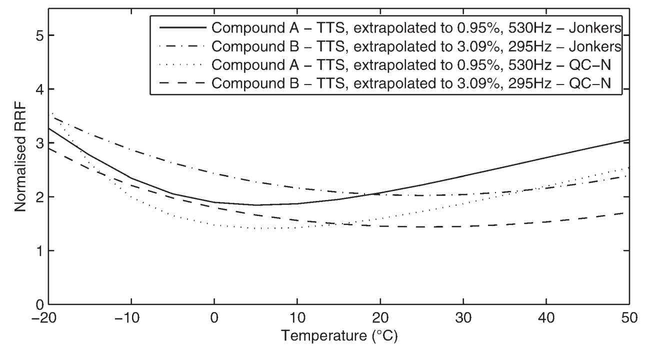


**Figure 12.** Normalized IRR verses temperature. Material properties are from time–temperature (TTS) tests done using a tension clamp, with a 0.05% strain amplitude that has been extrapolated to the approximated strain, using a strain amplitude correction factor.

cover thickness and the material properties. Figure 3 demonstrates the influence of strain on compound A and B, with compound A being more effected by larger strain values than compound B. In endeavor to obtain a more accurate prediction of IRR, the material strain effects need to be accounted for by approximating the strain and either performing the tests at this strain or by using the strain amplitude correction method described in Rudolphi.[9]

The most accurate way to approximate strain is by iterative methods because the strain depends on the belts storage modulus, which is dependent on the strain. Finite element analysis or models developed by Rudolphi and Reicks or Qui provide an estimate of indentation depth; however, for this article, a simple predictor for the contact length $a_0$ from Lodewijks will be employed to approximate the indentation depth $d$ in order to estimate the strain.[7,11,15]

The contact length $2a_0$ is predicted by the following equation: $a_0=\left(\frac{3WDh}{4E_1}\right)^{1/3}$, where the same system parameters are used for $W$, $D$, and $h$ as before. Lodewijks uses an iterative method to determine the storage modulus $E_1$; however, for this article, the value for $E_1$ was taken from the linear region of the strain sweeps in Figure 3, performed at 10 Hz and 20°C.[7] For compound A, $E_1 = 4.2 \times 10^7$ Pa and for compound B $E_1 = 7.1 \times 10^6$ Pa. If

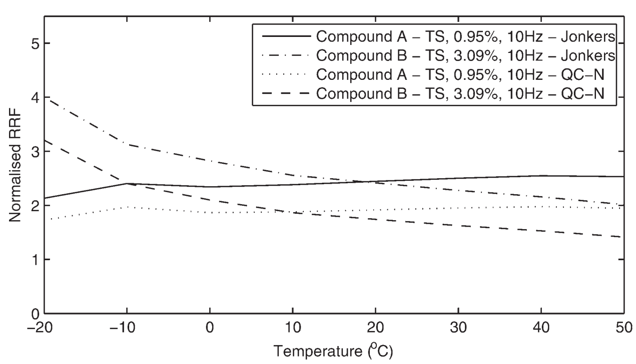


**Figure 11.** Normalized IRR versus temperature. Material properties taken from a temperature sweep (TS) performed at 10 Hz with 0.95 and 3.09% strain amplitude for compound A and B, respectively, using a the tension clamp.

the idler roll diameter, $D$ is much greater than the thickness of the bottom cover of the belt, the relationship $d \approx \frac{a_0^2}{D}$ can be used to calculate the indentation depth.[10] So, the strain estimated for the system described above for compound A is calculated as $d/h\times\ 100 = 0.95\%$ and the strain estimated for compound B is 3.09%.

A temperature sweep was performed on both compounds using the different estimated strain amplitudes for the described system, resulting in different values for $E'$ and tan$\delta$. The new values were applied to Jonkers equation and the QC-N model, with the results shown in Figure 11.

Using this material data with Jonkers model still overestimates the IRR, and the cross-over temperature is too high at 18.5°C. The magnitude and trend with temperature of the RRF for both compound A and B calculated using the QC-N model is a lot closer to the experimentally measured RRF compared to using material data from previous test modes. The cross-over temperature is at 9°C, which is also very close to the 7.5°C cross-over temperature determined experimentally.

As mentioned in QC-N Indentation Rolling Resistance Model section, material properties $E'$ and tan$\delta$ are dependent on the oscillation frequency. The indentation frequency for the described system can be calculated by dividing the belt speed, $v$, by the previously approximated contact length, $2a_0$. For a belt speed of 4 m/s, the approximated indentation frequency for Compound A and B are 530 and 295 Hz, respectively. The material properties used to calculate IRR in Figures 9–11 were all measured at 10 Hz. In order to get temperature-dependent material properties at these equivalent frequencies time–temperature tests were performed on each material, as described in QC-N Indentation Rolling Resistance Model section. The first test on each compound was performed with a strain amplitude of 0.05%, which is in the linear strain region. The second set of tests was performed in the nonlinear strain region, with a strain amplitude of 2% and the third set of tests were performed with a strain amplitude of 0.95% for compound A and 3.09% for compound B.

Material properties found by testing in the linear strain region were extrapolated to the strains calculated previously for each compound. This was done by multiplying the

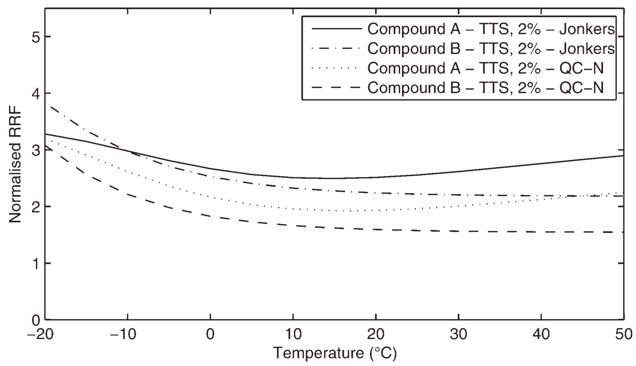


**Figure 13.** Normalized IRR verses temperature. Material properties are from time–temperature tests (TTS) done with a 2% strain amplitude, using a tension clamp.

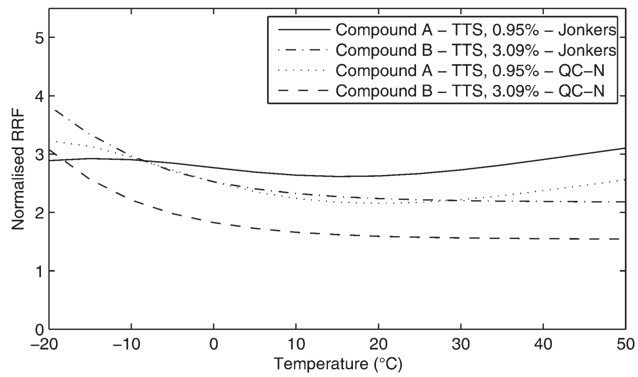


**Figure 14.** Normalized IRR verses temperature. Material properties are from time–temperature tests (TTS) done with 0.95 and 3.09% strain amplitude for compound A and B, respectively, using a tension clamp.

modulus values by factor $\frac{E'\ or\ E''(@0.95\%\ strain)}{E'\ or\ E''(@0.05\%\ strain)}$ for compound A and $\frac{E'\ or\ E''(@3.09\%\ strain)}{E'\ or\ E''(@0.05\%\ strain)}$ for compound B, where the values are measured from strain sweeps performed at each temperature. Figure 12 shows the RRF calculated using these material properties. Compared to the previously discussed test modes, this mode gives the worst prediction of the trend for the temperature dependence of compound A, this could be due to using the same strain amplitude factor for each temperature. The calculated magnitudes are high for Jonkers model, as expected, but are close for the QC-N model for temperatures between 0 and 20°C for both materials. This could be due to techniques used to shift the data in obtaining the master curves, where 20°C is used as the reference temperature and the assumed frequency of indentation.

Figure 13 shows the IRR calculated using the TTS data tested using a strain amplitude of 2%. Comparably to above modes, Jonkers equation gives a much higher prediction than the QC-N model, with the QC-N model being more accurate. The trend predicted for the RRF with temperature is close for compound B, but not for compound A. The RRF of compound A at 20°C is very close to the experimentally determine RRF, but deviates for temperature either side of 20°C. Once again this could be due shifting of data to obtain the master curve, where 20°C was the reference temperature. Additionally, strain does not have as large of an effect on the material properties of compound B, which could also be why the temperature-dependent trend of compound B is closer to the experimental one than for compound A.

Time–temperature tests were performed with strain amplitudes of 0.95 and 3.09% for compound A and B, respectively, to compare to the results of the TTS performed at 2%. The material properties determined for compound B gave a fairly good approximation for 10°C and below using the QC-N model; however, the material properties determined for compound A were worse than those found using a strain amplitude of 2%. This difference could be due to errors when approximating the strain amplitude used.

Figure 15 was included to further illustrate the difference in IRR calculated using properties from different test modes for the same material. Figures 15(a,b) are comparisons of the results from Figures 8–14 for compounds A and B, respectively.

The RRF calculations using the QC-N model for compound A, pictured in Figure 15(a), further demonstrate the effects of strain, or deformation, on the material properties and hence rolling resistance. The material properties from the temperature

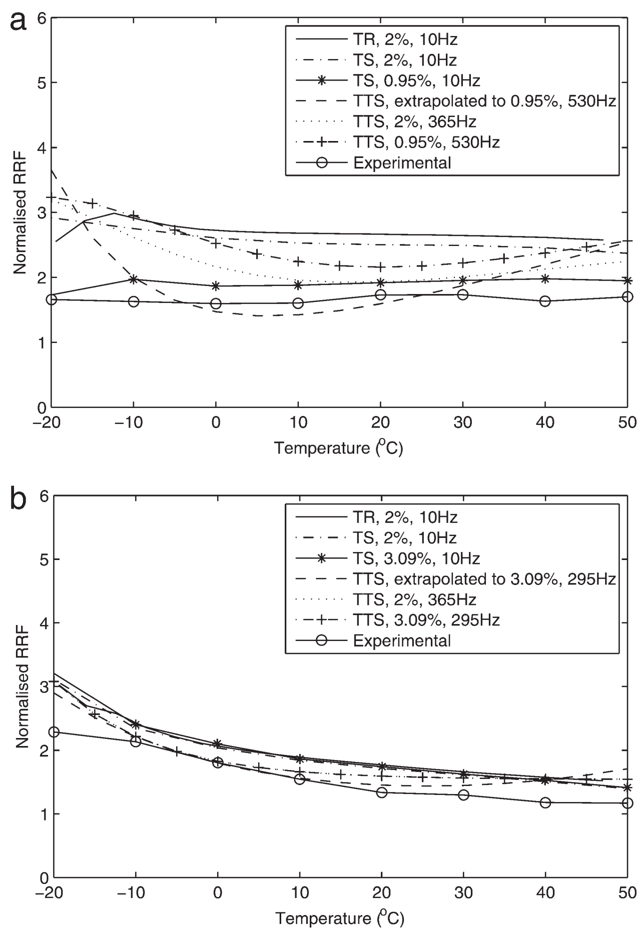


**Figure 15.** Comparison of normalized IRR, calculated using the QC-N model, using viscoelastic properties determined by various test modes: (a) compound A and (b) compound B.

ramp and temperature sweeps give the most accurate prediction of trend with temperature. The material properties from the master curves give the best approximation of magnitude at 20°C, which was used as the reference temperature for shifting the data, but the RRFs trend away from the experimental results for temperatures each side of 20°C. For compound A, the most accurate prediction of rolling resistance comes from applying material properties obtained from the temperature sweep performed at the approximated strain amplitude of 0.95% to the QC-N model.

As can be seen in Figure 15(b), the calculated rolling resistance factors using the QC-N model for compound B all increase as temperature decreases. This is similar in trend to the experimental data. The effect of strain on the material properties of compound B is only small compared to that of compound A, which could explain why using the various modes to obtain the material properties all give reasonably good predictions.

It is also worth mentioning that the material properties are not only depended on operating conditions, they depend on experimental technique. If a temperature ramp was performed on the same material, under the same conditions, but with a different machine and/or operator and/or clamp, the results could be different.

## POWER CONSUMPTION DEPENDENCE ON TEMPERATURE

The power demand of a simplified belt conveying system was calculated to demonstrate the influence a belts material has on the power consumption of a system.

The system modeled was a 10 km long horizontal overland conveyor, moving iron ore with a bulk density of 2200 kg/m$^3$ and surcharge angle of 20°. A 1.5-m wide belt was used, weighing 82 kg/m and traveling at 4m/s. Three-idler roll sets where used, with a diameter of 178 mm and a 35° trough angle. The carry side idler set spacing was 1.75 m and the return side spacing was 7 m.

The power demand of the system was calculated using a program developed by Ausling, based on the methods described by Wheeler.[8,16] The indentation rolling resistance component of the system was calculated based on the experimental results for the two belt compounds under equivalent conditions, including loading conditions. Operating temperatures need to be considered when selecting a belt for a system, for example, in Australia it would be possible for a belt temperature to reach −10°C on a winter's night and 40°C on a summer's day. Experimental data were used from tests performed with a belt temperature of −10 and 40°C to demonstrate the variation of power consumption with temperature.

The calculated results of power verse tonnage are shown in Figure 16. Compound A is not overly affected by temperature, whereas the performance of compound B is greatly affected by temperature. The operating temperatures would determine what conveyor belt would be best for this system. If the wrong material properties are used initially to approximate the indentation rolling resistance, the error will be carried over to the power calculations. Because there was such a large variation in results

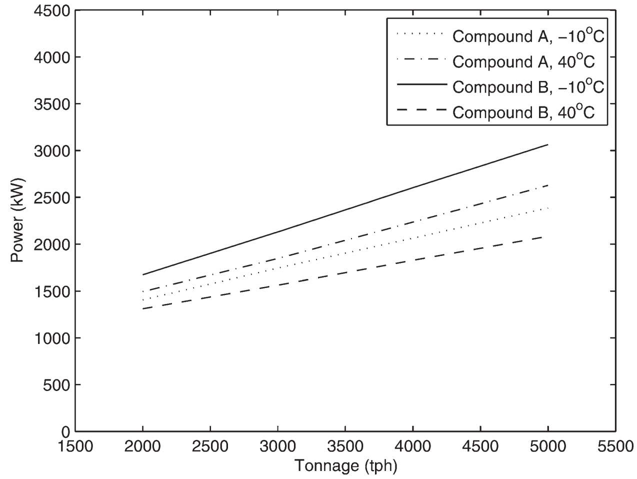


**Figure 16.** Power demand v tonnage of a 10-km overland conveying system for the two rubber compounds at two "extreme" temperatures.

from obtaining the viscoelastic properties using different testing modes, a large variation in calculated power would result. A material with a higher indentation rolling resistance could mistakenly be chosen for a system, resulting in a higher power demand. A higher power demand means higher capital and operating costs.

Note that temperature effects on idler roll grease were not taken into consideration when calculating the power demand of the system, in order to highlight the influence of the temperature-dependent viscoelastic properties of the belt only.

## CONCLUSIONS

The results given in this article show that the QC-N model gives a more accurate prediction of indentation rolling resistance than the more commonly used Jonkers equation.

The accuracy of an indentation rolling resistance model is greatly dependent on how the viscoelastic properties of the conveyor belt material are obtained. The viscoelastic properties of a belt are influenced by the operating conditions of a system, in particular belt load, temperature, speed and indentation depth. These conditions need to be considered when determining the material properties using rheological methods. It is important when performing rheological tests that the sample temperature reaches a constant value to obtain the most accurate property measurements, as the material properties can be very temperature dependent.

For the two compounds compared in this article, Figures 15 and 16 showed that there is not one dominant method for obtaining the most accurate material properties, especially when the material properties are highly strain dependent. However, approximating the strain and obtaining the material properties at that particular strain value does give a better prediction for the indentation rolling resistance for both compounds.

Figure 15 highlights the importance of calibrating analytical results with experimentally obtained values from specialized test facilities or field experiments when wanting to accurately calculate the power requirements of a system. Inaccuracies in measuring the material properties can lead to large miscalculations of power for overland conveying systems, which can result in increased capital and operating costs.

## REFERENCES


1. Hager, M.; Hintz, A. *Bulk Solids Handling* **1993**, *13*, 749.
2. Nordell, L. K. *Bulk Solids Handling* **1991**, *11*, 781.
3. Steven, R. B. High Tech Conveyor Belt Development for the World's Longest Single Flight Intelligent Conveyor. In Proceedings of the 9th International Conference on Bulk Materials Storage, Handling and Transportation, Newcastle, **2007**.
4. Nordell, L. Improving Belt Conveyor Efficiences: Power, Strength & Life With Overland System Case Studies. In 4th Annual Optimizing Conveyor Performance in Mining Confernce, Australiasian Mining & Energy Taskforce, Perth and Sydney, **1998**.
5. Lodewijks, G. Determination of Rolling Resistance of Belt Conveyors Using Rubber Data: Fact or Fiction? Beltcon 12, South Africa, **2003**.
6. Jonkers, C. *Fördern und Heben.* **1980**, *30*, 312.
7. Lodewijks, G. Dynamics of Belt Systems. In Ph.D Thesis, Chapter 5. Delft University of Technology, Netherlands, **1996**.
8. Wheeler, C. Analysis of the Main Resistances of Belt Conveyors. In Ph.D Thesis. University of Newcastle, **2003**.
9. Rudolphi, T. Applied Rubber Belt Cover Loss Prediction from Indentation. In SME Annual Meeting and Exhibit, Salt Lake City, Utah, **2008**.
10. Qui, X.; Chai, C. *J. Energy Eng.* **2011**.
11. Rudolphi, T.; Reicks, A. *Rubber Chem. Technol.* **2006** *79*, 307.
12. Wheeler, C.; Munzenberger, P. Indentation Rolling Resistance Measurement. Beltcon 16: Johannesburg, South Africa, **2011**.
13. Lodewijks, G. The Next Generation of Low Loss Conveyor Belts. Beltcon 16: Johannesburg, South Africa, **2011**.
14. Wheeler, C.; Munzenberger, P. A Pseudo 3D Analysis of the Indentation Rolling Resistance Problem. Beltcon 15: Boksburg, South Africa, **2009**.
15. Qui, X. *J. Eng. Mech.* **2006**, *132*, 1241.
16. Wheeler, C.; Ausling, D. *Bulk Solids Powder: Sci. Technol.* **2008**, *3*, 15.