Load Deflection Evaluation on Concrete Pavements

C.A. Lenngren
Department of Traffic and Roads, Lund University, Lund, Sweden

ABSTRACT: The sampling of time histories from falling weight deflectometer testing allows for plotting load-deflection curves. These curves reflect non-elastic properties. As linear-elastic models often are used for the backcalculation of pavement layer moduli, the curves provide information on the quality of the evaluation. Previous studies have shown that the influence of asphalt concrete visco-elasticity has a large influence of the shape of the curve, as the area enveloped is greater at e.g. higher temperatures. Also there is a difference between asphalt and Portland cement concrete when the unbound materials and subgrade conditions are similar. However, other predicaments influence the shape of the curve too. Either water or air moving in open materials will affect the deflection during the test. This effect is often seen while testing on unbound materials during construction. Further, inertia is playing a part in the dynamic behavior. While evaluating the dynamics it is not given which underlying effect is dominating the shape. However, it is a good guess that less area enveloped would mean less attenuation of energy added to the system. This is viable information as there is a need to design and construct pavements that keeps the rolling resistance to a minimum. Comparing asphalt with concrete pavements will reveal the visco-elastic effects, but within cement concrete pavements there is also some variability observed. The present paper presents some of the findings with a discussion on how to assess the various parameters. E.g. the effect of curling shows up as a larger area being enveloped. By continued research these findings lead a way to finding a model capable of describing the load-deflection envelope entirely, so that sustainable pavements could be refined for high volume roads and air fields as well.

KEY WORDS: PCC Pavements, Falling Weight Deflectometer, Rolling Resistance

1 INTRODUCTION

Transport operating costs are important and they depend on vehicle and road related concerns as well. 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.

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. As much of the losses attributed to rolling resistance are from the tires interacting with the pavement, lots of research work has been performed 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 possible 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 Portland cement concrete pavements are compared using the rolling resistance parameters derived from the field data. Testing also included some older PCC pavements, including near edge loads to see the consequences of upward curling. In addition, in spite of stiff and rigid pavements, the subgrade also influences the rolling resistance to a large degree.

1.1 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.

1.2 Previous Field Test

In 1995 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 within the pavement, which at the time of the study, was of no or little concern.

Several years later as the assumed energy efficient properties of concrete were claimed by the cement industry; the present author was reminded of this test. Common methods to assess rolling resistance involve fuel consumption measurements on different types of 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 the test 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 on a suitable field site on European Highway 4 (E4) about 40 km north of Uppsala, Sweden. 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. At the time, the road, a four lane rural freeway had been in use for about two years on the PCC and one year on the AC pavement part. Winters are cold and summers are moderately warm here; most precipitation occurs in July. Incidentally, the road crosses latitude 60°N right at the test area. The subgrade consists 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. Figure1 shows the E4 PCC response for one of the 50 kN drops being near the average work area of .5 Nm. Figure 2 shows a near average 50 kN drop for the reference asphalt pavement. Note that these load-deflection graphs do not represent hysteresis directly. Even if the work has been calibrated to fuel consumption tests, there is some uncertainty about the exact numbers.

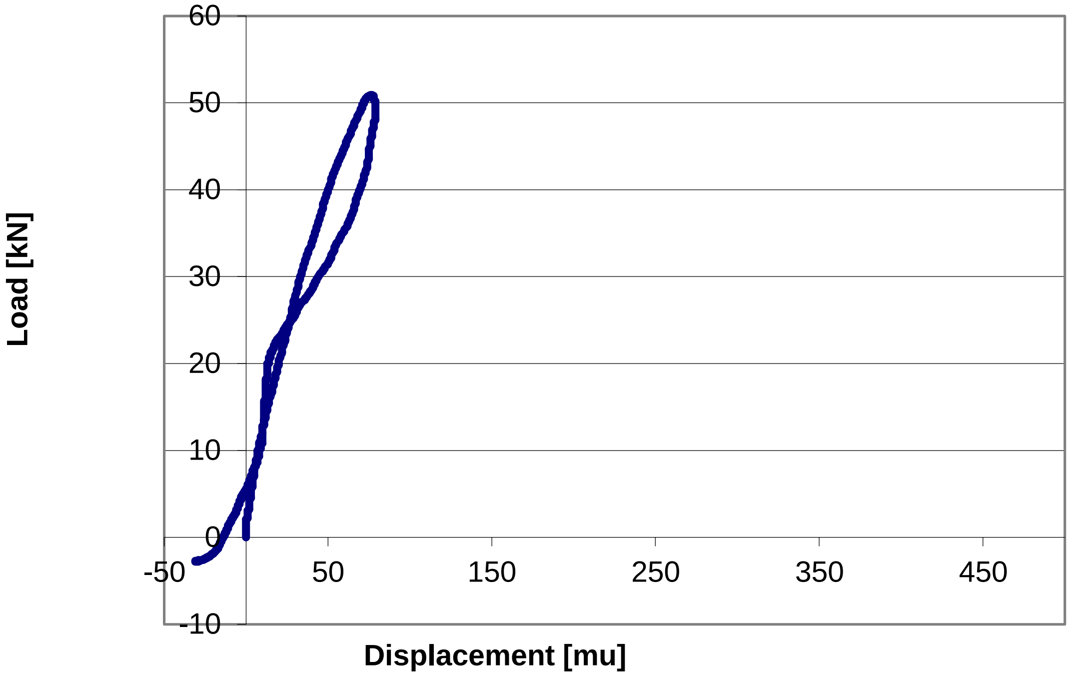

Figure 1: PCC Load displacement diagram for the center load sensor (D0). The enveloped area corresponds to a work of .423 Nm.

Figure 2 displays a relatively small area for the reference AC pavement corresponding to a work of 2.2 Nm. A common value for this type of pavement is around 5 Nm. Nevertheless, the work is four times greater than for the PCC nearby. The difference is significant. However, the relative difference on the total rolling resistance is certainly smaller as this represents only the pavement contribution. So the concrete road hysteresis is considerably better at .5 Nm. It shows that there is definitely a lot of potential to save fuel by choosing a higher quality pavement. Note that the deformation scale in the figures is intentionally set to correspond to the deflection on an intermediate road. Thus, the very good bearing capacity on these roads is demonstrated. The comparison at this site has been described at an earlier conference on bearing capacity, [Lenngren 2009].

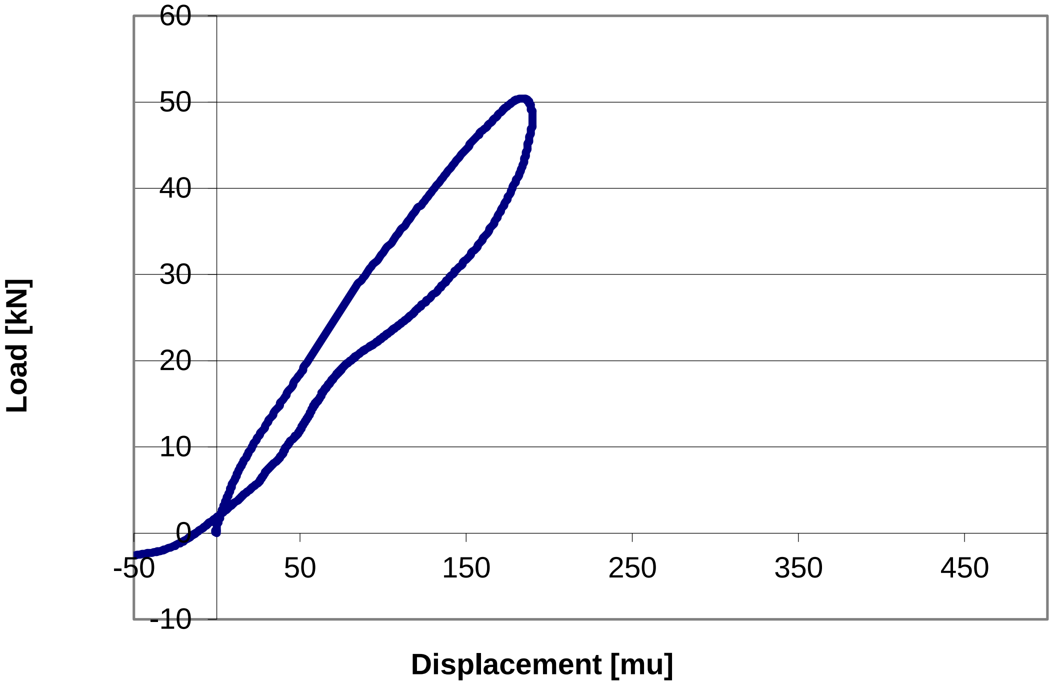

Figure 2: AC Load displacement diagram for the center load sensor (D0). The enveloped area corresponds to a work of 2.2 Nm.

2 FURTHER TESTING ON PCC PAVEMENTS

The results from the Björklinge test site were indeed homogenous and straight-forward in the sense that they did not vary within the tested respective areas of materials. However, it only represented one single site. Other tests on minor roads show that there are also significant losses in unbound materials due to damping and sometimes prevalent water will affect the results. Asphalt pavements vary during the year depending on the temperature and loading conditions. These effects have been thoroughly studied in the field and the laboratory as well. As regarding PCC pavements there much tests done with FWD time history data; one reason being that the bearing capacity is hardly an issue. The first jointed plain concrete pavement studies were tests at the center of the slab in the afternoon only. This was a concern of slab curling disturbing the contact between layers, which impedes the backcalculation of layer moduli. The question then arises whether the curling also affects the hysteresis? Further, at the Björklinge site there was an asphalt bound base, so testing a pavement without any asphalt bound layer at all was called for.

Thus, it was decided to do some additional testing at some other locations as well. One site was found on a rural freeway 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. A third section was found on E6 in the southwest and on the west coast of Sweden, where also some near edge testing was done.

The sites are shown in Figure 3. They are quite far apart and the distance between the E4 and E6 sites is over 600 km.

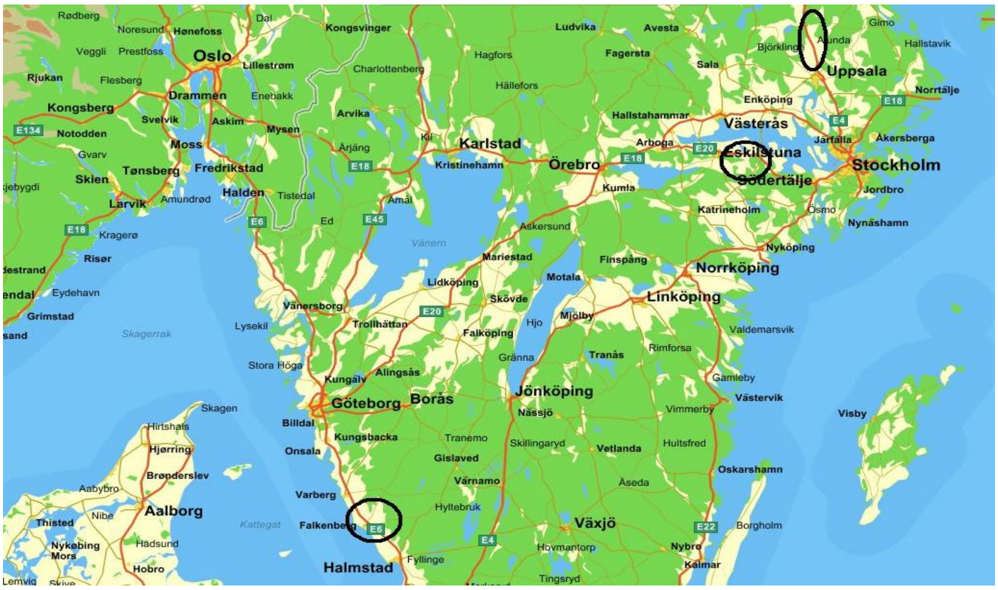

Figure 3: Test sites at three locations (map from www.eniro.se)

2.1 PCC with cement treated base on E20 at Eskilstuna

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.

Figure 4: The FWD at E20 testing near the edge of the slab.

The average mid-slab value for the PCC came out to be slightly lower than the E4 site at .360 Nm. Through a cut section the response was very stiff with a maximum deflection of 60 mu at 50 kN. The dissipated energy was only .280 Nm as is seen in Figure 5. The Figure shows the envelopes for the sensor in the middle of the load plate and the sensor at 120 cm. The rebound slopes suggest some heaving at the end of the test. The deformation is less than 10 mu and it could be an artifact of the calibration as a drift in the sensor readings. The nearby asphalt concrete also proved better than the corresponding Björklinge site with an average work of 1.20 Nm. It was also colder, about ten degrees Celsius, which is about five degrees colder than the annual mean for the pavement.

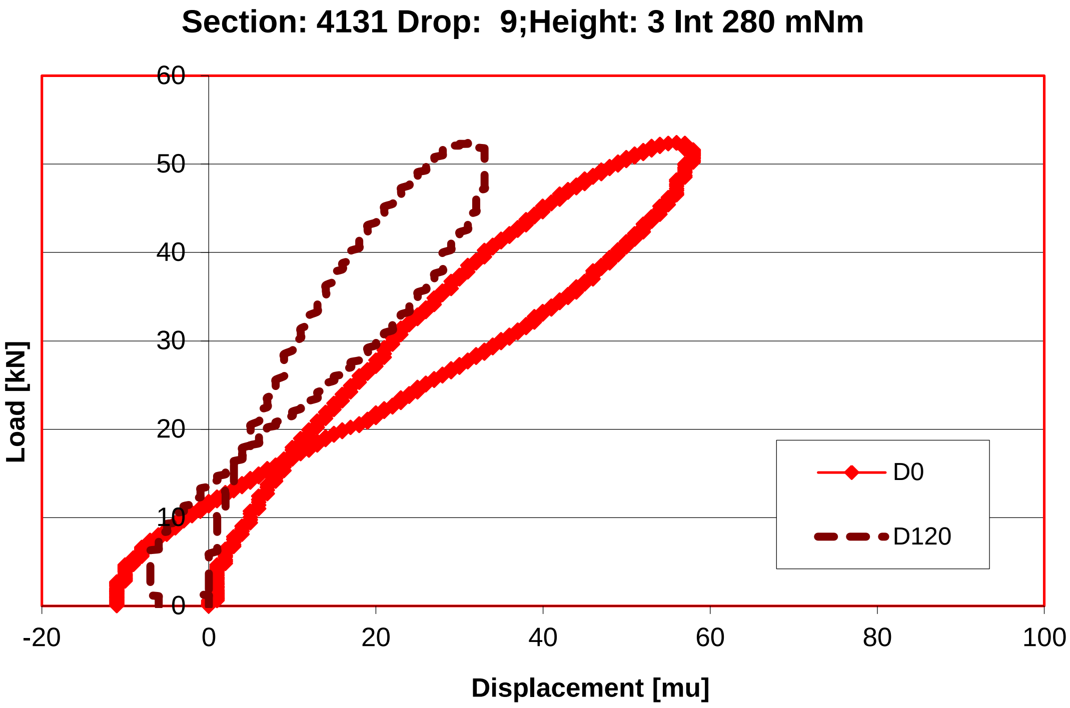

Figure 5: Load-Deformation diagram for a particularly stiff section. Sensors at center of loading plate (D0) and at 120 cm offset (D120).

As mentioned above, the upward curling of the slabs was anticipated to increase the dissipation of energy. Thus, some tests were done near the joint at the edge of the slab in the morning hours. 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 6. 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.

At E20 the reference asphalt pavement was somewhat better than the near edge results for the concrete one. The weighted average however, came out in favor of the concrete by a factor four; slightly less than the E4 site.

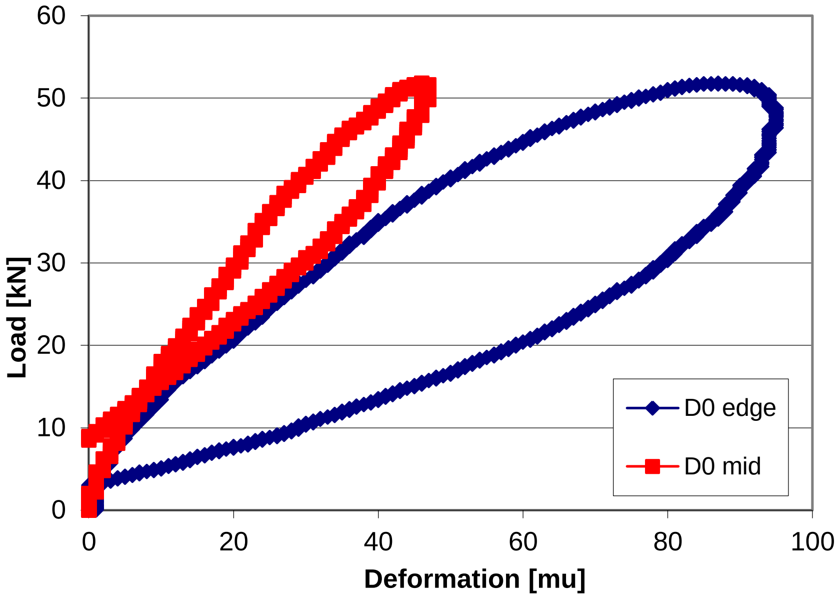

Figure 6: Load-Deformation diagram mid-slab (red) and near edge (blue) respectively.

2.2 E6 at Falkenberg

The measurements took place on 19 October 2010. The sky was overcast and the temperature moderate, only about 10 degrees C. The measurements were made at the center of the slabs of the jointed pavement and some tests at 60 and 35 cm from the edge respectively. Here the center slab hysteresis was greater than at the E20 site, or about 2.56 Nm slightly higher than the asphalt concrete near Uppsala. The subgrade was not so stiff here, which was revealed by a relatively open plot even for the outer sensors. So when comparing plots from all sensors there was a small difference between them. Figure 7 shows the load-deflection for seven sensors for the center slab at 70 kN. The relationship between the sensor at 120 cm and the one at zero was about 65%; a very high value. As the outer sensor was primarily responding to deep deformation, one might surmise that most of the surface deflection was responding to deformation occurring at some depth.

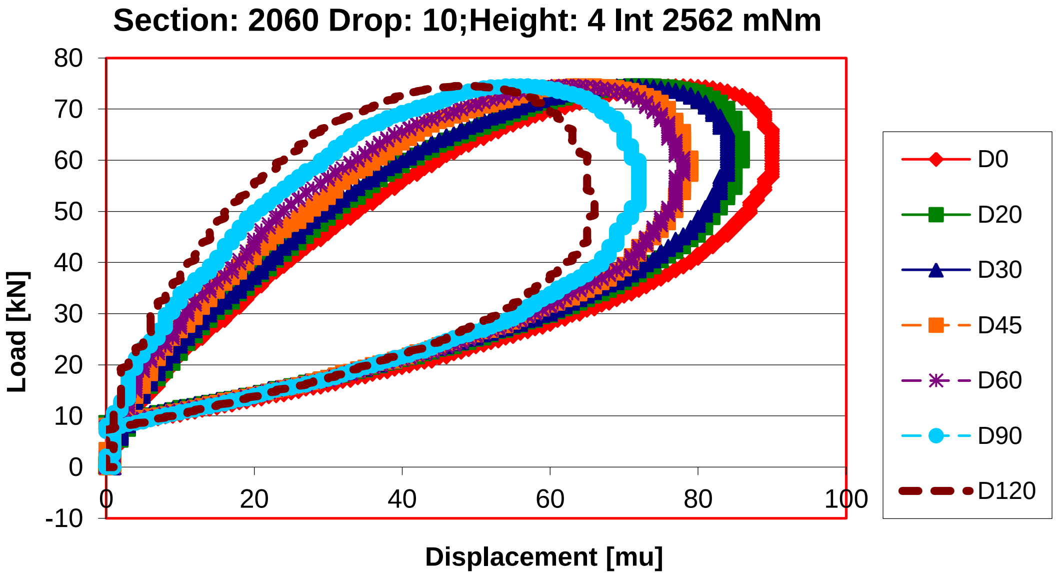

Figure 7: Load-Deformation diagram mid-slab for all sensors at 70 kN.

It is interesting to see what the effect is when the load approaches the edge of the slab. As mentioned above some tests were made closer to edge. The results are listed in Table 1 below for the 50 and 70 kN load as well. The plots for the 50 kN load is shown in Figure 8. The average value using a spline function along the slab turns out to be in the neighborhood of 1.6 Nm @50 kN or 30% higher than the mid-slab case. Considering that only a fraction of the traffic is travelling during the morning hours it is reasonable to believe that about 10 to 20 % more energy is lost to upward curling than for the non curled state. Conversely, one might add that continuously reinforced concrete pavements have a benefit of 10-20% over the plain jointed ones regarding rolling resistance.

Table 1: Estimated hysteresis loss (Nm) for various load situations

Load	Center Slab	60 cm from edge	At edge
50 kN	1.23	2.11	2.57
70 kN	2.56	4.27	5.18

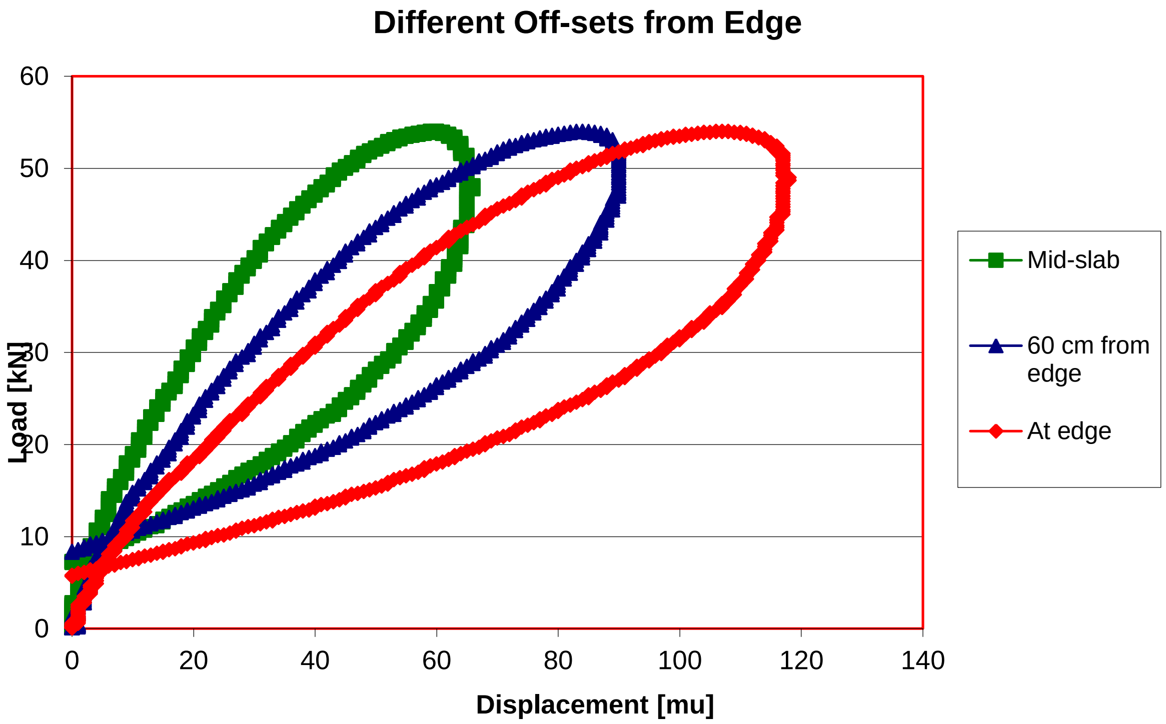

Figure 8: Load-Deformation diagram for different edge off-sets at 50 kN.

3 DISCUSSION

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 examples above show, the upward curling is indeed a negative factor on rolling resistance for plain jointed PCC pavements. Soft soils also contribute to the rolling resistance even for concrete pavements. If the E4 and E20 sites are considered as good subgrade examples, the relative difference between AC and PCC is a factor five to six. At the E6 site there was no comparative testing on asphalt concrete pavements, but it seemed as the subgrade contributed with more than 2 Nm for the 50 kN load. If a poor subgrade contributes with say 3 Nm the relative factor between pavement types becomes 1.5 only. The gain for selecting the PCC should still be about 1.8 Nm in any case at average temperatures. Clearly, more tests are needed, some have been done, and more results are underway to build a complete picture; incorporating diurnal and seasonal variation.

4 CONCLUSIONS

4.1 General Conclusions on pavement rolling resistance

Truck rolling resistance comprises a number of different components from internal friction to pavement-tire interaction. Field studies have shown a measureable difference between pavement types, but with inconclusive results. Tests must be done bi-directionally, but the wind speed may not be constant. Further the temperature affects the results in many ways.

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. The engine requires less fuel at low temperatures, but usually more fuel is needed at lower temperatures for other purposes. This is only one reason why it is difficult to discern differences through drive tests. Further, surface friction, joints and roughness all affect the drive test results too. The stationary FWD test eliminate many of these disturbing parameters and a thorough analysis of time history data can contribute to the understanding of pavement hysteresis.

At earlier tests the PCC pavement exhibited about four to five times lower work loss as AC pavements at the mean annual average temperature. However, the PCC tests were done when no curling was prevalent, so it is not justifiable to use these data for the carbon foot print as it is likely to be higher when accounted for in the life cycle analyses.

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 at various seasons could confirm this assumption.

4.2 Conclusions from new study on curling

On jointed PCC pavements, upward curling increases the rolling resistance. This effect is usually occurring in the morning hours and the result is up to four times higher losses near the edge of the slab. The losses are proportionally smaller on pavements resting on softer foundation, but in such cases the overall loss is higher due to damping in the soils and unbound layers. If diurnal change of traffic is factored in the upward curling seems to increase the rolling resistance with about 10 to 20 % over tests made at mid-slab resting on the base. Thus, there is also a small benefit for continuously reinforced concrete for sustainability.

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. These methods generate a large carbon footprint, but it may be balanced if traffic induced emissions are reduced.

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, 0., 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. (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 Tutumluer and Imad L. Al-Qadi. ISBN 978-0-415-87199-0