LOT WINTER DAMAGE THEORY: VALIDATION AND UNDERSTANDING OF WINTER DAMAGE IN POROUS ASPHALT

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ABSTRACT

For reasons of noise reduction the application of Porous Asphalt, PA, on the primary road network is mandatory in the Netherlands. At this moment approximately 90% of the primary road network has a PA surfacing. Ravelling is the predominant type of damage of PA and decisive for service life in most cases.
In order to explain ravelling and further optimize Dutch PA a meso scale mechanistic mixture design tool for PA was developed at the Delft University of Technology. This tool is called LOT (Lifetime Optimization Tool) and was developed in 2007 under commission from DVS (Centre for Transport and Navigation of the Dutch Ministry of Transport, Public Works and Water Management).
After the exceptionally cold 2008/2009 winter a theory explaining severe winter damage in PA was developed on the basis of LOT. Based on a representative case it was shown that LOT pinpoints exactly which phenomena cause winter damage, results were in full agreement with observed behaviour (1, 2). The 2009/2010 Dutch winter was again colder than normal and again winter ravelling damage developed in some stretches of motorway. After this winter BAM (the largest Dutch building contractor) and the Delft University of Technology took initiative in validating the LOT winter damage theory on basis of eight individual in-service road sections. This paper summarizes the validation work. It is shown that the ravelling performance of PA can well be explained by meso scale mechanics. Theoretical PA performance is in full agreement with observed behaviour

Keywords: Porous Asphalt, winter damage, ravelling, mechanistic mix design

1. INTRODUCTION

For reasons of noise reduction the application of Porous Asphalt, PA, on the primary road network is mandatory in the Netherlands. At this moment approximately 90% of the primary road network has a PA surfacing. Ravelling, i.e. the loss of stone from the road surface, is the predominant type of damage of PA and decisive for service life in most cases.

LOT is a meso scale mechanistic Lifetime Optimization Tool for Porous Asphalt. LOT is elaborately discussed in other literatures. [1, 2]. One year after completion of LOT in the winter of 2008/2009 extremely aggressive ravelling developed at short sections of Dutch motorway. Just after these severe damages were reported LOT was utilized in an effort to explain the observed aggressive winter ravelling. By consideration of a single representative case, making use of available data, it was shown that LOT is well capable in explaining observed winter damage [1, 2].

Unfortunately the 2009/2010 Dutch winter was again more severe than usual and again extremely aggressive ravelling was observed on stretches of motorway. This second event triggered the Delft University of Technology and BAM to validate the capabilities of LOT in explaining winter damage. DVS kindly joined this effort and it was decided to validate the LOT winter ravelling theory against observed behaviour of eight stretches of motorway. Hereto the road owner, DVS, took cores from the eight involved road sections. In section 2 the validation work is discussed. Basically this section summarizes the inputs for the LOT PA ravelling performance calculations. In section 3 the results of the validation work are discussed. In this section the theoretically explained performance of the eight sections is put in perspective by comparison with the performance of a virgin PA surfacing. This paper closes with conclusion drawn in section 4.

2. VALIDATION

The Dutch winter of 2009/2010 was more severe than normal and similar to the winter of 2008/2009 aggressive ravelling was observed at stretches of motorway. BAM and DVS were interested in the work on winter damage done by the Delft University of Technology and it was decided to validate the LOT winter ravelling theory presented in (1, 2, 4) by comparing theoretical results with true pavement performance of individual sections of motorway. Results of this work are discussed in the sections hereafter.

2.1 Road sections

Table 1 gives a summary of the road sections involved in the validation exercise. Row 0 presents the road section. Row 1 gives the year of construction and row 2 gives an indication of observed damage. Distinction is made between no damage,0 , typical aggressive winter ravelling,1 , and ravelling not clearly related to the winter, 2.

To help interpret results a reference case is also included in this work, last column in Table 1. The reference case considers a standard Dutch PA 0/16 with a 70/100 pen bitumen as per Dutch National Standard, RAW 2005 (5).

Figure 1: Left: section A15_1995, 15 years in service and hardly damaged. Right: N3_2004, 6 years in service and suffering from severe winter damage.

Figure 1 gives an impression of considered pavement conditions. Section A15_1995 is more than 15 years in service and apart from some isolated and very small spots of damage this section shows no damaged. The figure also gives an impression of the much younger section N3_2004, which is only 6 years in service. As shown this latter section suffers from severe ravelling damage.

Table 1: Summary of sections involved in the validation exercise

0		A15_2006	N3_2004	N9_2002	A200_2002	A4_1997	A15_1995	A12_1992	A12_1987	Reference
1	Year of completion	2006	2004	2002	2002	1997	1995	1992	1987	Virgin
2	Damage*	0	1	1	2	0	0	1	0	n.a
3	PA thickness [mm]	41	45	50	38	49	41	49	40	50
4	AC thickness [mm]	333	211	210	337	254	213	270	363	200
5	Base material	-	Furnace slag	Lava stone	-	Crushed concrete	Sand cement	Concrete on 150 mm sand cement	-	Unbound base reference
6	Base thickness [mm]	0	350	500	0	250	225	230	0	225
7	Sand sub base thickness [mm]	1000	700	1000	0	1000	1000	0	1000	1000
8	Subgrade	Clay	Clay	Clay	Sand	Clay	Clay	Sand	Clay	Clay

* **0: No damage, 1: Typical winter damage, 2: Ravelling damage that could not be related to the winter.**

2.2 Pavement structures and deflection curves

The LOT winter damage simulations require pavement deflection as input. A good indication of the structure of the involved road sections is obtained from the full depth cores that were purposely drilled into the base. From these cores the thickness of the PA surface layer, the combined thickness of the dense asphalt concrete layers and the type of base material could easily be determined, see Figure 2 and rows 3, 4 and 5 of Table 1. The base thickness, sand sub-base thickness and the type of subgrade were obtained from the road owner DVS and are listed in rows 6, 7 & 8 of Table 1.

Figure 2: Left: Indication of blast furnace slag base. Centre: Indication of sand sub-base. Right: measurement of total asphalt thickness.

Table 2: Summary of Multi Layer Analyses response inputs.

Material	Stiffness [MPa]	Poisson's ratio [-]	Material	Stiffness [MPa]	Poisson's ratio [-]
PA @ -10°C	10475	0.35	DAC @ -10°C	20950	0.35
PA @ 0°C	8625	0.35	DAC @ 0°C	17250	0.35
PA @ +10°C	6000	0.35	DAC @ +10°C	12000	0.35
PA @ +20°C	3750	0.35	DAC @ +20°C	7500	0.35
Clay	55	0.4	Sand	100	0.4
Blast furnace slag	1000	0.4	Crushed concrete	600	0.4
Unbound base reference case	400	0.4	Concrete base	15000	0.15
Sand cement	8000	0.2	Lava stone upper 250 mm	150	0.4
Lava stone lower 250 mm	100	0.4			

On the basis of the previous pavement deflection curves were determined using Multi Layer Analyses (Weslea) for -10°C, 0°C, +10°C and +20°C. The stiffness inputs for these calculations are listed in Table 2. The majority of the response inputs listed in Table 2 follow from the Dutch design code (8), however, some listed response inputs were estimated and are in agreement with general practice in the Netherlands.

Combined the Tables 1 and 2 give all pavement related information required for the calculation of deflection profiles at -10°C, 0°C, +10°C and +20°C. Figure 3 gives an impression of obtained results at -10°C for the deflection under a 50 kN wheel load.

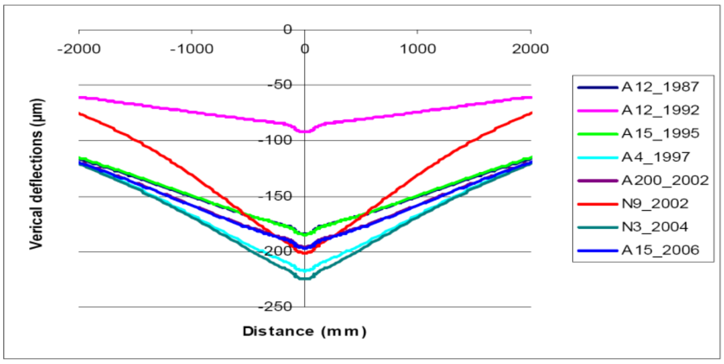

Figure 3: Visualization of the deflection of the involved pavements @ -10°C under a 50 kN load.

2.3 Porous Asphalt mixtures

In this validation work use is made of the idealized 2D PA model as available in LOT (1, 2, 3, 4). Determination of the geometry of this model requires the following:

1. Mineral grading; this determines the equivalent stone size of the mixture,
2. Bitumen content; combined with the amount of mineral < 2 mm this determines the amount of mortar in the mixture,
3. Void ratio; this determines the level of in-situ compaction.

The listed information was retrieved from the drilled cores and is listed in Table 3. Row 1 lists the grading of the mixtures. In row 2 the equivalent stone diameter for the fraction > 2 mm is given. Row 7 lists the bitumen content of the various mixtures. Dutch PA mixtures should have approximately 4.5% bitumen. As indicated the mixtures involved in this validation work on average have 3.7% bitumen, while a lowest value of 3% was determined. The cause of these low values lies beyond the scope of this validation research. Literature however indicates that mortar in PA tends to erode away (6, 7). It is believed that the low values found in this work subscribe these findings.

Table 3: Summary of PA mixture composition

0		A15_2006	N3_2004	N9_2002	A200_2002	A4_1997	A15_1995	A12_1992	A12_1987	Reference case
	C 16.0 [%]	0.53	2.92	2.08	0.47	1.36	0.57	2.6	0.93	Dutch National Standard, RAW 2005, (8)
	C 11.2 [%]	23.11	21.04	33.71	19.56	23.61	25.91	25.38	19.66	
	C 8.0 [%]	57.34	52.72	69.24	56.36	56.53	55.42	48.83	56.43	
	C 4.0 [%]	75.97	73.1	86.89	84.87	77.31	75.86	72.04	76.28	
1	2 mm [%] "on seive"	81.04	80.18	88.73	87.45	82.92	82.09	81.47	83.48	
	1 mm [%]	84.26	84.32	90.09	89.62	85.83	84.7	84.12	86.69	
	0.5 mm [%]	87.56	87.32	91.14	91.53	89.17	88.27	86.32	88.89	
	0.25 mm [%]	89.97	89.33	93.69	93.39	91.17	90.59	88.59	90.5	
	0.063 mm [%]	94.13	93.14	95.65	95.57	94.84	94.23	93.84	94.42	
2	Equivalent grain diameter [mm]	8.24	7.94	8.53	7.49	8.17	8.26	7.78	7.95	9.6
3	Mix density at 0% voids [kg/m³]	2550	2567	2583	2517	2486	2503	2549	2500	2480
4	Density mineral in mortar [kg/m³]	2700	2633	2718	2587	2612	2634	2640	2617	2650
5	Density stone [kg/m³]	2743	2728	2723	2732	2659	2656	2705	2644	2650
6	% stone [%]	84.3	84.3	88.7	87.5	83.7	84.7	84.1	86.7	80
7	% bitumen on 100% [%]	4.52	3.3	3.03	3.57	4.22	3.84	3.58	3.72	4.5
8	% air voids [%]	20	20.8	21.8	21.8	23.1	20.6	19.1	21.3	20

2.4 Mortar response

In LOT simulations the Visco Elastic behaviour of mortar is of crucial importance. This behaviour is determined by DSR measurements on 6 mm diameter mortar specimens made of the mortar from the sections involved, see Figure 4. DSR response measurements are done at frequencies from 0.1 to 400 rad/s and at temperatures ranging from -10 to +50

°C. Figure 5 gives the obtained Master Curves of involved mortars at -10°C. In LOT simulations the measured Visco Elastic behaviour is respected with high accuracy by use of the well known Prony series model.

Figure 4: A: retrieving mortar from the heated mix, B: pre heating moulds in oven, C: finalized specimen in DSR ready for testing.

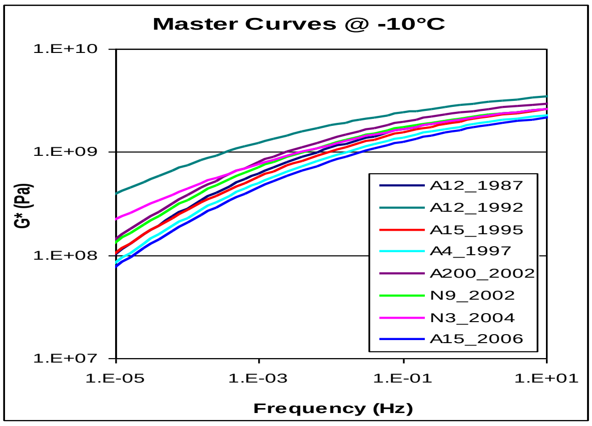

Figure 5: G* stiffness master curves for involved mortars in the frequency window where flexibility or relaxation is required, see section 2.8.

2.4 Traffic and wheel load

Traffic counts were available for three road sections:
1. A12: Wageningen – Oosterbeek, 2008 in both directions
2. A15: Deil – Meteren, 2008 in both directions
3. A15: Arkel –Leerdam, 2007 in both directions

By combination of these data the normalized traffic distribution presented in Figure 6 is obtained. In combination with axle load measurements reported elsewhere (8) it was conclude that the slow lanes of Dutch motorways are daily subjected to 11450 equivalent 100 kN standard axle loads on average.

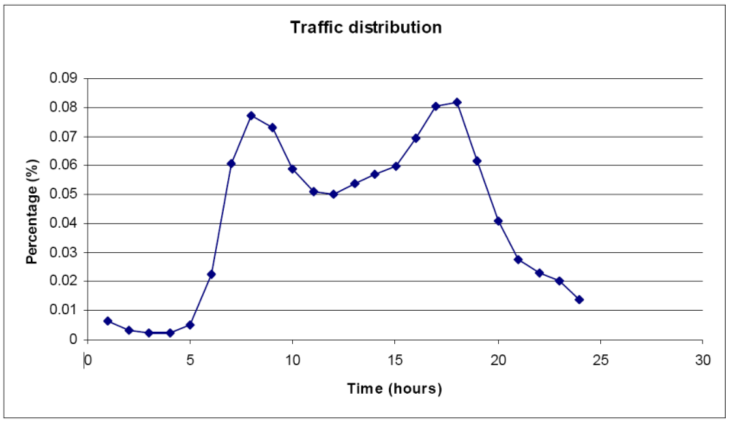

Figure 6. Normalized traffic distribution for Dutch motor ways (A12 2008, A15 2007, A15 2008).

2.5 Temperature loading

Table 4: Local extreme winter days at four locations in the Netherlands for the 2008/2009 and 2009/2010 winters. For each location the two coldest days and the two days with largest ΔT are listed.

	De Bilt (central)			Hoogeveen (north)		
	Date dd-mm-yy	Tav. [°C]	ΔT [°C]	Date dd-mm-yy	Tav. [°C]	ΔT [°C]
2008/2009 local extremes	10/01/2009	-7.1	6.9	31/12/2008	-7.2	6.2
	09/01/2009	-6	8.7	30/12/2008	-5.5	6.4
	03/01/2009	-3.7	10.5	14/02/2009	-0.4	8.6
	07/01/2009	-1.6	10.2	06/01/2009	-5.2	8.4
2009/2010 local extremes	19/12/2009	-8.1	6.8	19/12/2009	-9.3	4.3
	26/01/2010	-6.9	6.4	03/01/2010	-8.8	10.7
	27/01/2010	-3.3	15.6	27/01/2010	-3.1	13.5
	21/02/2010	-0.2	8.7	0.3-01-10	-8.8	10.7
	Volkel (south)			Maastricht (south)		
	Date dd-mm-yy	Tav. [°C]	ΔT [°C]	Date dd-mm-yy	Tav. [°C]	ΔT [°C]
2008/2009 local extremes	06/01/2009	-10.9	11.9	06/01/2009	-12	8.3
	10/01/2009	-9.4	8.1	09/01/2009	-10	11
	07/01/2009	-8.7	15.3	07/01/2009	-9.5	13.4
	06/01/2009	-10.9	11.9	10/01/2009	-7.5	11.4
2009/2010 local extremes	19/12/2009	-10.8	9.4	19/12/2009	-9.5	8
	07/01/2010	-7.2	8.3	08/01/2010	-7.5	8.1
	27/01/2010	-3.8	15	27/01/2010	-4.5	10.2
	17/02/2010	-2.1	10	17/02/2010	-1.5	9.5

From data of the KNMI, Royal Netherlands Meteorological Institute, the average daily temperature fluctuation in the centre of the Netherlands (i.e. in the municipality of de Bilt) in the 2009/2010 winter months of December, January and February was determined. Results indicated that temperatures on average reach a maximum at 14:30 PM, temperatures are lowest after 03:30 AM and start rising at 8:30 AM.

For practical reasons these temperature fluctuations are described by a sinusoidal signal that has a maximum at 14:30 PM and subsequently a minimum at 2:30 AM.

An offset (average temperature) and amplitude can be assigned to the sinusoidal signal. By doing so the modelled temperature signal may be calibrated to represent the temperature fluctuations on various winter days. These winter days are defined by a combination of the average temperature ($T_{average}$ = offset) and the temperature difference between day and night ΔT.

Table 4 gives an indication of winter days with the lowest $T_{average}$ and largest ΔT at four locations for the 2008/2009 and 2009/2010 winters. As shown the combination of $T_{average}$ / ΔT can reach values of -10°C / 10°C and beyond depending on the location of the weather station.

3. RESULTS

3.1 Introduction

In the LOT winter damage theory three types of loading are combined:
1. Wheel load passages, i.e. contact forces being applied to surface stones as the wheel patch passes.
2. Pavement deflection, i.e. deformation of the PA road surfacing as a result of the deflection curve generated by the wheel load.
3. Temperature stresses that develop as material shrinkage and expansion due to temperature fluctuation is prevented by surrounding material.

In simulations for validation of LOT's capabilities in explaining winter damage these loads are as follows:
1. Passing wheels have a contact length of 170 mm, the contact pressure is 0.89 MPa.

2. The wheel load magnitude equals 50 kN, leading to a 100 kN standard axle load. In combination with the pavement structure this determines the considered deflection bowls see section 4.2.
3. In the simulations the temperature of the PA follows a sinusoidal. The offset ($T_{average}$) of this signal and the amplitude (half the difference between day and night temperature, ΔT) are varied.

3.2 Reference case

LOT is a straight forward tool for the computation of ravelling damage in porous asphalt. LOT uses laboratory data as input and obtained results are not corrected or adjusted in any way. LOT computes the life expectancy of most severely stressed locations of mortar bridges that hold the material together. This implies that LOT computes the moment of damage initiation and not so much the moment of true loss of surface stones. For this reason results are made relative to a reference case with known performance. In this work the ravelling performance of a standard Dutch PA 0/16 made with straight run bitumen 70/100 PEN placed on a representative pavement structure serves as that reference. Information about the reference pavement structure and the PA mix is listed in Tables 1, 2 and 3. Figure 7 gives the ravelling performance of the reference case. The figure indicates that -not taking into account the effects of traffic wander - PA in the reference case can survive (1/0.00667=) 150 severe winter days with an average temperature of -10°C and a ΔT of 10°C before the first in mixture damage develops. It is also shown that maximum ravelling performance (1,518,278 days to first damage) is at 0°C.

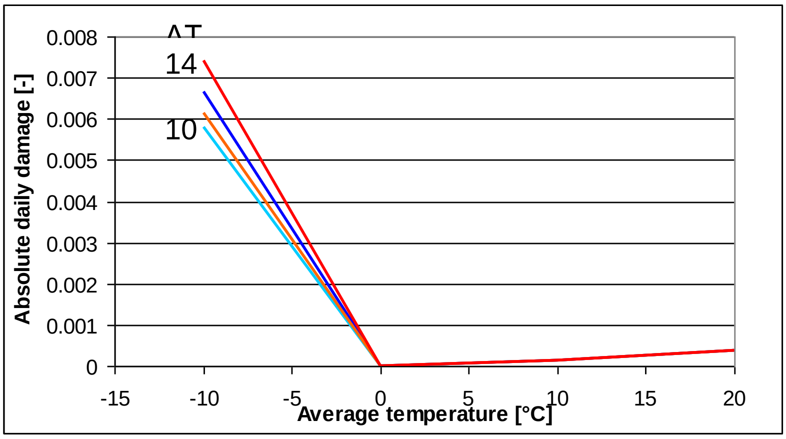

Figure 7: Absolute theoretical ravelling performance of the reference 70/100 PEN straight run bitumen PA 0/16 mm on a representative Dutch motorway.

3.3 Individual road sections

Eight in-service road sections are considered in this research. An impression of the theoretical ravelling performance of these individual sections is given in Figure 8. In this figure the performance of each individual road section is made relative to the performance of the reference case at 0°C. The presented plot is valid for a 6°C difference between PA surface day and night temperatures. As indicated the worst performance is found at an average temperature of -10°C, where the relative performance can easily reach a value of for instance 1 million. This huge number indicates that the considered section at an average temperature of -10°C and a ΔT of 6°C performs 1 million times worse than the virgin reference mixture at 0°C.

Figure 8 clearly indicates that the ravelling performance of the eight considered road sections deteriorates as average day temperatures approaches -10°C. This is especially the case when the difference between day and night temperatures (ΔT) increases. From Figure 7 it is learned that also virgin PA mixtures with PEN 70/100 bitumen suffer from this general trend. However, for the reference mixture the relative daily damage at -10°C and ΔT=10°C equals approximately 10,000 (=1,518,278 /150). From this observation it is concluded that all eight in-service PA pavements are much more vulnerable to winter damage than the reference pavement with a virgin PEN 70/100 PA 0/16.

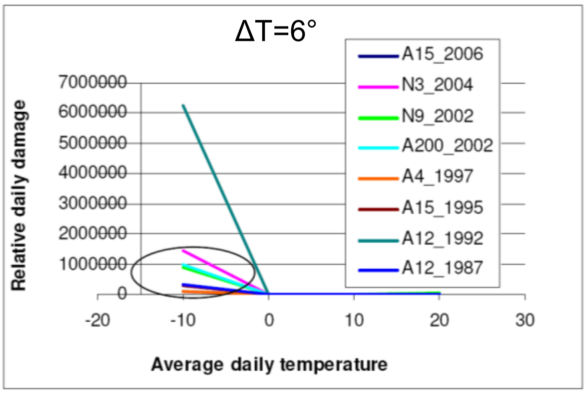

Figure 8: Relative ravelling performance of eight individual pavements for a 6°C difference between day and night PA surface temperatures.

3.4 Validation

The LOT explained theoretical performance for a day with an average temperature of -10°C is compared with observations in practice. Figure 9 gives the relative daily damage at -10°C for the eight considered pavements plotted against the year of construction. Data labels indicate observed ravelling damage in practice (0= no damage, 1= winter damage, 2 ravelling damage not related to winter). The 2010 pavement gives results for the reference pavement, i.e. a virgin pavement.

As indicated results for pavements in which no ravelling damage was observed show low values of relative daily damage. Pavements that showed winter ravelling damage have much more relative daily damage as is the case for the pavement with ravelling damage not directly linked to the winter. It is also observed that there is no relation between the date of construction and observed or computed performance.

From these observations two conclusions are drawn. Firstly a direct relation exists between observed (winter) ravelling damage and theoretically explained pavement performance. This conclusion supports the developed theory of LOT and its capability to explain winter damage. Secondly it is observed that both young and old pavements may resist winter conditions or suffer from winter damage from both a theoretical and practical point of view. The fact that there is no direct relation between PA age and performance indicates that much better types of PA may be developed on the basis of this work.

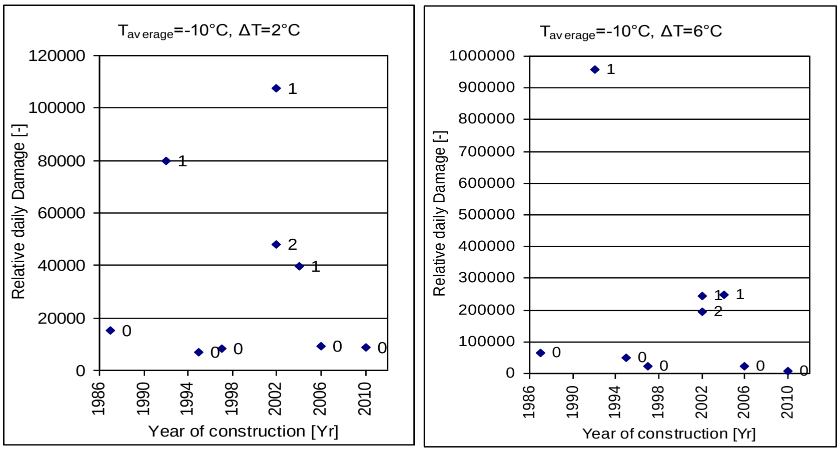

Figure 9. Relative daily damage at $T_{average}$ is -10°C and ΔT is 2 and 6 °C respectively. Data labels indicate ravelling damage (0= no damage, 1= winter damage, 2 ravelling damage not related to winter).

3.5 Explanation of winter damage

In [1, 3] it was concluded that the PA surface is subjected to three types of loading.

1 Individual surface stones are subjected to contact forces by passing tyres that act to jerk away these surface stones. To resist this type of loading PA need to be strong. The frequency of this type of loading at 80 km/h for tyre prints with a length of 170 mm is in the range of 60 to 125 Hz.

2 As loads pass the pavement deflects. PA can only follow these pavement deflections and is thus subjected to prescribed deformation. To resist this type of loading PA needs to be flexible. At 80 km/h this leads to frequencies in the order of 5 to 10 Hz.
3 As temperatures fluctuate over the day the pavement surface shows the urge to shrink and expand. To compensate for this urge PA needs to be flexible. As temperatures vary over a 24 hour period these loadings have a frequency in the order of 1.2E-05 Hz.

At low temperatures the mortar of especially aged PA may not be flexible enough to compensate for the type 2 and 3 loading. Figure 5 gives an impression of the master curves at -10°C for the various types of PA considered here. As indicated the mortars of the N3_2004, the A200_2002 and especially the A12_1992 are relatively stiff. The mortars of the A15_2006 and the A4_1997 are softest in the frequency window of 1E-05 to 10 Hz. This is in full agreement with Figure 9 which indicates that damage develops in the 1992, 2002 and 2004 pavements, both in theory and practise. Similarly the figure indicates no damage in the 1997 and 2006 pavements.

From this it may be concluded that mortar response is an important quantity in explaining winter damage susceptibility.

4. CONCLUSIONS

After the 2009/2010 winter the LOT winter damage theory was validated against the observed performance of eight in-service pavements on the Dutch primary road network. The following conclusions can be drawn.
1. LOT results were in full agreement with observed performance in practice. The performance of all in-service pavements was far less than that of the virgin reference case. However it was observed that sections in which ravelling damage developed performed extremely poor, see Figure 9.
2. In explaining obtained results it was found that the relaxation behaviour of mortar in range of 1E-5 to 1E+1 Hz is important. In this frequency window PA does require flexibility in stat of strength.
3. There is a strong relation between the G* master curve at -10°C in the mentioned frequency range and obtained LOT theoretical performance and observed ravelling damage. This relation subscribes this explanation.
4. There is no relation per se between pavement age and mortar response or PA performance. Old pavements may well perform well while young pavements may lack performance.

Practically the work discussed here leads to the following conclusions:
1. Old PA mixtures may still poses good performance in practice and theory. This implies that the quest to come to high performance PA is very realistic and may well lead to results that exceed expectations.
2. The work indicates that young pavements may poses poor ravelling performance in both practice and theory. This implies that performance based quality control measures can be developed.
3. The behaviour of mortar is of large influence in theoretically explaining PA ravelling performance. For future work the development of a truly realistic and fast/cheap mortar aging protocol or apparatus is of larger importance.
4. A mechanistically guided process of developing high performance PA is feasible today.

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