

Pavement Type Hysteresis and Truck Rolling Resistance

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Abstract

Portland Cement Concrete (PCC) pavements usually incur higher investment costs than Asphalt Concrete (AC) alternatives. In a life cycle analysis the higher cost is justified by lower maintenance costs, less and fewer traffic flow intrusions, and a longer technical life. All these factors contribute to a reduction of the carbon footprint. To further improve the sustainability of PCC pavements the rolling resistance should be lower on stiff and elastic materials like e.g. steel. To prove this thesis, studies of fuel consumption have been made where a truck is driven over different pavement structures. However, it is difficult to precisely access how much can be attributed to the pavement structure. Many factors affect the rolling resistance, such as roughness, texture, air flow et cetera. The present paper presents a different approach analyzing data from a falling weight deflectionometer, (FWD). Pavement hysteresis is assessed by evaluating time histories. Thus, energy losses due to the properties of the pavement structure can be estimated. It was found that the visco-elastic properties of the asphalt had a great influence of the curve in warm and hot weather. Water present and the subgrade material also affected the curve due to the material damping properties. At one field site, a motorway consisted of asphalt concrete and PCC pavement on very similar unbound materials. The difference in energy losses between the two was found significant and it is suggested that it is accounted for when comparing the two materials for life cost analysis purposes.

Introduction

Transport operating costs are important for the optimization of transportation. The well-known Highway Design Manual (HDM) series of programs issued by the World Bank illustrates this fact by having a very detailed input concerning the vehicle fleet. Road roughness affects among other things, the vehicle speed, rider comfort, vehicle wear and accidents. All these can be attributed to costs. Most road authorities now run Pavement Management Systems (PMS), which are relying heavily on user costs.

In addition to actual costs for e.g. fuel, in recent years the carbon footprint is associated as an extra cost previously ignored. Needless to say the vehicle operating costs are more important than ever, so a higher investment cost could very well be justified by lower emissions. It has been claimed that the truck rolling resistance is indeed lower on concrete pavements and thus carbon dioxide emissions would be reduced too. However, it is based on assumptions that about a third of the measured fuel losses due to coasting are lost in the pavement. In reality, this amount is highly variable depending on the materials, the temperature and other factors.

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Fuel consumption is depending on acceleration, wind resistance, and rolling resistance. The wind resistance is a function of the vehicle and wind speed. The rolling resistance is depending on the tire friction, internal friction for engine and drive train, plus a component of deforming the surface. The energy is lost as heat as can be seen shortly after a rain shower when pavements dry up quickly in the wheel tracks. Much of the losses attributed to rolling resistance are from the tires interacting with the pavement. Thus, lots of research work has been sponsored by the tire industry. Obviously, at times friction is needed to control the vehicle, but coarse macro-texture or tire treads usually demands more fuel. The pavement surface condition affects the fuel consumption also. At a full-scale pavement test facility in Nevada automated trucks on WesTrack demanded 4% less fuel after the track was resurfaced, (Mitchell 2000). The influence of the pavement profile including joints on rolling resistance is rather easy to determine with a truck suspension model, but the losses within the pavement layers and soil are much more difficult to assess. By using a stationary, but dynamic load it is interesting to test the energy attenuation losses in the pavement layers and the soil. On a comparative basis one could see if any pavement type has an advantage over the other. In the present paper asphalt and Portland cement concrete pavements are compared using the rolling resistance parameters derived from the field data. Further testing was also carried out on some older PCC pavements. They showed that the subgrade also influences the rolling resistance.

Research Significance

The present paper demonstrates a way to assess pavement contribution to truck rolling resistance from a technical point of view. It is important for calculating the total carbon footprint, which in turn is important for calculating the sustainability of various pavement types.

Dynamic Testing of Pavements

A theoretical study backed up by laboratory testing on the visco-elastic properties of asphalt concrete was conducted by LCPC in France, (Chupin et al., 2010). The study concluded that the visco-elastic effect was not significant for an increase of fuel consumption; except for hot conditions. However, the results were not verified in the field. In reality there are a number of factors contributing to hysteresis, not only visco-elasticity.

In the mid 1990:ies a large correlation study was carried out in Sweden regarding a high-speed Road Deflection Tester, RDT, (Andrén 1999). Over 100 pavement sections were tested and compared with Falling Weight Deflectometer (FWD) data. Time histories were sampled so that the effects of truck speed could be assessed. At a dual carriageway test site one direction of the freeway was constructed as an asphalt concrete pavement and the other direction constructed at a later stage was a PCC pavement. At the time it was considered interesting to compare the two pavement types as the subgrade, traffic and environment were practically the same. Both sections turned out to have excellent bearing capacity, but the PCC was as expected, much stiffer and did not exhibit temperature related behavior. In the following analysis load-deflection graphs showed less area inside the curve for the PCC plots. The size of the area reflects the energy losses, which however at the time of the study, was of no or little concern.

Several years later as the alleged energy efficient behavior of concrete was claimed by the cement industry; the present author came to think of this test. The common method seemed to involve fuel consumption measurements on different pavements. These are difficult to carry out as there are many other factors including temperature and wind direction to cope with. The FWD however is stationary and does not depend on the wind. The old data seemed ideal for investigating the pavement contribution to the rolling resistance. A quick check of the historic data showed that there really were too few tests and that the sampling rate was barely adequate for this purpose. It was then decided to do a larger study with more modern equipment.

Field test. A suitable field site was found on European Highway 4 (E4) about 40 km north of Uppsala, Sweden. The road, a four lane freeway had been in use for about two years on the PCC and one year on the AC pavement part. At the Björklinge interchange, the road pavement type changes from PCC to AC, with only a slight drop in average daily traffic at the interchange. Winters are cold and summers are moderate here; most precipitation occurs in July. Incidentally, the road crosses latitude 60°N right at the test area. The subgrade consisted mostly of glacial till at the test sections, even though the landscape is shifting from old seabed, flat farmland to undulating forest in the area; see Figure 1, courtesy of Google Earth.

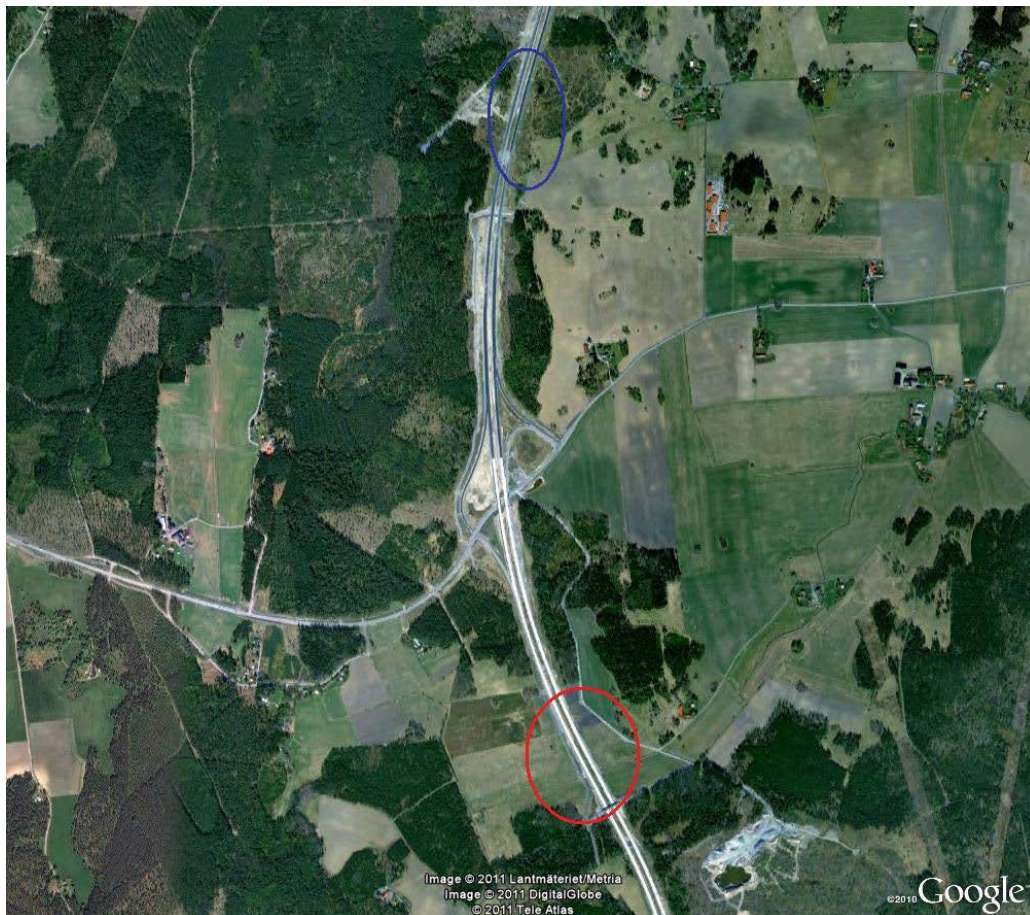


Figure 1. Test near Björklinge Sweden site as seen from above, Google Earth.

The testing occurred at the evening on 2 September, 2008. This time of day was planned so there would be little bending in the concrete slabs due to temperature gradients. The weather cooperated as most of the day had been overcast with some light rain occurring now and then. The air temperature kept constant at 16°C and the AC pavement temperature was recorded 18°C at two different depths. Thus, no gradients were expected in the pavement. From an evaluation standpoint this was most fortunate as the layers could be treated as homogeneous. Another bonus was the fact that the temperature was close to the annual average for the AC pavement in this area. Further, the site also coincided with a fuel consumption measurement test carried out by the Swedish Transport Research Institute a few months earlier, (Hultqvist 2010). In comparison with the vehicle fuel consumption test; note that the present paper deals with dissipation of energy in the pavement. Thus, it is related to truck fuel consumption only. Passenger car differences in fuel consumption are mostly depending on the surface characteristics of the road, which do not affect the FWD testing at all.

Due to traffic management control, all testing was done in the right wheel track in the northbound, right lane. A seating load of 50 kN was used, and then three load levels of 36, 51 and 65 kN that were repeated twice for a total of 10 drops per station. Twenty-eight stations were sampled each on the PCC and AC sections respectively. Figures 2 and 3 show the two respective sites and Table 1 and 2 show the layer thicknesses and back-calculated moduli for the two pavement types.

Table 1. Pavement layer thicknesses and Moduli for the PCC pavement

Layer	Thickness [mm]	Modulus [Mpa]
PCC (Fixed)	200	50000
Asphalt Base	100	10000
Unbound layers	780	180
Subgrade	Semi-infinite	370



Figure 2. The FWD at the PCC test site on highway E4.

Table 2. Pavement layer thicknesses and Moduli for the AC pavement

Layer	Thickness [mm]	Modulus [Mpa]
Asphalt layers	170	12200
Unbound layers	1080	240
Subgrade	Semi-infinite	375

Results of stiffness. The various layers were back-calculated for stiffness. The PCC stiffness was assumed to be a constant 50 GPa as it otherwise would be difficult to assess the properties of the rather thin asphalt bound base beneath it. A four-layer system was used for the PCC model; for the AC only three layers were needed. The subgrade and unbound base layer properties were found to be similar for the two cases. Note that the unbound layers are somewhat stiffer for the AC case, reflecting the higher stress situation in these materials. Details about the properties can be found in a report by (Lenngren 2009).



Figure 3. The AC test site on highway E4.

Time histories. As a standard procedure the load pulse is not altered for a single test, only the magnitude of the load is. Thus, the bulk or deviator stress influence on the modulus can be established.

By plotting the load and the deformation a curve resembling a hysteresis diagram is formed. For a perfect linear elastic response only a straight line will be projected. For most pavements there will be some internal damping by the materials and for asphalt there is also a visco-elastic response. A typical reaction from a 50 kN load on an intermediate road on cohesive soils is shown in Figure 4. If water is present in unbound materials it could also affect the shape of the curves if the liquid is pushed aside by the load. This could be detected as the outer sensors will experience some heaving in the process. It can be observed during the construction of subbase layers, but very rarely on modern high volume roads.

Seven sensors at different offsets 0 – 120 cm are plotted. Most of the area within the curve can be attributed to the damping of the soils. In the figure seven curves are shown with different offsets from the center of the load. D0 is the deformation in the center of load and comprises deflection in all materials under the load. D120 on the other hand is at an offset 120 cm away from the center and it represents the deformation deeper down in the structure. By carefully evaluating the different curves it is possible to derive layer moduli and layer attenuation as well.

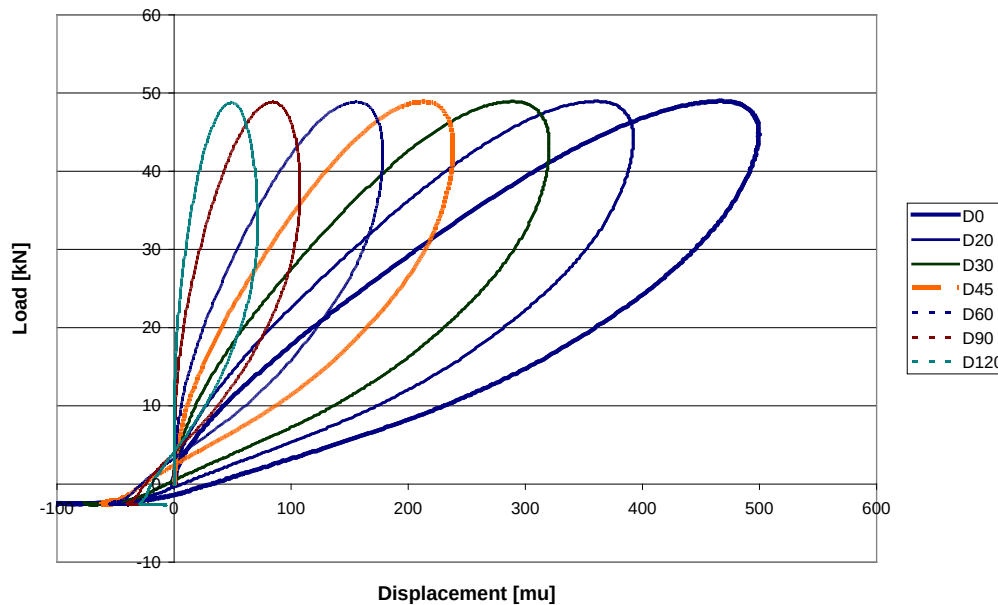


Figure 4. Load-Deflection diagram from an intermediate AC road. curves represent different offsets from the center of the load.

Energy loss estimation, a first attempt. The exact loss of energy to the pavement system is difficult to assess directly by these measurements. There is a combination of different processes that affect the deformation over time. Further, there are some concerns about the measurement. There is a rubber plate between the load cell and the pavement that may affect the results. The machine is calibrated with this in mind, but nevertheless it is an uncertainty. Further, the data acquisition deteriorates with time, so the tail end of the curve has to be managed somehow. During the test procedure, there is also a slight shift of the load to the support legs that may also influence the results. In the present paper some decisions had to be made about treating the data. They may not be the best way to reflect absolute numbers and they are not validated through experimental setups. However, they represent a first trial.

A time history evaluation program was written to manage the data, try various different ways of handling the tail data, present the material, and export to spreadsheet programs. As the data were sampled at a 100 ns rate the difference in deformation for each step was small, the area under the curve was estimated by adding the product of load and delta-deformation over a given time span. As the rise time of the machine used is approximately 25 ms, about 50 ms is a good value to start with for a time window. On a road surface there is always some noise going on mostly due to passing traffic. Therefore it is difficult to define the start of a load by just reading the load cell value as it is fluctuating. Instead the curve is defined in time by the instant where the load reaches 5% of the peak load. Then it is up to the analyst to sample from that point or some other preset value. The peak load is depending somewhat to the stiffness of the specimen, so it will in turn affect the start point. However, at this end of the curve it is not that important as any accumulated area is small. It was noticed at the present site that the sampling offset varied a few milliseconds for the reason just mentioned. Handling the tail end is more difficult. First of all, there is a drift in the sensor output. The time it takes for the displacement sensor to reach zero

varies depending on the specimen. There is a small shift of the dead weight from the support legs to the loading plate et cetera. For the present case it seemed like the time for the load or any displacement sensor to reach zero varied too much. The sampling window was then kept constant to 60 ms from the start time, approximately 10 ms before the 5% maximum load was reached. A Simpson's rule integration was also tried on these curves in addition to the step approximation. Generally, it yielded a 2% smaller surface as the slope on average for the deflections are in that range, so this was to be expected. However, for some of the lower loads, it seemed as the simple step accumulation was less affected by the tail end effects. In the following the step approximation is used.

Results

Figure 4 shows time histories from an intermediate two-lane road AC pavement road. It yielded a hysteresis loss of approximately 8.4 Nm for the standard axle wheel load. This will be approximately 17 J per 10 ton axle, for the 60 ms duration. This corresponds to 280 Watt at continuous operations. If 100 kW is needed for coasting a 40 ton vehicle, a little bit more than one percent or 1 kW can be attributed to the rolling resistance on this type of road, (Taylor et al. 2001 and 2006). Four times 280 Watt is just about 1 kW. Bear in mind though, there are some uncertainties about these values. They need to be calibrated, but it seems that they are fairly close to the experimental data.

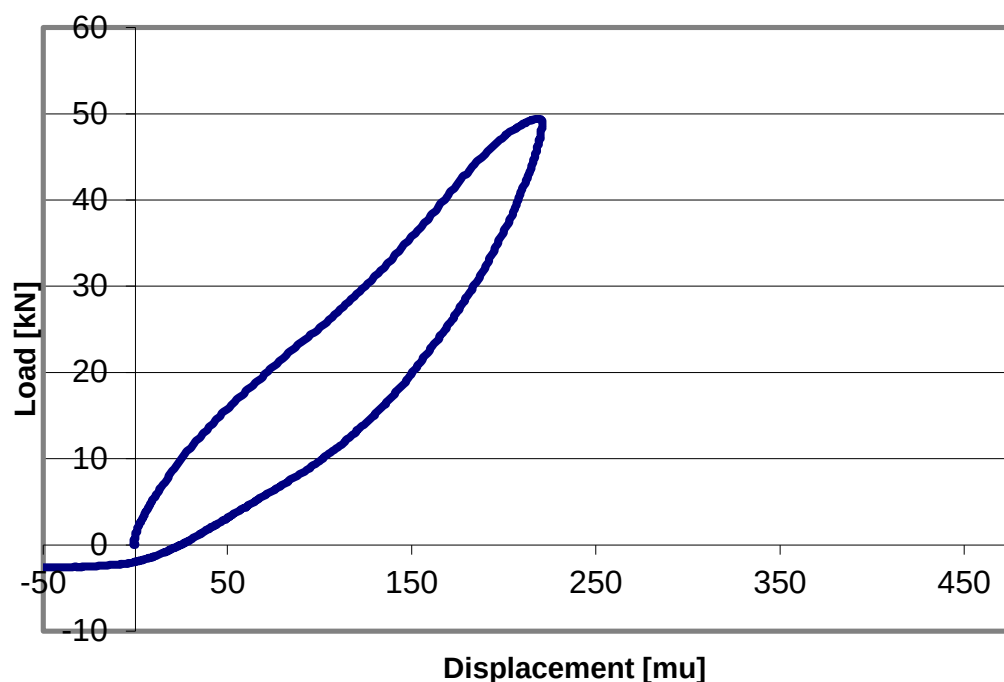


Figure 5. Load displacement diagram. Asphalt Concrete on stiff unbound materials

Figure 5 shows a load-displacement diagram on a typical asphalt concrete motorway. The asphalt layers combined are 185 mm and the granular layers are well compacted and stiff. So this is the expected attenuation from the asphalt layer or about 4Nm.

Figure 6 shows the E4 PCC response for one of the 50 kN drops being near the average work area of .5 Nm. It is drawn to the same scale as Figure 5 and ob-

viously the stiffness is indeed high as the maximum displacement is a mere fifth of a millimeter. The response is not entirely elastic; the slab is after all resting on a 10 cm thick asphalt layer. Nevertheless, little hysteresis work is excited and thus the pavement response contribution to rolling resistance ought to be just about as low as it can be.

Figure 7 shows a near average 50 kN drop for the asphalt pavement. It too displays a relatively small work area, even though it is four times greater than for the PCC example. The difference is significant. The relative difference on the total rolling resistance is of course smaller as this represents only the pavement contribution. It is obvious that the asphalt road is much better than the intermediate example seen in Figure 4 with a value of about 1 Nm. The concrete road hysteresis is still even better at .5 Nm. It shows that there is indeed a lot of potential to save fuel by choosing a higher quality pavement. Note that the deformation scale in figures 5 - 7 is deliberately set to correspond to the deflection on an intermediate road. Thus, the very good bearing capacity on these roads is demonstrated.

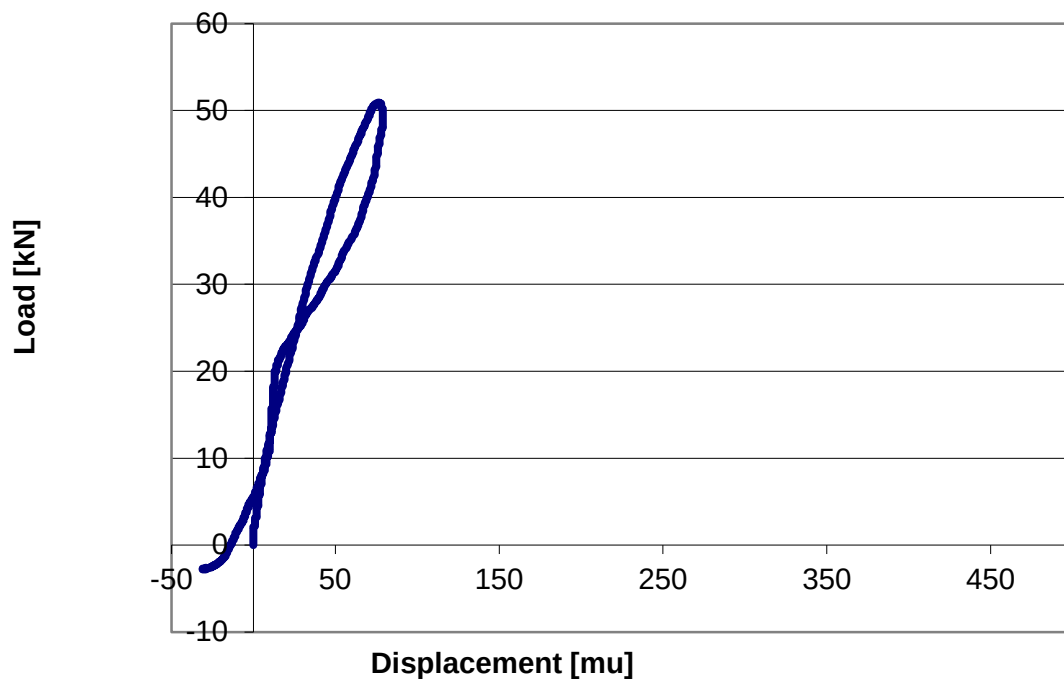


Figure 6. PCC Load displacement diagram. Do area is .423 Nm.

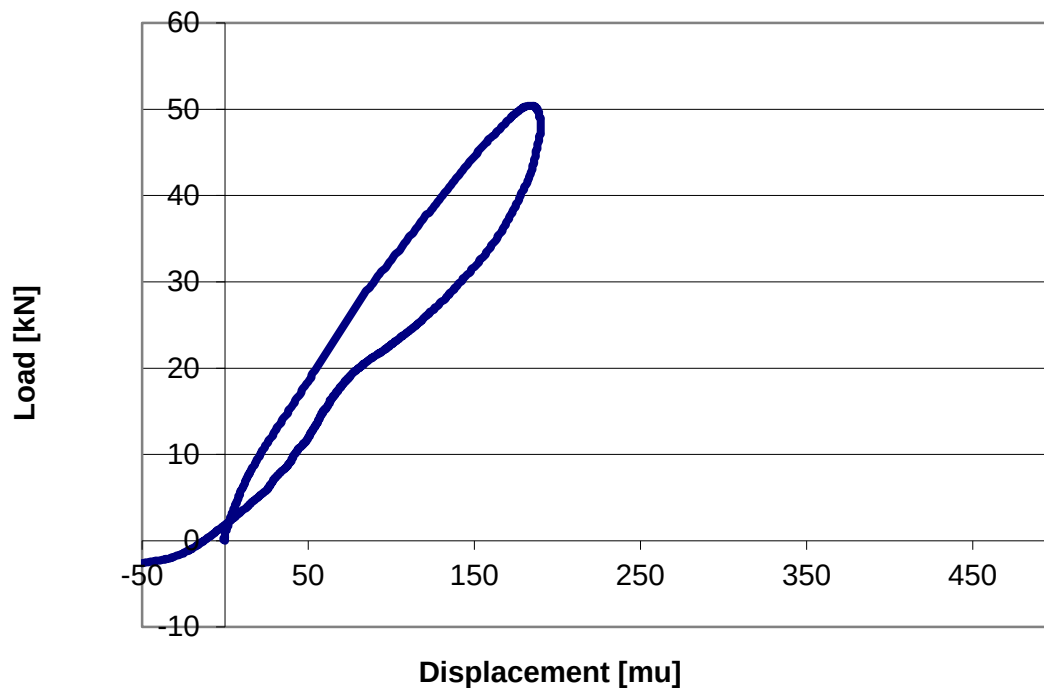


Figure 7 AC pavement Load-Displacement diagram. Do area is 2.2 Nm.

Other Testing

The results from the Björklinge test site were indeed homogenous and straightforward in the sense that they did not vary within the tested respective areas of materials. Thus, it was decided to do some additional testing at some other locations as well. One site was found on E20 between towns Eskilstuna and Strängnäs. At this site there was a plain jointed slab pavement resting on a cement treated base layer, hence there was no bituminous material present. Further to the east there was a comparable section of an asphalt pavement, exposed to the same amount of traffic, but a few years older than the PCC. A third section was found on E6 in the southwest and on the west coast of Sweden. There was no comparable asphalt pavement on this part however, and the investigation is yet not finished by the deadline of the present paper.

E20 at Kjula. The slabs rest on a cement treated base at this location, so there is no asphalt base involved in this case. The measurements took place on 28 October 2010. The sky was overcast and the temperature moderate, so the gradient in the slab was assumed to be moderate. The measurements were made at the center of the slabs of the jointed pavement. With no asphalt bound base even a more elastic response than the Björklinge site was anticipated. The average mid-slab value for the PCC came out to be slightly lower than the E4 site at .360 Nm. The nearby asphalt concrete was also better than the Björklinge site with an average of 1.20 Nm, but it was also colder about 10 degrees Celsius, which is 5 degrees colder than the annual mean.

However, as some curling was anticipated, some tests were done near the joint at the edge of the slab. These tests rendered values in the 2.0 to 2.5 Nm range and should be accounted for in the carbon footprint analysis. The two center deflection curves from their respective locations on the slab are plotted to the load in Figure 8. Not only is the deflection about twice as big, but the area inside the loop is six to eight times larger. Surely, the excess hysteresis is depending on

the height and length of the curling. An average for the slab was calculated for the mid-morning time of the analysis and was found to be about .50 Nm.

So are concrete pavements always a better alternative concerning rolling resistance? It seems that they are on an average basis, but there are situations when the difference is small. AC pavements are indeed stiff during much of the winter months, so the difference will be negligible during the cold months.

Like the example above shows the upward curling seems to be a detrimental factor; like soft soils involved too. If the E4 site is considered as a good subgrade example, the relative difference between AC and PCC is a factor 5. But if a poor subgrade contributes with another 3 Nm the relative factor becomes 1.5 only. The gain for selecting the PCC should still be 1.8 Nm in both cases. Clearly, more tests are needed, some have been done, and more results are underway to build a complete picture; incorporating diurnal and seasonal variation.

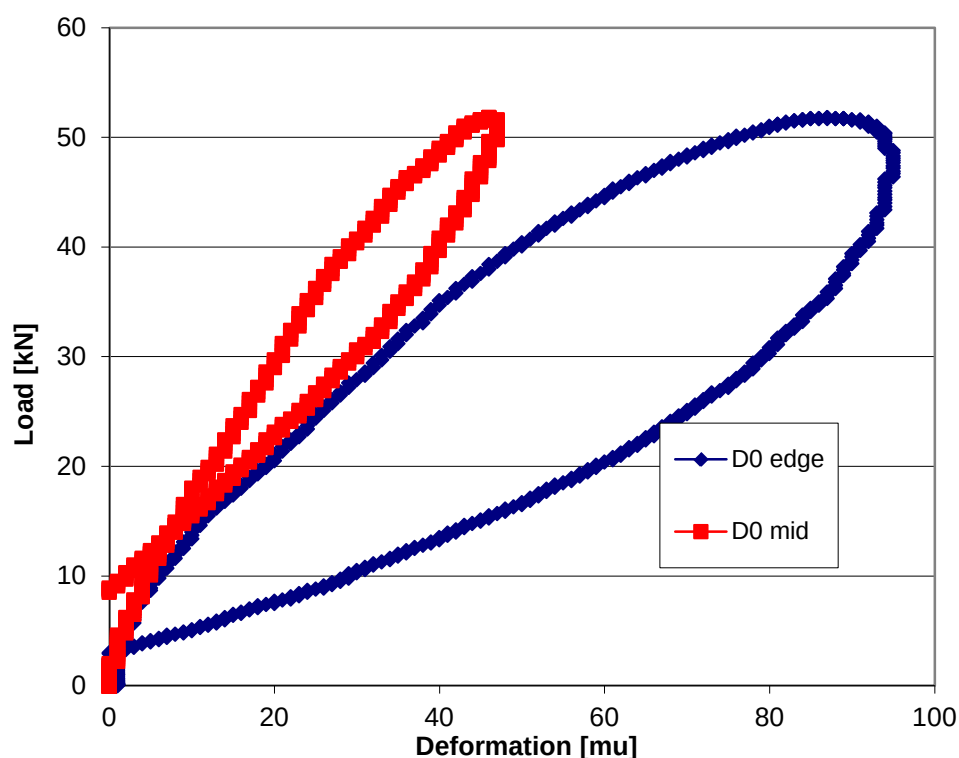


Figure 8. Load-Deformation diagram mid-slab (red) and near edge (blue) respectively.

Conclusions

Truck rolling resistance comprises a number of different components from internal friction to pavement-tire interaction. Field studies have shown a measurable difference between pavement types, but with inconclusive results. Test must be done bi-directionally, but the wind speed may not be constant. Further the temperature affects the results in many ways. Fuel consumption is affected, but the visco-elasticity of asphalt pavements does so in an opposite manner.

An estimate from drive tests indicates that at least a third of the rolling resistance can be attributed to the pavement, maybe more so on smaller roads. For AC pavements higher values can be expected at hot weather and lower ones at cold temperatures. Truck fuel consumption is also depending on the temperature, but usually more fuel is needed at lower temperatures for other purposes.

So this is why it is difficult to discern differences through drive tests. Further, surface friction, joints and roughness all affect the drive test results as well. A thorough analysis of FWD time history data can contribute to the understanding of pavement hysteresis and how much it contributes to rolling resistance.

In the present test the PCC pavement exhibited about four to five times lower work loss as AC pavements at the mean annual average temperature. Other tests show that thick asphalt pavements have high hysteresis at hot temperatures. By theory they should also be less visco-elastic and more elastic at lower temperatures. More field testing could confirm this assumption.

On jointed PCC pavements, upward curling increases the rolling resistance. It remains to be seen if the effect diminishes when the temperature gradient changes sign.

For thin pavements quite large rolling resistance is due to the soil and unbound materials. Poorly compacted materials mean large losses. Other, highly compacted friction material exhibited an almost linear elastic response and thus very losses were kept low. Thus, extra efforts like extended compaction during the construction of roads could be worthwhile if these measures are included in life cycle cost analyses.

The pavement does contribute significantly to truck rolling resistance and this should be factored in when choosing pavement type. The FWD can be used for environmentally proofing selected highways. The FWD seems to be viable for this purpose. However, there are a few uncertainties of how to treat the tail end of the time history curve. Some studies need to be done to improve calibration and the test methods as such.

The contribution to rolling resistance from the subgrade can be significant, and soil lime and cement stabilization could be much more cost effective than previously thought.

References

- Andrén, P. (1999) *High-speed rolling deflectometer data evaluation*, Nondestructive Evaluation of Ageing Aircraft, Airports, and Aerospace Hardware III. Proceedings of SPIE. Ajit K. Mal Editor Volume 3586, pp 137-147.
- Chupin, O., Piau, J-M, Chabot, A. (2010) *Effect of Bituminous Pavement Structures on the Rolling Resistance*. Proceedings The 11th International Conference on Asphalt Pavements. Nagoya, Aichi, Japan August 1 to 6, 2010
- HDM-4
http://www.worldbank.org/html/fpd/transport/roads/rd_tools/hdm4.htm
- Hultqvist, B-Å (2010) *Measurement of Fuel Consumption on an Asphalt Pavement and a Concrete Pavement in Sweden*. 11th Symposium on Concrete Roads Seville, Spain October 2010.
- Lenngren C.A. (1994) *Non-Destructive Testing Utilizing Controlled Variable Rise Time*, Proceedings Fourth International Conference on Bearing Capacity of Roads and Airfields, Vol. 1, pp 467-490.
- Lenngren, C.A. and Hansson J. (2004) Comparing FWD Initial Tests with HVS

Induced Initial and Long-Term Rutting. Proceedings 2nd international Conference on Accelerated Pavement Testing, Minneapolis, MN USA. On CD-ROM

Lenngren C.A. (2009) *Pavement Contribution to Truck Rolling Resistance*, Proceedings of the Eighth International Conference on Bearing Capacity of Roads and Airfields. Champaign, Illinois, USA. Edited by Errol Tutemlauer and Imad L. Al-Qadi. ISBN 978-0-415-87199-0

Magnuson, A.H., Lytton, R.L., Briggs, R.C.(1991) *Comparison of computer predictions and field data for dynamic analysis of falling weight deflectometer data* Transportation Research Record 1293, Backcalculation of Pavement. Washington D.C.

Mitchell Terry (2000) *WesTrack Track Roughness, Fuel Consumption, and Maintenance Costs* TechBrief, USDOT, Federal Highway Administration, January 2000.

Taylor, G. Marsh, P. and Oxelgren, E. (2001) *Effect of Pavement Type on Fuel Consumption* NRC Centre for Surface Transportation Technology. IRF World Congress, June 2001

Taylor, G. Patten, J.D. (2006) *Effect of Pavement Type on Fuel Consumption – Phase III*. NRC Centre for Surface Transportation Technology. Technical Report CSTT-HVC-TR-068