Model for Birth and Growth of Transversal Heaves in Asphalt Pavement with Hydraulic Blast Furnace Slags Base

L.J.M. Houben and M.F.C. van de Ven
Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

ABSTRACT: In the Netherlands blast furnace slags (BFS) are used on a wide scale in road bases for many decades. An example is a 10 km long stretch of the motorway A32, built in the years 1986-1988. Some 10 years after construction the first transversal heaves occurred at the pavement surface. Since then the number of heaves has considerably increased and the heaves keep on growing in height.
In 2007 research was carried out into the BFS base of the A32. This research included, a.o.:
1. Inventory of the number, length and height of the transversal heaves;
2. Materials research on bound BFS, obtained by taking cores out of the pavement;
3. Development of a mechanical model which describes the birth and growth of the transversal heaves.

KEY WORDS: Blast furnace slags, heaves, mechanical model

1 INTRODUCTION

In the Netherlands blast furnace slags (BFS) are used on a wide scale in road bases for many decades, e.g. on a 9.3 km long stretch (km 29.7 to km 39.0) of the motorway A32, built in the years 1986-1988. With the aim to obtain a high stiffness of the base (and thus to save on the required asphalt thickness) the BFS contained 5-15% by mass granulated blast furnace sand.

Some 10 years after construction the first transversal heaves occurred at the pavement surface. Since then the number of heaves has considerably increased and the heaves keep on growing in height. The heaves not only have a negative effect on the driving comfort and the traffic noise but also may effect the traffic safety, e.g. if trucks loose (part of) their payload.

In 2007 an extensive research was carried out into the BFS base of the A32 motorway stretch, especially on the western carriageway between km 32.3 and km 33.5. This research, done in commission of and in cooperation with the Regional Service Noord-Nederland and the Centre for Transport and Navigation of the Dutch Ministry of Transport, Public Works and Water Management, is summarised in this paper.

2 PAVEMENT STRUCTURE MOTORWAY A32

The motorway A32 was constructed in the years 1986 to 1988. The pavement structure consists of 200 mm asphalt concrete layers, 200 mm BFS base and a sand sub-base (variable thickness) on the natural clay subgrade.

Prior and during construction a number of tests have been done on the BFS base material.

These tests included the grading, resistance to chalk and iron (both were o.k.), crushing factor (o.k.) and hydraulic activity (measured as increase of CBR-value). After 7 days the CBR-value was 1.6 to 2.3 times higher than after 0 days, after 28 days the CBR-value was about 4 times higher than after 0 days. The applied BFS material was very strongly hydraulic.

3 PATTERN OF HEAVES

For this research ARAN measurements (ARAN = Automated Road ANalyser) were performed on the motorway A32 on 24 April 2007. After a first visual analysis of the measurement results the sections from km 32.3 to 33.5 and the one from km 37.0 to 39.0 were appointed as potential locations for FWD measurements and coring to be done later.

From the ARAN measurements an inventory was made of the location, height and length of the heaves. The average spacing between the heaves varies per traffic lane and per road section from 40 to 100 m. On some places clusters of heaves were present where the spacing was only 5 to 20 m. The height of the heaves varied from 3 to 27 mm, and their length was 1 to 6 m. The growth rate (increase of the height) of the heaves was on average about 1 mm per year but varied from 0 to 4 mm per year. The location and height of the heaves on the western carriageway of the section from km 32.3 to km 33.5 is given in Figure 1.

Based on the analysis of the ARAN measurement results, finally 2 short road sections have been selected for FWD measurements and coring. Both sections concern the right traffic lane of the western carriageway. The 1st section is from km 33.159 to km 33.271 and contains 3 ‘average’ transversal heaves with spacing of about 40 m. The 2nd section, from km 32.597 to km 32.665, contains a very large and a very small transversal heave with a spacing of 15 m.

For the analysis of the FWD measurement data, reference is made to (Houben, 2008).

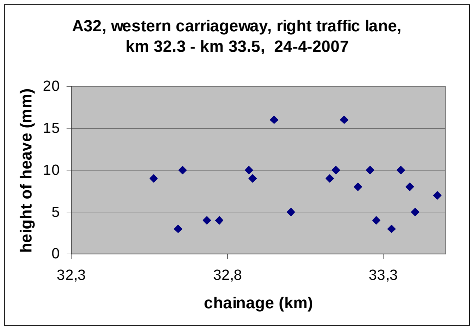

Figure 1: Location and height of the transversal heaves on the right traffic lane of the western carriageway of the A32 between km 32.3 and km 33.5 on 24 April 2007.

4 MATERIALS RESEARCH

The materials research was done on BFS material, obtained at 23 May 2007 through 29 cores taken from the right traffic lane of the western carriageway. 17 cores were taken in the 1st section, 12 cores in the 2nd section. One core was taken in the centre of each of the 5 heaves, other cores were taken at short distances of the heave centre and midway some heaves.

All the data in this chapter is valid for the BFS base material which has an age of 20 years. In every core the grading of the BFS material (Houben, 2008) was coarser than the grading of the original material, applied in the 1980s, so binding of the BFS had occurred in all cases.

The dry density of the bound BFS base material of the A32 was on average 2029 kg/m^3, with a very small coefficient of variation of 2.3%.

The materials research concentrated on the bound BFS material as this condition is held responsible for the occurrence of transversal heaves. Through sawing 15 specimens were obtained from the 29 cores. The low specimens have been used to measure the dynamic modulus of elasticity and the indirect tensile strength and the high specimens to measure the coefficient of linear thermal expansion and the compressive strength. The test results are:

- coefficient of linear thermal expansion: $6.8*10^{-6}$ to $8.8*10^{-6}$ °C^{-1}, on average $8*10^{-6}$ °C^{-1};
- dynamic modulus of elasticity: 800 to 12,500 MPa, on average about 4,000 MPa;
- indirect tensile strength: 0.4 to 0.7 MPa, on average 0.52 MPa;
- compressive strength: 2.0 to 3.8 MPa, on average 2.7 MPa.

In the failure tests the bound BFS material exhibited brittle behaviour.

5 MECHANICAL MODEL FOR BIRTH AND GROWTH OF TRANSVERSAL HEAVES

5.1 Introduction

A mechanical model has been developed which enables the analysis of the birth and growth of transversal heaves in (asphalt) pavements with a hydraulic BFS base. It is assumed that the binding of the hydraulic BFS leads to obstructed expansion resulting in increasing longitudinal compressive stresses in the base. The binding of the BFS also leads to (relatively small) temperature effects and an increasing compressive strength of the road base.

Transversal heaves (i.e. crushing of the bound BFS base material over a certain length) occur when the compressive stress exceeds the compressive strength, present at that moment. Through the heaves a certain amount of stress relaxation occurs in the still bound material in between the crushed zones. The chemical process, and the temperature effects, of the still bound base however proceed, and at a certain moment new transversal heaves occur midway the existing heaves. This mechanism may repeat itself a number of times and in the extreme case this leads, on the (very) long term, to complete crushing of the whole bound BFS base.

5.2 Temperature of the road base

In the Netherlands the mean temperature of the base is estimated as 15°C, and that temperature is present around May 1 and November 1. The yearly temperature amplitude is about 10°C. In a year the development of the base temperature is about a sine. If the road base is constructed t_1 months after May 1, then the temperature T_1 at the time of construction is:

$$T_1 = 15 + \Delta T_1 * \sin(30 * t_1) \quad (°C) \tag{1}$$

where: ΔT_1 = temperature amplitude (°C) of the base, taken as $\Delta T_1 = 10$°C
t_1 = time of construction of the base (in months after May 1), with $0 \le t_1 \le 11$

The temperature T_2 of the road base at any time t is equal to:

Construction at February 1: $T_2 = 15 + \Delta T_1 * \sin(30 * t - 90°)$ (°C) (2a)
Construction at May 1: $T_2 = 15 + \Delta T_1 * \sin(30 * t)$ (°C) (2b)
Construction at August 1: $T_2 = 15 + \Delta T_1 * \sin(30 * t + 90°)$ (°C) (2c)
Construction at November 1: $T_2 = 15 + \Delta T_1 * \sin(30 * t + 180°)$ (°C) (2d)

where: t = time (in months after the time of construction of the base), so the age of the base

The difference ΔT_2 between the temperature of the base at time t and the temperature during construction is equal to:

$$\Delta T_2 = T_2 - T_1 \qquad (°\mathrm{C}) \tag{3}$$

5.3 Time-dependent behaviour of blast furnace slags road base

Models to describe the time-dependent mechanical behaviour of hydraulic BFS bases are not known. Therefore, as far as available, the models (formulas) for concrete are used (Eurocode 2, 2005). The relevant applied formulas for the bound BFS base are given hereafter.

Compressive strength: $\sigma_c = e^{s*[1-\sqrt{240/t}\,]} * \sigma_{c20y}$ (MPa) (4)

where: s = parameter, for which the value s = 0.25 is used (Eurocode 2, 2005)
t = age of the base (months)
σ_{c20y} = compressive strength after 20 years

Modulus of elasticity: $E = \beta * \sigma_c{}^{\gamma} * E_{20y}$ (MPa) (5)

where: γ = parameter, for which the value $\gamma = 0.3$ is used (Eurocode 2, 2005)
E_{20y} = modulus of elasticity after 20 years
β = parameter; its value follows from the boundary condition: $\beta * \sigma_{c20y}{}^{\gamma} = 1$

For the coefficient of linear thermal expansion of a bound BFS base it was assumed:

Coefficient of thermal expansion: $\alpha = \dfrac{E}{E_{20y}} * \alpha_{20y}$ ($°\mathrm{C}^{-1}$) (6)

where: α_{20y} = coefficient of linear thermal expansion after 20 years ($°\mathrm{C}^{-1}$)

The thermal deformation (strain) of the bound BFS base is then equal to:

Thermal strain: $\varepsilon_T = \alpha * \Delta T_2$ (m/m) (7)

The chemical deformation (expansive strain) of the bound BFS base was assumed as:

Chemical strain: $\varepsilon_{ch} = 1 - e^{-d*\sqrt{t}}$ (m/m) (8)

where: d = parameter

The total obstructed deformation (strain) ε of the bound BFS base is equal to:

Total strain: $\varepsilon = \varepsilon_T + \varepsilon_{ch}$ (m/m) (9)

The stress in the bound BFS base due to the obstructed deformations is equal to:

Compressive stress: $\sigma = E * \varepsilon$ (MPa) (10)

This occurring stress is not corrected for stress relaxation as no information at all is available

The value of the parameters in some of these formulas is determined on the basis of the performed materials research on the bound BFS base material (Table 1). The value of the remaining relevant parameters is determined by comparing, assuming average mechanical properties of the road base material and construction of the base (20 years ago) at average temperature (at May 1), the calculation results of the model with the heave pattern (spacing between the heaves and height of the heaves) as measured in 2007 (see chapter 3). So the model was calibrated based on materials research and in situ ARAN measurements on A32.

Table 1: Mechanical properties of the bound BFS base used in the analysis of the birth and growth of transversal heaves.

	Magnitude mechanical property		
	low	average	high
Tensile strength after 20 years, σ_{t20y} (MPa)	0.4	0.5	0.6
Compressive strength after 20 jaar, σ_{c20y} (MPa)	2	3	4.5
Modulus of elasticity after 20 years, E_{20y} (MPa)	2000	4000	7000
Coefficient of linear thermal expansion after 20 years, α_{20y} (°C^{-1})	$7*10^{-6}$	$8*10^{-6}$	$9*10^{-6}$
Parameter d of chemical deformation (eq. 8)	$50*10^{-6}$	$58*10^{-6}$	$70*10^{-6}$

5.4 Mechanical model

The developed mechanical model that describes the birth and growth of the transversal heaves in a (asphalt) pavement with a hydraulic BFS base is basically the same as the model that describes the phenomenon of (horizontal) buckling of long welded railway tracks at very high temperatures. But in the case of the hydraulic BFS base the mode of failure is, at a certain moment, local crushing of the base material over a certain length.

In this paragraph the failure process of the hydraulic (bound) BFS base is described up to the birth of the first series of transversal heaves (the primary/secondary heaves). For the mechanics of following series of heaves reference is made to (Houben, 2008).

The spacing between the primary heaves is determined by the so called ‘breathing length’ (Figure 2). This is the part of a very long structure that undergoes horizontal displacements in case of temperature changes (or another variable influencing factor). This phenomenon also occurs on long welded rails.

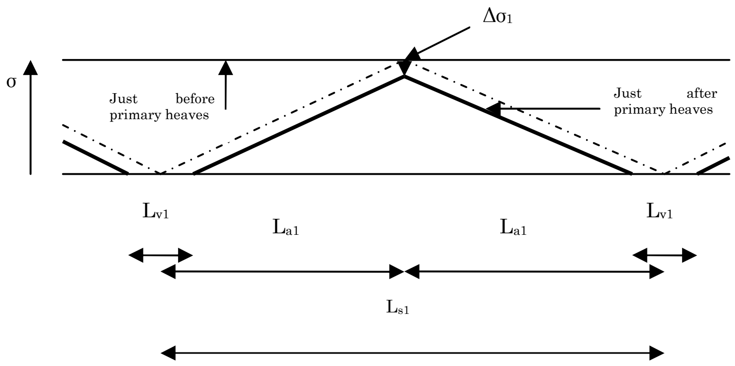

Figure 2: Compressive stresses in bound BFS base at the time of the primary heaves.

The breathing length L_{a1} at the primary heaves follows from the equation:

$$L_{a1} = 1000 * \frac{E * \varepsilon}{\gamma * f} \qquad \text{(m)} \qquad (11)$$

where: E = modulus of elasticity (MPa) of bound BFS base at time of primary heaves (eq. 5)
ε = maximum total obstructed deformation (compressive strain) of the BFS base at time of primary heaves (eq. 9)
γ = volume weight of bound BFS base; taken as $\gamma = 20$ kN/m^3 (see chapter 4)
f = coefficient of friction of the bound BFS base with the surrounding layers

The distance L_{s1} between 2 primary heaves is equal to 2 times the breathing length:

$$L_{s1} = 2 * L_{a1} \qquad \text{(m)} \qquad (12)$$

Because of the length L_{v1} of the crushed zone, taken as $L_{v1} = 3.5$ m (see chapter 3), a reduction $\Delta\sigma_1$ of the maximum compressive stress (between 2 primary heaves) occurs that is equal to:

$$\Delta\sigma_1 = 0.5 * \frac{L_{v1}}{L_{a1}} * \sigma \qquad \text{(MPa)} \qquad (13)$$

where: σ = maximum compressive stress in BFS base at time of primary heaves (eq. 10)

After the occurrence of the primary heaves the maximum compressive stress σ_1 in the bound BFS base (midway between 2 subsequent primary heaves) further increases due to the ongoing chemical process (and the temperature effect) according to (see also Figure 3):

$$\sigma_1 = \sigma - \Delta\sigma_1 \qquad \text{(MPa)} \qquad (14)$$

where: $\Delta\sigma_1$ = reduction of the max. compressive stress at time of primary heaves (eq. 13)

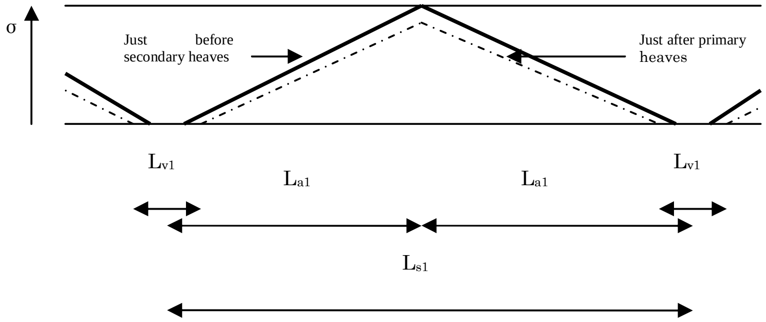

Figure 3: Build-up of compressive stresses in the bound BFS base between the primary and the secondary heaves.

The maximum compressive strain in the base, according to Hooke's law, is equal to:

$$\varepsilon_1 = \frac{\sigma_1}{E} \qquad \text{(m/m)} \qquad (15)$$

The shrinkage of the crushed zone (ΔL_{v1}) after the primary heaves is equal to:

$$\Delta L_{v1} = 1000 * \frac{E * \varepsilon_1^{\,2}}{\gamma * f} - \Delta L_{v1} \text{(at time of primary heaves)} \qquad \text{(m)} \qquad (16)$$

where: ε_1 = maximum total obstructed compressive strain of bound BFS base (eq. 15)

It is assumed that the asphalt layer is pushed upward at every primary heave due to the shrinkage of the crushed zone in the period after the occurrence of the primary heaves. It appeared from the ARAN measurements on the motorway A32 that the shape of the heaves is triangular to sinusoidal. Assuming that the volume of the crushed zone does not change, for both shapes of the heave it follows for the height h_{s1} of these primary heaves (Figure 4):

$$h_{s1} = 2 * \frac{\Delta L_{v1}}{L_{v1} - \Delta L_{v1}} * h_f \qquad \text{(mm)} \qquad (17)$$

where: L_{v1} = length (m) of the crushed zone at the primary heaves; taken as L_{v1} = 3.5 m
ΔL_{v1} = shrinkage (m) of the crushed zone at the primary heaves (eq. 16)
h_f = thickness (mm) of the BFS base; taken as h_f = 200 mm (see chapter 2)

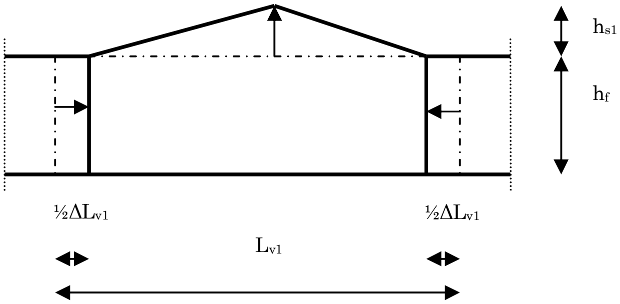

Figure 4: Schematized growth of the primary heaves.

At the time of the primary heaves the reduction $\Delta\sigma_1$ of the maximum compressive stress (eq. 13) is small ($\Delta\sigma_1 \approx 0.1$ MPa). Therefore the maximum compressive stress σ_1 in the bound BFS base (eq. 14) reaches again the compressive strength σ_c (eq. 4) soon after the primary heaves. This leads to new crushed zones (secondary heaves) midway the primary heaves (Figure 5).

The breathing length L_{a2} at the secondary heaves is equal to:

$$L_{a2} = 0.5 * L_{a1} - 0.25 * L_{v1} - 0.25 * L_{v2} \qquad \text{(m)} \qquad (18)$$

where: L_{a1} = breathing length (m) at the primary heaves (eq. 11)
L_{v2} = length (m) of crushed zone at the secondary heaves; taken as L_{v2} = 3.5 m

The distance L_{s2} between a primary and a secondary heave is half the distance between 2 primary heaves:

$$L_{s2} = 0.5 * L_{s1} \qquad \text{(m)} \qquad (19)$$

Because of the length L_{v2} of the crushed zone of the secondary heave, again there is a reduction $\Delta\sigma_2$ of the maximum compressive stress (midway 2 primary heaves) in the intact, bound part of the base. In this case the stress reduction is equal to:

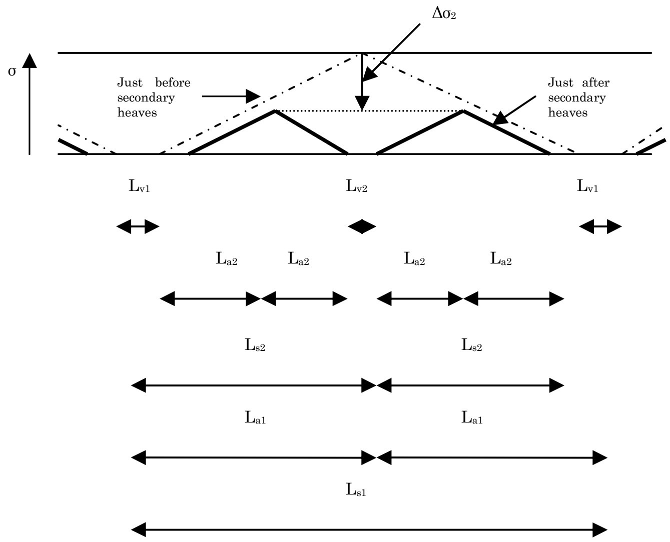

Figure 5: Compressive stresses in bound BFS base at time of secondary heaves.

$$\Delta\sigma_2 = 0.5 * \sigma_1 * (1 + \frac{L_{v2}}{L_{a2}}) \quad \text{(MPa)} \qquad (20)$$

where: σ_1 = max. compressive stress in bound BFS base at time of secondary heaves (eq. 14)

Because of the small reduction $\Delta\sigma_1$ of the maximum compressive stress in the intact, bound part of the base (eq. 13) the secondary heaves occur very shortly afterwards the primary heaves (in the calculations, presented in paragraph 5.5, for average mechanical properties of the bound BFS base and construction of the base at May 1: 1 month later). Therefore it is assumed that the primary and secondary heaves occur at the same time, i.e. at the time that the compressive stress σ (eq. 10) for the first time is equal to the compressive strength σ_c (eq. 4).

In this case the following equations are valid for the breathing length L_{a12}, the spacing L_{s12} between the heaves (so between a primary heave and the adjacent secondary heave) and the reduction $\Delta\sigma_{12}$ of the maximum compressive stress midway between 2 heaves in the intact, bound part of the base:

$$L_{a12} = 1000 * \frac{E * \varepsilon}{\gamma * f} \quad \text{(m)} \qquad (21)$$

$$L_{s12} = L_{a12} \quad \text{(m)} \qquad (22)$$

$$\Delta\sigma_{12} = 0.5 * \sigma * (1 + \frac{L_{v12}}{L_{a12}}) \quad \text{(MPa)} \qquad (23)$$

where: L_{v12} = length (m) of crushed zone at primary/secondary heaves; taken as L_{v12} = 3.5 m

For the spacing between the heaves on the motorway A32, 20 years after construction, average values between 40 m and 100 m have been found (see chapter 3). It will appear later from the analysis with the model that 20 years after construction of the BFS base only primary and secondary heaves are present. The spacing between these heaves is equal to L_{s12} (eq. 21 and 22), so the spacing between the heaves is greater when the coefficient of friction f is smaller. Realistic values for L_{s12} are obtained if the coefficient of friction f in eq. 21 has a quite large value. For the occurrence of the primary/secondary heaves f = 2 has been applied.

In itself it is quite logical that until the moment of the occurrence of the primary/secondary heaves a quite large value has to be taken for the friction between the bound BFS base and the surrounding pavement layers. This is explained by the probably quite good bond between the base and the asphalt and by the fact that, until the occurrence of the primary/secondary heaves, the base and the asphalt do not move with respect to each other (in horizontal direction).

It appeared from the calculations with the model to be presented later that, especially in case of high mechanical properties of the bound BFS base, further series of heaves (tertiary, quartary and cinquary heaves) occur within the considered period of 50 years (600 months). As the mathematical formulations for the birth and growth of these series of heaves are similar as for the primary/secondary heaves, they are not given here.

The mechanical model is calibrated for the case of average mechanical properties of the bound BFS base of the motorway A32 and construction of the base, 20 years ago, at May 1 i.e. at the average temperature of 15°C. The calibration result was that both the calculated number of heaves (i.e. the spacing between the heaves) and the growth of the heaves is equal to the average measured values thereof on the motorway A32.

5.5 Calculation results for different mechanical properties and times of construction of the BFS base

Calculations with the mechanical model have been done, for a period of 50 years (600 months), for 12 combinations of mechanical properties of the BFS base (low, average, high) and time of construction of the base (February 1, May 1, August 1, November 1, when the temperature during construction is minimum, average, maximum and average, respectively). The mechanical model yields the time of occurrence of the subsequent series of transversal heaves, the spacing between the heaves and the growth of all heaves as a function of time.

Figure 6 gives an overview of the times of birth of the subsequent series of transversal heaves and the spacing between adjacent heaves for the 12 combinations. The time of birth of the first series of primary/secondary heaves is also visible in Figure 7 that shows primarily for the 12 combinations the growth of these heaves. The upper 4 lines in Figure 7 apply to high mechanical properties of the bound BFS base, the central 4 lines are valid for average mechanical properties and the 4 lines in the lower right corner for low mechanical properties.

In the case of average and high mechanical properties of the BFS base, after the first series of primary/secondary heaves other series of heaves grow that can be deducted from Figure 7.

The combination of average mechanical properties of the bound BFS base and construction of the base at May 1 agrees best with the pattern of heaves as observed on the motorway A32. This is logical as the mechanical model was calibrated for this combination.

The most important findings from the calculations with the developed mechanical model are:

1. the process of birth and growth of transversal heaves in hydraulic BFS bases is a long lasting process (many decades) and finally results in complete destruction of the base;
2. with respect to the birth and growth of the transversal heaves, the mechanical properties of the BFS base (caused by the hydraulicity (binding) of the slags) are dominant compared to the temperature effects in the bound base;
3. high mechanical properties of the bound BFS base and a low temperature during construction are not favourable; the stiffer the base and the lower the temperature during construction, the earlier the transversal heaves occur, the more heaves occur and the faster the heaves grow in height;

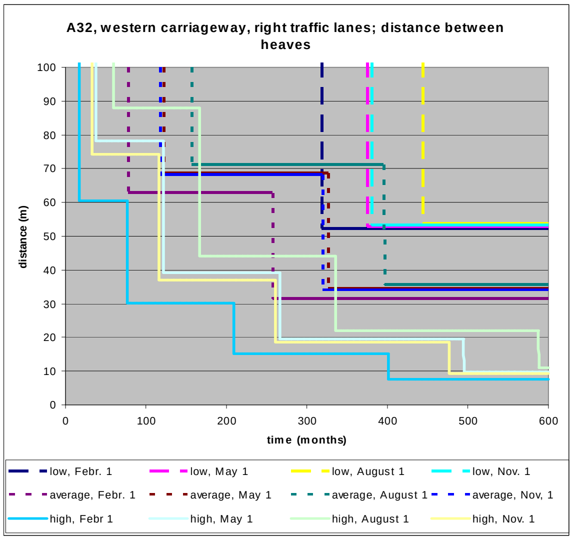

Figure 6: Overview of calculated times of birth of subsequent series of transversal heaves and the spacing between adjacent heaves.

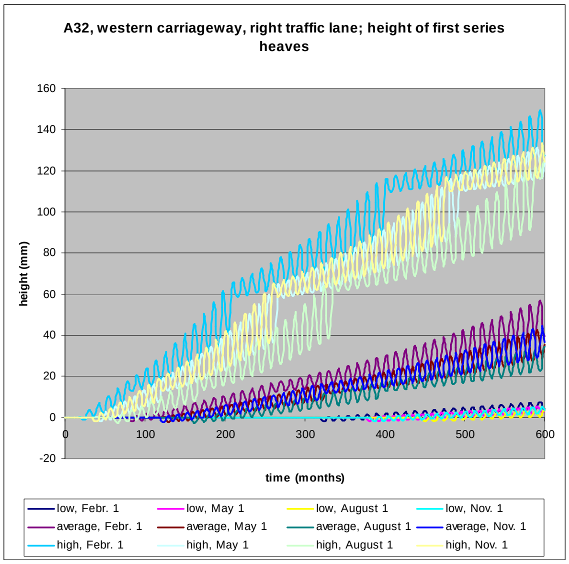

Figure 7: Overview of calculated (growth of the) height of first series of transversal heaves.

The practical consequence is that, in order to limit the birth and growth of transversal heaves, the BFS base material should be only lightly hydraulic and preferably constructed in the summer period.

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