

Determination of rolling resistance of belt conveyors using rubber data: fact or fiction?

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Summary

This paper discusses the nature and importance of the indentation rolling resistance for modern belt conveyors. It provides a mathematical model to calculate it and describes rheological tests that can be done to measure the viscoelastic properties of the conveyor belt's cover material. Finally, it provides an answer to the question: determination of rolling resistance of belt conveyors using rubber data: fact or fiction?

1 Introduction

A belt conveyor is a mechanical conveyor frequently and worldwide used to continuously transport a certain material or people from a place A to a place B at a capacity C. When ordering a belt conveyor, a client normally is concerned about issues like performance (can we move C from A to B?), reliability, maximum wear rates, total cost of ownership, complexity of the system etc. During large projects the client normally provides specifications but does not specify specific types or sizes of components, although most major clients have a preferred supplier list. Assuming that the performance, reliability, maximum wear rates etc. are guaranteed by the belt conveyor supplier, they can select the actual component types and sizes.

To reduce the investment and operating costs of a belt-conveyor system it is important to determine and analyse the influences of the plant parameters and the operating parameters on the energy consumption. In terms of the indentation rolling resistance this implies that the dependence of this resistance on the roll radius, idler spacing, belt speed and radius of curvature should be known. It is also important to know the influence of the belt material and belt structure on the indentation rolling resistance and therefore on the energy consumption of the belt.

One of the most important components of a belt conveyor is the conveyor belt itself. The conveyor belt can make up till about 70% of the costs of a conveyor and the rolling resistance associated with the rubber (the indentation rolling resistance) can account for about 50% of the total rolling resistance [1]. The selection procedure of the conveyor belt should therefore be taken seriously.

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It is well known that using standardised design methods like DIN 22101 or CEMA to calculate the power consumption of a belt conveyor generally leads to an overestimation of the power consumption and thus of the belt tensions. One reason is that these design methods fail to take the viscoelastic or mechanic/dynamic rubber compound properties into account. They can therefore not distinguish between the power characteristics of a belt made off one rubber compound or the other. Since the late fifties of the last century quite a few researchers worked on models that can be used to predict that part of the rolling resistance that stems from the rubber compound: the indentation rolling resistance. The use of these models provided insight into the nature of this resistance [2]. With this insight models have been developed that enable a link between the mechanic/dynamic properties of rubber compound and the later systems power consumption [3].

Although unknown power consumption may seem only a matter of costs, it also seriously affects the conveyors performance. Knowledge of rubber compound properties is therefore important because it partly determines the size and settings of components like motors and brake systems. For example, the application of a low loss rubber compound on a belt of a long overland system is a good way to reduce the overall operating costs. In case of an incline belt conveyor however, the extra costs of belting are not worth the effort since most of the power is used to raise the material. The total power consumption is therefore not noticeably decreased by the use of a low loss rubber. On a decline belt conveyor the application of a low loss rubber may be a bad idea since it may increase the size and complexity of the brake system.

2 Recent South African projects

In the last three years, three South African projects involving long overland belt conveyors have been realised²:

- 1) CRU-II, Middelburg for Ingwe,
- 2) Optimum, Hendrina for Ingwe, and
- 3) Savmore, Piet Retief for the Kanga Group.

During all three projects the quality, in particular of the rubber covers, and the supplier of the conveyor belting were serious issues for discussion. The next three paragraphs explain the specific matters.

2.1 CRU-II.

After adjudicating tenders from several top-ranking world contenders, Middelburg Mine Services awarded the contract for a 14,5 km overland

conveyor system to BATEMAN. The project was executed by Bateman Engineered Technologies. The conveyor system is part of phase II of the R480M Coal Resources Utilisation Project (CRU II) initiated by Ingwe Coal Corporation Limited and was commissioned in May 2000.

In the tendering stage of the project, the belt conveyor system was presented, and later sold, as a high tech system utilising low indentation loss compound for the belt's covers. The biggest advantage of using a low loss rubber for the belt was a serious decrease in expected power consumption of the total system. The designs of the individual belt conveyors then were based on using belts with low loss covers. The anticipated supplier for the CRU-II belting was Bridgestone. During the course of the project however, the client requested that they could use alternative (read non low-loss rubber) belts as a replacement belt. The main reason for this was that Ingwe wanted to have a better position to negotiate for replacement belting. The design was therefore slightly altered, in particular the settings of major components as the drives and the brake systems, to enable the application of alternative belting. After completion of the system Optimum used a Dunlop SA belt to replace part of the original Bridgestone belting without any serious problem.

2.2 Optimum.

Ingwe has awarded BATEMAN a turnkey contract for a 21 km overland-conveyor system to be supplied to Optimum Colliery. It includes all design, supply and erection, inclusive of civil works. The system will comprise five belt conveyors ranging in length from 2.7 km up to 6.1 km.

The Optimum project, see Figure 1, knew a short-track design phase. The design of the system was in principle a further development of the system designed for CRU-II, including the application of conveyor belting with low loss rubber compounds. However, because of the short-track development there was not enough steel cord belting available on the world-market at the time. As a result, the client had to buy a mixture of Dunlop and Bridgestone belting. One of the main design principles of the Optimum overland belt conveyor system was standardisation of components. Therefore, all belt conveyors in principle should allow for the use of either Dunlop or Bridgestone belting. Because the problem with shortage of belt supply was known at a relatively early stage of the project, most components of the belt conveyors could still be standardised but were tuned for the specific belting used on individual conveyors.



Figure 1: *Belt Conveyor KW-05 of the Optimum overland system.*



Figure 2: *The Savmore overland belt conveyor.*

2.3 Savmore

Kangra Group (Pty) Ltd's Savmore Colliery, near Piet Retief in the Mpumalanga Province of South Africa, has awarded BATEMAN a contract for a 6,5 km overland conveyor. The conveyor will link Savmore's new Maquassa West shaft with the existing plant at Maquassa East and will carry 1 000 t/h of run-of-mine coal.

The Savmore project was developed at the same time as Optimum and therefore the Kanga Group had the same belt shortage problem as Ingwe. However, there was only one long overland belt conveyor in the Savmore project and Savmore decided to buy the belt directly from Goodyear and provided it to Bateman as a free issue. Although the design of the Savmore belt conveyor was based on the assumption that it should be able to utilise basically any modern conveyor belt, the dynamic/mechanic properties of the specific conveyor belt were still required to optimise the system by tuning the components. The dynamic/mechanic properties of the Goodyear belt however were not known and Goodyear was not able or unwilling to supply either rubber mechanic/dynamic properties or a sample of the specific rubber used. As a result the performance of that specific conveyor belt, and thus the conveyor system, were unknown during the commissioning stage.

3 Viscoelasticity³

In this section a model will be presented that can be used to represent the viscoelastic behaviour of the material of a conveyor belt's cover.

Most belt covers are made of rubber or polyester material. The constitutive behaviour of these materials is visco-elastic as can be learned from the time-dependency of the stress-strain relations, [2]. The most important environmental parameters that affect the dynamic response of visco-elastic materials are temperature, frequency and the amplitude of an imposed load [4]. It is also important to know the exact compound of the material. In rubber for example the amount of carbon black influences the material properties considerably [5].

The constitutive equation for a isotropic linear visco-elastic material can be written in general tensor form [6]:

$$\sigma^d(t) = \int_{-\infty}^t \Psi(t-t') \frac{\partial \gamma^d(t')}{\partial t'} dt' \quad (1)$$

in which $\sigma^d = \sigma - (\frac{1}{3} \text{tr} \sigma) \mathbf{I}$ is the deviatoric stress tensor and $\gamma^d = \gamma - (\frac{1}{3} \text{tr} \gamma) \mathbf{I}$ the deviatoric strain tensor. The fourth order tensor

³ This section is based on Chapter 3 of [3].

function $\Psi(t)$ is called the relaxation function and specifies the stress response to a unit strain increment. It can be written as:

$$\Psi(t) = \Psi_\infty + \int_0^\infty g(\tau) \exp\left(-\frac{t}{\tau}\right) d\tau \quad (2)$$

where $g(\tau)$ is the relaxation spectrum which can be discrete or continuous and τ the relaxation time. If in the uni-axial case a pulse-spectrum $g(\tau) = \sum_{j=1}^N g_j \delta(\tau - \tau_j)$ is used then the relaxation function is equal to:

$$\Psi(t) = \Psi_\infty + \sum_{j=1}^N g_j \exp\left(-\frac{t}{\tau_j}\right) \quad (3)$$

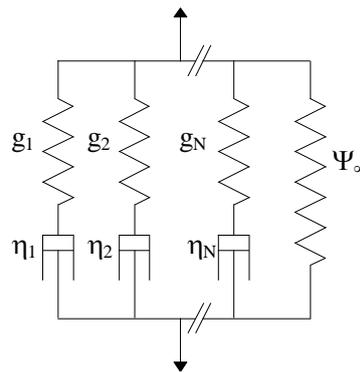


Figure 3: *Generalised uniaxial Maxwell model.*

This material model is known as the generalised Maxwell model. Figure 3 shows this uniaxial case. In this model a number of damping coefficients η_j is used which are related to specific relaxation times τ_j , in order to be able to represent the constitutive behaviour of a material for a wide range of loading frequencies. If this range is relatively small for a specific application then it is sufficient to use one relaxation time which fits for that range. In such a case a three parameter model, or a so called standard linear solid model, results that is the simplest model that can describe the relaxation of a material and situations of constant stress or high strain rates, see Figure 4.

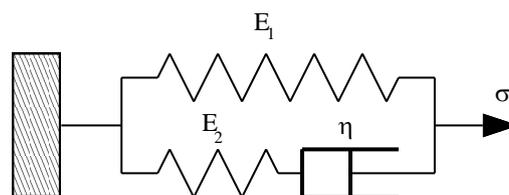


Figure 4: *Three parameter Maxwell model (standard linear solid model).*

The relaxation function of the three parameter model is:

$$\Psi(t) = E_1 + E_2 \exp\left(-\frac{t}{\tau}\right) \quad (4)$$

where the relaxation time $\tau = \frac{\eta}{E_2}$. For a three parameter Maxwell model the storage modulus is:

$$E'(\omega) = \frac{E_1 E_2^2 + \omega^2 \eta^2 (E_1 + E_2)}{E_2^2 + \omega^2 \eta^2} \quad (5)$$

where ω is the circular frequency of deformation. The loss factor $\tan\delta$ is in this case defined by:

$$\tan\delta = \frac{E''}{E'} = \frac{\omega \eta E_2^2}{E_1 E_2^2 + \omega^2 \eta^2 (E_1 + E_2)} \quad (6)$$

The damping factor η_i of the three parameter Maxwell model can then be written in terms of the loss factor:

$$\eta_i(\delta) = \frac{2 \pi \tan\delta}{2 + (\pi + 2\delta)\tan\delta} \quad (7)$$

From experiments it can be learned that a real rubber cannot be modelled with one relaxation time. However, if the differences in belt speed are not too large, in fact the belt speed of conveyor belts varies from 0.1 m/s to 10 m/s, then it is sufficient to choose one relaxation time. This relaxation time must be chosen in agreement with the time it takes for a material point of the belt cover to pass the contact zone between belt and roll. The storage modulus, the loss modulus and the loss factor have been obtained from experiments for a SBR rubber[2]. The results are depicted in the Figures 5, 6, and 7 as a function of temperature and deformation rate. As can be seen in Figure 7, the resilience of the SBR rubber of the belt cover passes through a minimum, and thus the loss modulus through a maximum.

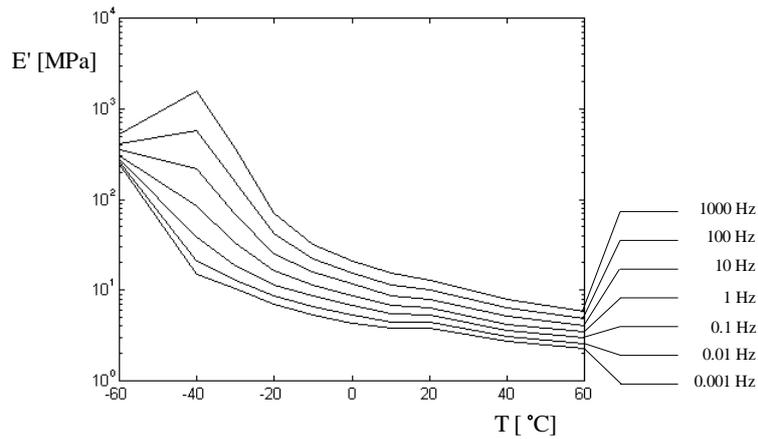


Figure 5: The storage-modulus as a function of temperature and deformation rate [2].

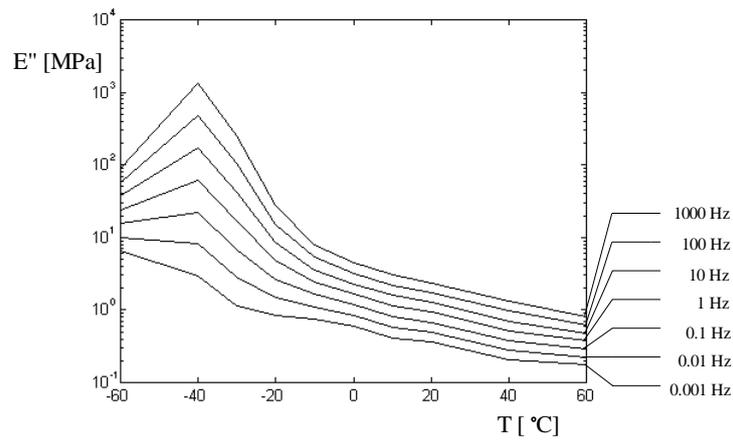


Figure 6: The loss-modulus as a function of temperature and deformation rate [2].

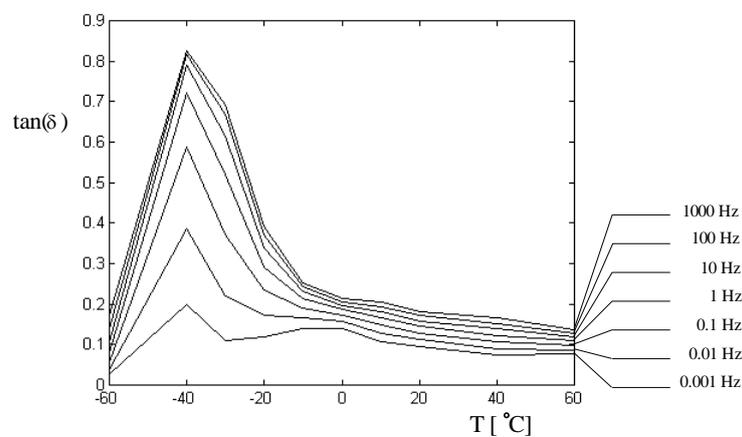


Figure 7: The loss-factor as a function of temperature and deformation rate [2].

4 Rheological testing⁴

In this section rheological tests, in particular dynamical mechanical tests, are described that can be used to gather information on the viscoelastic properties of rubber compounds.

4.1 Rheological test modes and methods

The response of a viscoelastic material to mechanical deformation involves a series of molecular, segmental, and conformational changes. These changes are not instantaneous, some are quick, others slow. The net effect is that the response of a viscoelastic material to mechanical deformation can spread over a wide and continuous time spectrum ranging from years to microseconds. To obtain accurate and useful data, tests must be performed in the same time scale as the phenomenon under study.

No single test mode can span the total time range. There are three conventional test modes that can be used to obtain data: steady, dynamic, and transient. The choice for a specific test mode is determined by the required information and the nature and geometry of the sample. A steady test uses continuous rotation to apply the strain and provide a constant shear rate. The resultant stress is then measured when the sample reaches a steady state. In a dynamic test, an oscillatory strain is applied to a sample, and the resulting stress is measured. Dynamic tests can be made using free oscillations at the resonance frequency of the test material (for example, the torsion pendulum), or with a sinusoidal (or other waveform) oscillation at a forced frequency chosen from a wide available range. In a transient test, the response of a material as a function of time is measured after subjecting the material to an instantaneous change in strain, strain rate, or stress.

From the data obtained from the rheological tests equivalent data for the other type measurement in the desired logarithmic time scale can be obtained. The key element is that the dynamic frequency of oscillation directly links the material time and laboratory time (the time scale t in seconds is the reciprocal of the frequency ω), and dynamic data can be directly related to steady data through the Cox-Merz relation. By employing the Boltzmann principle and time-temperature superposition, data can be obtained to predict material behavior outside the range of conventional rheometers.

⁴ This section is based on [7].

4.2 Dynamic Mechanical Test

In a dynamic mechanical test, an oscillating strain (sinusoidal or other waveform) is applied to a sample and the resulting stress developed in the sample is measured. For solids that behave ideally and follow Hooke's law, the resulting stress is proportional to the strain amplitude, and the stress and strain signals are in phase. If the sample is a fluid and it behaves ideally, then the stress is proportional to the strain rate, (Newton's law). In this case, the stress signal is out of phase with the strain signal, leading the strain signal by 90° . The stress signal generated by a viscoelastic material can be separated into two components: an elastic stress T' that is in phase with the strain, and a viscous stress T'' that is in phase with the strain rate (90° out of phase with the strain). The elastic stress is a measure of the degree to which the material behaves as an elastic solid. The viscous stress is a measure of the degree to which the material behaves as an ideal fluid.

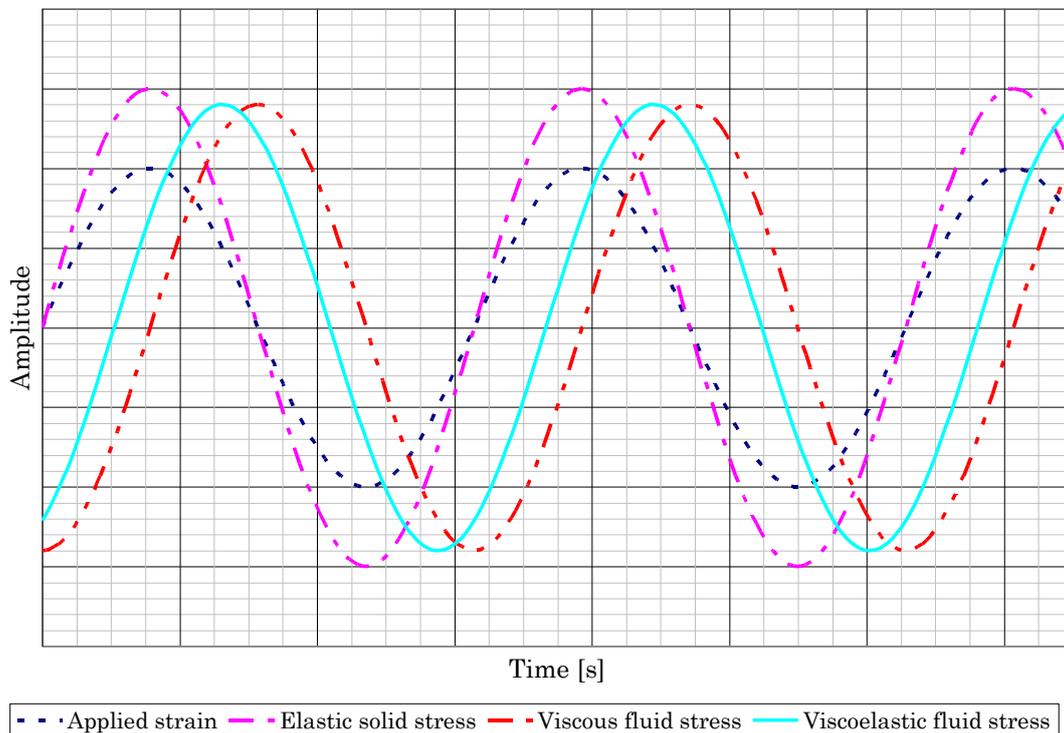


Figure 8

By separating the stress into these components, the material's dependence on strain amplitude and strain rate can be measured simultaneously. Figure 8 shows the behavior of elastic, viscous, and viscoelastic materials. The elastic and viscous stresses are related to material properties through the ratio of stress to strain, the modulus. The ratio of the elastic stress to strain is the storage (or elastic) modulus E' . The ratio of the viscous stress to strain is the loss (or viscous) modulus E'' . When testing is done in shear

rather than in tension or compression, G' and G'' designate the storage and loss moduli, respectively.

4.3 Dynamic Test Modes.

Forced frequency rheometers control oscillation frequency, oscillation amplitude, and test temperature in a dynamic test. A typical test holds two of these constant while systematically varying the third. Strain sweeps, frequency sweeps, temperature sweeps, time sweeps, and time/cure are the basic test modes, a sweep being a continuous variation of the parameter in operator- selected steps.

Strain sweep

Usually, the rheological properties of a viscoelastic material are independent of strain up to a critical strain level, γ_c . Beyond this critical strain level, the behavior is non-linear and the moduli decline. So, measuring the strain amplitude dependence of the storage and loss moduli is usually the first step taken in characterizing viscoelastic behavior: A strain sweep will establish the extent of the material's linearity.

Frequency sweep

In a frequency sweep, measurements are made at different oscillation frequencies at a constant oscillation amplitude and temperature. This test mode is especially important in testing of solid samples, since key transitions are known to shift with oscillation frequency. For many materials, as the frequency is increased, transitions occur at higher temperatures. Also, some transitions shift different amounts, depending on their degree of frequency-dependence. This fact helps locate some transitions in multicomponent systems, if one component is more frequency-dependent than another. In general, as frequency changes, the temperature of the secondary transition shifts more than does that of the glass transition.

Temperature sweep

Temperature sweeps characterize the temperature dependence of the material's rheological parameters, information vital in processing liquid materials. For solids, the degree of crystallinity and other morphological features can be examined in this way. This test mode provides, perhaps, the most sensitive means for measuring the glass transition and other secondary transitions, knowledge of which can identify softening points and useful temperature ranges in solid materials. These transitions are characterized by measuring the dynamic moduli and $\tan \delta$ at a selected frequency in a temperature sweep. The glass transition is detected as a sudden and considerable decrease in the storage modulus E' and an

attendant peak in the $\tan \delta$ curve. The temperature at which this transition occurs is called the glass transition temperature T_g .

Time sweep

A material's chemical, mechanical, or thermal stability can be sensitively assessed in a time sweep by simply measuring the modulus or viscosity at a constant temperature, frequency, and strain in a selected atmosphere over an extended period of time. In addition, time sweeps can be used for studying chemical and thermal degradation of materials. For example, in conventional thermal degradation studies, samples are exposed in an oven to an elevated temperature.

Time/Cure

The time/cure mode, besides being used in studies of thermal transitions in solids, is used to measure the initial viscosity, minimum viscosity, approximate gel point, and optimum heating-rate of thermosets during curing.

For the determination of the mechanic/dynamic properties of rubber compound of conveyor belts normally the temperature sweep test mode, or sometimes the frequency sweep test mode, is used.

4.4 Test equipment

For performing mechanic/dynamic tests on elastomers as rubber rotational and linear test geometries are available. If a rotational test geometry is used then the sample is sheared and G' and G'' are determined. If a linear test geometry is used then the sample is tensioned (or compressed) and E' and E'' are determined. Normally conveyor belt manufactures supply vulcanized sheets of rubber as sample material for testing the mechanic/dynamic properties. If the mechanic/dynamic properties of vulcanized rubber are to be determined then normally a linear test geometry is used. If, on the other hand, the mechanic/dynamic properties of unvulcanized rubber are to be determined then a circular test geometry is used. In this paper the test geometries are restricted to the linear geometries.

If a linear test geometry is used then one of the following four geometries can be chosen (also see Figure 9):

- three point bending
- dual cantilever
- tension
- compression

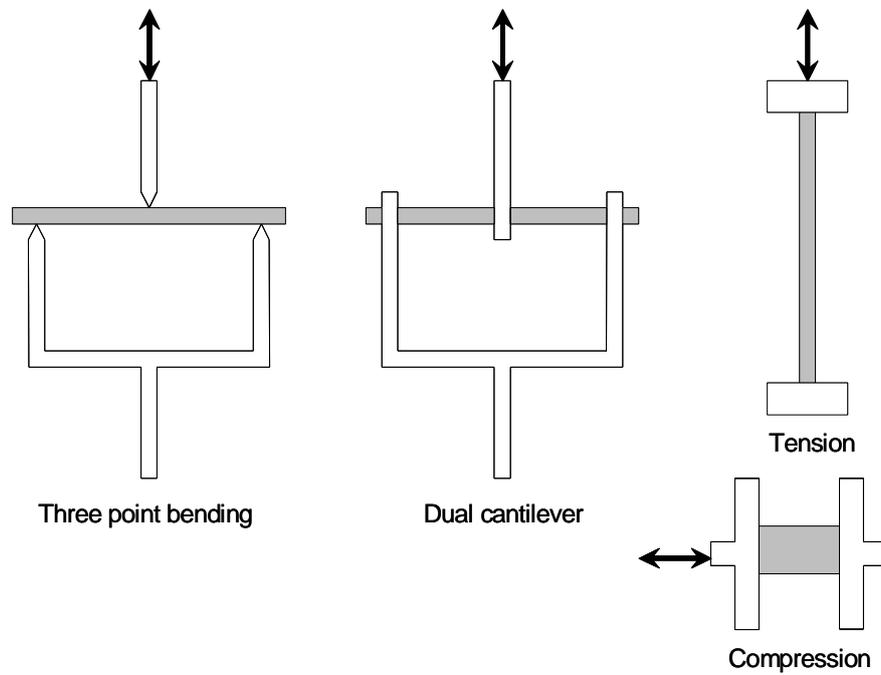


Figure 9: *Linear test geometries.*



Figure 10: *Rheometric RSA II Rheometer.*

Any of the test geometries shown in Figure 9 can be used in a rheometer as for example the in Figure 10 shown Rheometrics RSA-II that is widely used. The three point bending geometry is not often used because some slippage can occur during testing at the knife edges. Compression is ideal geometry for elastomers but its use is restricted by possible overload of the rheometer. The two most frequently used geometries are the dual cantilever and tension mode as both enable pretension of the sample without the danger of slippage of the sample in the bracket. The best choice of test geometry is the subject of an industry funded research

project between the Transport Engineering and Logistics group of Delft University of Technology and the Rubber Technology Group of Twente University, both located in the Netherlands.

5 The indentation rolling resistance

5.1 Introduction

The rolling resistance accounts for the major part of the resistances. Parameters that determine the rolling resistance of the belt are the belt speed, the diameter and material of the idler rolls, the belt parameters such as width, material, temperature, tension, lateral load, and the idler pitch and trough angle.

In general the rolling resistance consists of the indentation rolling resistance, the rotation inertia of the rolls of the idlers and the friction of the bearings of the idler rolls. In this paper only the indentation rolling resistance is considered since only that resistance is determined by the rubber compound of the belt's covers⁵.

Idler rolls are made of a relatively hard material like steel or aluminium whereas the belt covers are made of much softer material like rubber or PVC. Therefore the belt cover is indented by the roll due to the weight of the belt and the bulk material when the belt moves over a roll. Due to the visco-elastic properties of the cover material the recovery of the compressed part will take some time. This results in an asymmetric stress distribution between the belt and the roll which yields a resultant resistance force; the indentation rolling resistance force. The strength of this resistance force depends on the constitutive behaviour of the cover material, the radius of the idler roll, the vertical force due to the weight of the belt and the bulk solid material, and the radius of curvature of the belt.

5.2 Rolling contact of linear visco-elastic bodies

The constitutive behaviour of the rubber belt cover material can be modelled by a three parameter Maxwell model as described in section 3. The various sources of energy dissipation in rolling may be classified into those that arise through micro-slip and friction, those that are due to inelastic properties of the material and those due to roughness of the (rolling) surfaces. In this section the rolling friction due to the inelastic properties of the belt cover material is considered that forms the largest contribution.

During rolling the material lying in front of the contact zone between belt and roll is being compressed whilst that at the rear is being relaxed. A

⁵ The analysis set forth in this chapter is based on Chapter 5 of [3].

visco-elastic material relaxes more slowly than it is compressed so that the belt and the roll separate at a point ($x=-b$, $x'=-a'$) closer to the centre line ($x = 0$) than the point where they first make contact ($x=a$, $x'=a'$), see Figure 11. In the figures the belt and the roll are depicted upside down which is done for simplicity only. The asymmetric contact-phenomenon and the resulting asymmetric stress distribution result in a resistance force.

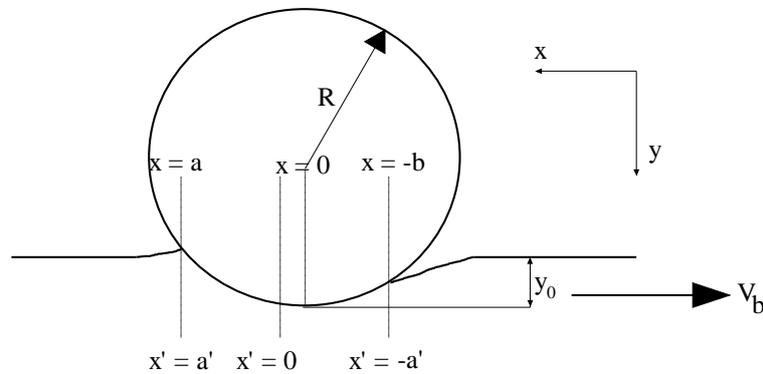


Figure 11: *Idler rolling over incompressible half space.*

If the pressure distribution at any point of the contact area has to be calculated analytically then the solution of an integral equation for the pressure is required. The solution that evolves from this approach is relatively complicated and cannot be used directly when calculating the rolling resistance of belt conveyors.

A more convenient approach to determine the pressure distribution at any point of the contact area is to assume that the belt covers can be modelled by a simple Winkler visco-elastic foundation model rather than by a visco-elastic layer, see Figure 12.

The visco-elastic foundation of depth h , rests on a rigid base and is compressed by the rigid roller. There is no interaction between the springs of the foundation which implies that shear between adjacent elements of the model is ignored. The inertia of the foundation material is also neglected. If the indentation depth is small compared to the thickness of the belt cover and it is assumed that the carcass material is undeformable then the visco-elastic Winkler model can be applied to approximate the deformation of the belt covers due to the indentation of the roll.

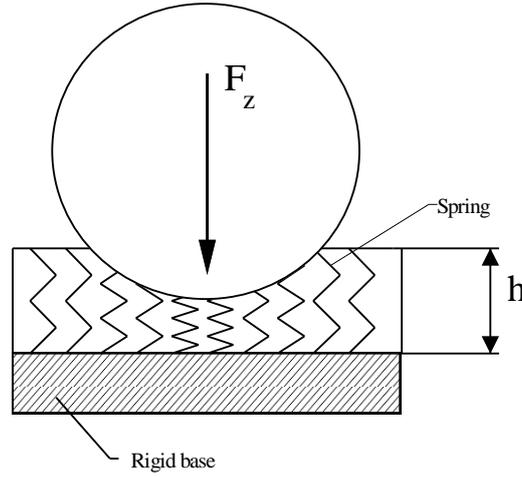


Figure 12: Winkler foundation model.

Using the simple Winkler visco-elastic foundation model and the three parameter solid Maxwell model yields the stress distribution between roll and belt cover:

$$\sigma(x) = a^2 \left\{ \frac{E_1}{2Rh} \left(\frac{a-x}{a} \right) \left(\frac{a+x}{a} \right) + \frac{E_2 k}{Rh} \left[(1+k) \left(1 - \exp\left(-\frac{1}{k} \frac{a-x}{a}\right) \right) - \left(\frac{a-x}{a} \right) \right] \right\} \quad (8)$$

where E_1 and E_2 are constants from the three parameter Maxwell model, R the radius of the idler rolls, h the effective belt cover thickness and $k = (V_b \tau) / a$.

The ratio b/a can be calculated with equation (8) since $\sigma(-b) = 0$. If the belt moves at a constant speed then the distributed vertical force can be calculated by integrating equation (9):

$$F_z = \int_{-b}^a \sigma(x) dx \quad (9)$$

Since F_z is constant for a stationary moving belt and the ratio b/a is known from equation (8), the length a can be calculated from equation (9).

In order to calculate the rolling friction, moments have to be taken about the centre of the roll:

$$M = \int_{-b}^a \sigma(x) x dx \quad (10)$$

The total distributed frictional force then follows from:

$$F_i = \frac{M}{R} = \frac{E_1 a^4}{8R^2 h} \left[1 - 2 \left(\frac{b}{a} \right)^2 + \left(\frac{b}{a} \right)^4 \right] + \frac{E_2 a^4 k}{R^2 h} \left[k^3 - \frac{k}{2} \left(1 + \left(\frac{b}{a} \right)^2 \right) + \frac{1}{3} \left(1 + \left(\frac{b}{a} \right)^3 \right) - k(1+k) \left(k + \frac{b}{a} \right) e^{-\frac{1}{k} \left(\frac{a+b}{a} \right)} \right] \quad (11)$$

Finally, the indentation rolling resistance factor, defined as used in DIN 22101, follows from:

$$f_{im} = \frac{F_i}{F_z} = \frac{F_z^{\frac{1}{3}} h^{\frac{1}{3}}}{D^{\frac{2}{3}}} F_{RM} \left(k, \frac{a}{b}, E_1, E_2 \right) \quad (12)$$

in which D is the diameter of the roll.

The effect of the interaction of the springs, and thus the accuracy of the Winkler approach, can be estimated by comparing the results obtained by Hunter [8] and May [9]. The indentation rolling resistance according to Hunter is :

$$f_{ih}^* = \frac{1}{R} \left(b - \frac{V_b \tau}{1 + f^*} - \Gamma_1 \left(\frac{a}{a_0} \right)^2 \right) \quad (13)$$

where a and a₀ can be calculated from the boundary conditions.

The indentation rolling resistance according to May is :

$$f_{im} = \frac{F_i^*}{F_z^*} \quad (14)$$

where the vertical (normal) force and the indentation resistance force are:

$$F_z^* = \frac{E_1 a_0^3}{6Rh} \left(2 - \left(\frac{b}{a_0} \right)^3 + 3 \left(\frac{b}{a_0} \right) \right) + \frac{2E_2 k a_0^3}{Rh} \left(1 - \left(\frac{b}{a_0} \right)^2 \right) \quad (15)$$

$$F_i^* = \frac{E_1 a_0^4}{8R^2 h} \left[1 - 2 \left(\frac{b}{a_0} \right)^2 + \left(\frac{b}{a_0} \right)^4 \right] + \frac{E_2 a_0^4 k}{R^2 h} \left[k^3 - \frac{k}{2} \left(1 + \left(\frac{b}{a_0} \right)^2 \right) + \frac{1}{3} \left(1 + \left(\frac{b}{a_0} \right)^3 \right) - k(1+k) \left(k + \frac{b}{a_0} \right) e^{-\frac{1}{k} \left(\frac{a_0+b}{a_0} \right)} \right] \quad (16)$$

The correction factor to take shear in the rubber into account then is:

$$f_s = \frac{f_{ih}^*}{f_{im}^*} \quad (17)$$

which indicates the accuracy of the Winkler model. The total indentation resistance factor then is equal to:

$$f_i = f_s f_{im} \quad (18)$$

6 Discussion

In Chapter 1 of this paper the importance of the indentation rolling resistance of rubber conveyor belts was highlighted and its effect on three projects was illustrated in Chapter 2. Chapter 3 then introduced the concept of visco-elasticity that could be determined by performing mechanic/dynamic tests described in Chapter 4. Chapter 5 presented a model to predict the indentation rolling resistance using measured mechanic/dynamic properties of the belt. Today, this model has been adopted by a number of institutes and companies around the world.

The key question now is: how accurate is the prediction of the indentation rolling resistance of conveyor belting using the theory given in Chapter 5 (or another theory) and the test procedures given in Chapter 4? The only way to accurately measure the power consumption of a belt conveyor is to measure torque in the shaft of the drive pulley. This procedure is described by Lodewijks and Kruse in [10]. The most important conclusion in that paper is that the deviation between theory and practice is around 5% (which is excellent), or 15% (theoretical overestimation) in case of design calculations. In addition it was found that the error made during the field tests is at least 5%. Statements that the deviation between theory and practice can be less than 5% are not based on scientific evidence.

Since 2000 an extensive research project has been initiated by the author to extend the use of the theory given in Chapter 5 to application in pouch conveyors and pipe conveyors [11]. From comparison between the results of field measurements and theoretical predictions it could be concluded that the deviation between theory and practice is between 5% for conventional belt conveyors and 15% for pipe conveyors if the effect of the repeatability of mechanic/dynamic tests is known [12].

The repeatability, and equal important the exchangeability, of the results of mechanic/dynamic tests of rubber compound is still under research. One major problem today is that there is still no standardised way to measure the mechanic/dynamic properties of a rubber compound for application in conveyor belting. The procedures themselves, as described in Chapter 4, are standardised. The specific equipment and the applicability of one test method versus another however are not, and as stated before subject for

further study in the Netherlands. Even if at two independent laboratories the exact same rubber is tested with two identical rheometers, then the results of the mechanic/dynamic tests can still differ. As an example, Figure 13 shows the results of tests done at the laboratory of Transport Engineering and Logistics of Delft University of Technology and at another extern laboratory. As can be seen in that figure the deviation between the test results can be a factor two for low temperatures!

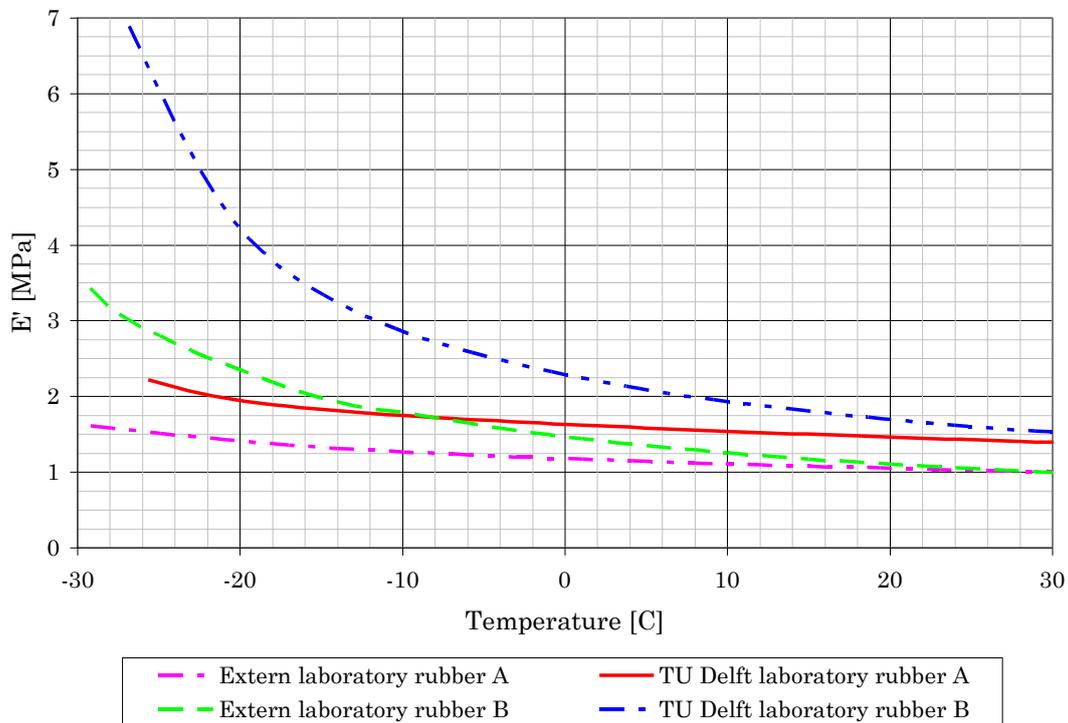


Figure 13: Comparison of the results of mechanic/dynamic tests (scaled to 1 MPa).

This means that using the results of mechanic/dynamic tests of a certain machine as input parameters of a specific model for the indentation rolling resistance may yield substantial errors. As a result, models for the determination of the indentation rolling resistance, and therefore design methods, need to be tuned for a specific rheometer. It is therefore not yet possible to exchange calculation results obtained with one design method and the other using the same set of mechanic/dynamic parameters.

7 Conclusions

The analysis set forth in this paper can be summarised as follows.

It is a fact that:

- there are theoretical models to describe the visco-elastic behaviour of rubbers and that predict the power consumption of belt conveyors.
- there are scientifically accepted methods to measure the mechanic/dynamic properties of rubber.
- the performance of two rubber compounds can be compared to each other. This comparison can only be done when it is based on tests performed on one specific rheometer. The results of the mechanic/dynamic test then can be used as input parameters for the model presented in Chapter 5, which enables comparison in terms of indentation rolling resistance force and/or factor.
- the power requirements of a belt conveyor can be estimated using computational design tools (see Chapter 5) provided that they are tuned for the results of the mechanic/dynamic rubber compound tests performed on a specific test facility.

It is fiction that:

- the application of mechanic/dynamic properties of rubber measured at a specific rheometer can be used in any design model yielding the same accurate prediction of the power consumption of the system.
- the deviation between the power consumption of belt conveyors predicted by theoretical models and measured in practice can be less than 5%.
- the indentation rolling resistance is always the driving design parameter for long overland systems. In some conveyor systems, like down hill systems, a high loss compound may be beneficial. In other systems, like major incline conveyors, the use of low loss rubber is irrelevant.
- the measurement of power consumption of a new belt conveyor should be done as soon as possible after installation to enable comparison between theory and practice. The rubber properties change rapidly during the first half year after installation and therefore power measurements before half a year of running do not give a representative image of the power consumption of the system. This effect should also be taken into account when measuring the mechanic/dynamic properties of the rubber compound.

8 References

- [1] Lodewijks, G. (1997), *The Power Consumption of Belt Conveyors*, BULK 5 (2), pp. 66-74.
- [2] Lodewijks, G. (1995), *The rolling resistance of conveyor belts*, Bulk Solids Handling 15, pp. 15-22.
- [3] Lodewijks, G. (1996), *Dynamics of Belt Systems*, Ph.D. Thesis TU Delft, ISBN 90-370-0145-9.
- [4] Eirich, R.F. (1978), *Science and Technology of Rubber*, Academic Press, London.
- [5] Mey, S. de and Amerongen, G.J. van (1969), "Dynamic-Mechanical Characteristics of Rubber Compounds", *Rubber Chemistry and Technology* 21, pp. 1215-1232.
- [6] Struik, L.C.E. and Berg, J.W.A. van den (1989), *Kunststoffen*, Lecture book Twente University, Enschede.
- [7] Rheometric Scientific (1997), *Understanding Rheological Testing*, brochure.
- [8] Hunter, S.C. (1961), "The Rolling Contact of a Rigid Cylinder with a Viscoelastic Half Space", *Journal of Applied Mechanics* 28, pp. 611-617.
- [9] May, W.D., Morris, E.L. and Atack, D. (1959), "Rolling Friction of a Hard Cilinder over a Viscoelastic Material", *Journal of Applied Physics* 30, pp.1713-1724.
- [10] Lodewijks, G., Kruse, D.J. (1998), *The power of field measurements – part I*, Bulk Solids Handling 18, pp. 415-427.
- [11] Lodewijks, G. (2000), *Modern Closed Belt Conveyor Systems*, Conference on transportation of bulk solids materials, Dusseldorf, October 2000.
- [12] Lodewijks, G. (2002), *Comparison of theory and practice in power predictions of belt conveyors*, Report Delft University of Technology, reportnr. 2002.TT.5212.