RESISTANCE OF AGED ASPHALTIC CONCRETE TO WAVE ATTACK

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In this paper the resistance of aged asphaltic concrete to wave attack is considered. This is done by comparing the flexural strength of three dike revetments that vary from age and construction quality. Ageing influences the strength of asphaltic concrete. For aged asphaltic concrete the regular fatigue curves describe the strength incorrect. Therefore an adapted fatigue curve has been developed which takes into account the flexural strength at one load repetition.

INTRODUCTION

Application of asphaltic concrete revetments

Asphaltic concrete is used as a sea dike revetment to protect the dike body from erosion. It is a commonly used revetment type in The Netherlands but asphaltic concrete coastal revetments are applied in many other countries as well, including Germany, United Kingdom, Italy and Japan. The Shell bitumen hydraulic engineering handbook (Schönian, 1999) gives a detailed description of the application of asphalt in coastal engineering worldwide. In The Netherlands application on a large scale took place after the flooding of part of the Southwest of The Netherlands in 1953. After this disaster a great number of dikes had to be repaired quickly and this was possible with the use of asphalt as a revetment material. Asphalt could be placed much faster then the materials usually applied at that time, such as basalt columns. Asphalt was used on a large scale as well to protect the sand body of the dams that were constructed to close the estuaries in the Southwest of the Netherlands. The most common asphalt types are asphaltic concrete and fully grouted stones. For an example of a closure dam with an asphalt dike revetment, see figure 1.

Dikes that are (partly) covered with asphalt dike revetments nowadays protect approximately 400 kilometers of the Dutch coastline. The asphalt revetment is located in the wave attack zone, and usually it is the only protection of the sandy dike body. The significant wave height of a typical design storm amounts from 1 or 2 meters, up to 4.6 m.

In the past years extensive research on the flexural strength of aged asphaltic concrete was carried out by KOAC-NPC, in collaboration with Deltares and commissioned by Rijkswaterstaat (Ministry of Infrastructure and Environment) and Stowa (Foundation of applied research for the Dutch Water Boards).

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Figure 1. The Brouwersdam a closure dam with an asphalt dike revetment (source: Rijkswaterstaat, www.kustfoto.nl)

Resistance to fatigue, the classical approach

Asphalt is sensitive to fatigue and therefore the fatigue properties are used to express the flexural strength. The fatigue properties, the relation between the bending stress in a material (σ) and the number of loadings to failure (N_f) are normally assumed to be linear on a log-log scale. In figure 2 an example is given of a fatigue curve for a asphaltic concrete dike revetment.

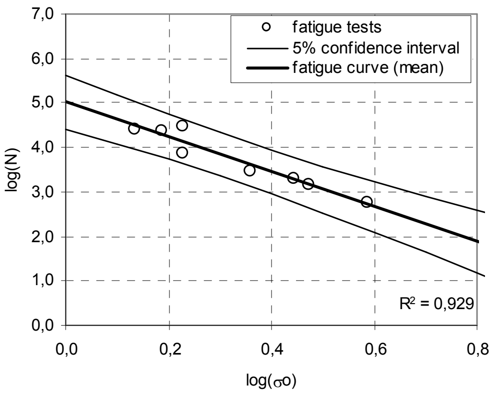

Figure 2. Fatigue curve (Flaauwe werk dike)

The fatigue properties are derived with three point bending tests on specimens from the revetment. Twenty years ago this test was developed to determine the actual strength of asphaltic concrete dike revetments (Montauban and Van de Ven, 1993). Fatigue tests are carried out by applying a sinusoidal force with a positive offset on a beam (220x50x50mm) by a temperature of 5°C and a loading frequency of 1 Hertz, see figure 3.The force is chosen such that the beam will yield at 100 to 50.000 load repetitions.

Figure 3. three point bending test, start of yielding

The fatigue properties can be expressed with:

$$\log(N_f) = \log(k) - a \cdot \log(\sigma_o) \qquad (1)$$

In which: N_f = number of loads to failure at stress level σ_o, σ_o = applied bending stress (N/mm^2), a and k = coefficient and intercept of the fatigue curve.

Experience with this model has shown several limitations, especially with aged asphaltic concrete. The variation in the result of fatigue tests increases with the age of the asphalt, resulting in a less reliable fatigue curve. This unreliable fit often results in a flat, less inclined fatigue curve. Extrapolating the curve to one load repetition suggests a very high flexural strength, see figure 4. This is in contradiction with the fact that the overall strength was found to be decreasing in time. For this reason an adapted material model has been developed.

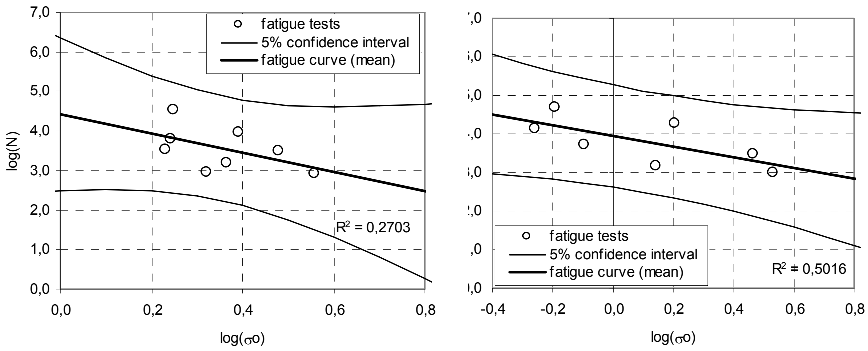

Figure 4. Fatigue curve of the Hondsbossche seawall (left) and the Hellegatsdam (right), both revetments with aged asphaltic concrete

AGEING

The properties of asphalt are changing in time due to the exposure to oxygen, water and ultraviolet light. The most important ageing mechanisms influencing the strength in time are stripping of the mixture and hardening of the bitumen.

Stripping

Intrusion of moisture causes a loss of adhesion; stripping of the revetment. Stripping is separation of the bitumen from the aggregate surfaces due to the action of moisture. Stripping reduces the flexural strength of the asphaltic concrete. In Dutch practice asphaltic concrete is covered with a surface treatment to avoid direct contact with water. A low void ratio slows down the process of stripping. A salt environment can accelerate the process of stripping.

Hardening of bitumen

Exposure to light and atmosphere causes hardening of the bitumen. This influences the material properties such as the stiffness modulus, yield stress and the elongation at break. Hardening of the bitumen causes the material to become more brittle; the flexural strength increases and the elongation at break decreases. As a result the material becomes more sensitive for cracking. Cracks in aged asphaltic concrete are often temperature cracks, caused by hardening of the bitumen. Higher temperatures and larger void ratios leads to a higher rate of hardening.

Both process influence the flexural strength of asphaltic concrete in time causing a decrease of the average strength and an increase of the variation in strength.

ADAPTED MATERIAL MODEL

Case studies

A material model that gives a good description of the strength at a limited number of load repetitions is needed for safety assessments on asphaltic concrete dike revetments. To feed this model with data a new test was introduced: determination of the flexural strength at one load repetition on beams using a the three point bending test. The following test conditions are used: a temperature of 5°C and a loading rate of 0,35 mm/s (which leads to an elongation rate which is approximately equal to the elongation rate in the fatigue tests).

Tests were carried out material taken from several dikes to determine both the fatigue properties and the flexural strength. For this purpose cores with a diameter of 250 mm were drilled out of the revetment. From every core two beams (220x50x50 mm) were taken. It is assumed that the properties of the two beams are equal. The first beam was used to determine the flexural strength (at one load repetition) the second beam was used to perform a fatigue test. The results of the fatigue tests are presented in the figures 2 and 4. Some basic properties and the flexural strength are presented in table 1. The age in table 1 is the number of years between the construction of the revetment and performance of the tests.

Table 1: basic data of dike revetments in case studies

dike	Age (years)	voids (%)			flexural strength (MPa)		
		n	x	s	n	x	s
Hellegatsdam	48	7	8,9	4,5	7	4,8	3,4
Hondsbossche	34	8	5,6	3,4	8	5,5	1,3
Flaauwe werk	22	8	3,8	0,9	8	5,4	0,7

In table 1 is n = number of samples, x = mean, s = standard deviation

Both age of the revetment and void ratio are indicators for the asphalt quality and strength. The asphalt quality decreases in time and a high void ratio results in a accelerated process of stripping.
The considered revetments are three typical examples from the total population. The Hellegatsdam was constructed six years after the flooding in 1953 and has a high average and standard deviation of the void ratio. This results in a revetment with both locations with a high strength, due to hardening of the bitumen, an a low strength, due to stripping. The overall asphalt quality is poor.
The Hondsbossche seawall was constructed in 1970. As a result of improvements in mixture design both average and standard deviation of the void ratio are less, compared with the Hellegatsdam. The asphalt quality can be classified as moderate.
The Flaauwe werk dike was constructed in 1984 with modern equipment and further optimized mixture design. This resulted in a low average and a low standard deviation of the void ratio. The Flaauwe werk dike has a revetment with a good asphalt quality.

Determining the adapted fatigue curves

Based on of a large set of experimental data the following basic principles for the material model were established:

- The model should take into account the flexural strength at one load repetition and should therefore be curvilinear on a log-log scale.
- The model should be suitable to deal with a large variation in the test results. To reduce the variation (σ_o/σ_b)), with σ_o = applied bending stress in the fatigue test and σ_b= flexural strength at one load repetition, is used as the independent variable instead of σ_o: Variation in N_f given a σ_o can mostly be explained by the variation in σ_b. This method is also known from fatigue curves for concrete pavements in road engineering.

From the literature, no examples are known of a curvilinear fatigue curve on a log-log scale. Therefore a new model had to be developed. It was preferred to develop a model based on linear regression because this allows to determine the confidence interval and thus a comparison can be made with the confidence interval of the traditional fatigue curve. With the following relation, estimates for α and β can be determined with the use of linear regression:

$$\log(\log(N_f) = \log(\beta) + \alpha \log(\log(\sigma_b) - \log(\sigma_o)) \qquad (2)$$

In which: N_f = number of loads to failure at stress level σ, σ_o = applied bending stress in fatigue test (N/mm^2), σ_b = flexural strength at one load repetition, α and β= regression coefficients.

From a statistic point of view this is not an elegant solution because the measured variable N_f is made depended from both the independent variable σ_o and the measured variable σ_b. As a part of the research project a Bayesian analysis was carried out (Telman, 2008) and it turned out that the more practical approach, as presented in this paper, did not lead to significantly different results. Data derived from both flexural strength tests and fatigue tests are given in table 2.

Table 2: flexural strength an fatigue test results

Flaauwe werk			Hondsbossche zeewering			Hellegatsdam		
σ_b	σ_o	N_f	σ_b	σ_o	N_f	σ_b	σ_o	N_f
6,7	1,7	29103	6,7	1,8	36035	2,9	1,4	1500
5,4	1,4	26544	5,2	1,8	6591	9,5	2,9	3000
5,2	1,5	22908	6,7	2,5	9635	1,7	0,8	5500
4,9	1,7	7386	4,2	1,7	3498	3,3	0,6	50000
4,7	2,3	2986	6,5	3,0	3078	8,3	1,6	18500
4,9	2,8	2046	4,8	2,3	1603	1,0	0,6	14000
5,0	3,0	1442	6,7	3,6	849	6,6	3,4	1000
6,3	3,9	556	3,4	2,1	899			

The calculated values for α and β are presented in Table 3.

Table 3: values for α and β

Dike	α	β
Hellegatsdam	0,23	4,59
Hondsbossche	0,44	5,53
Flaauwe werk	0,39	5,46

In figure 5 the resulting fatigue curves for the three considered revetments are presented.

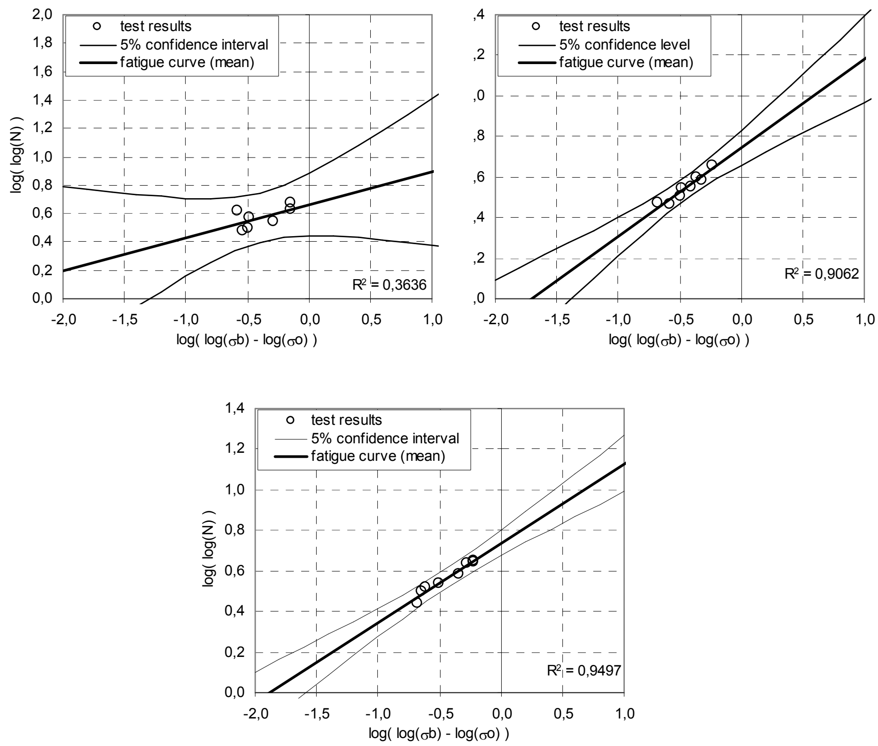

Figure 5. fatigue curves with a double log-log scale: Hellegatsdam (upper left), Hondsbossche seawall (upper right) and Flaauwe werk dike (bottom).

Presenting the relation on a log-log scale gives:

$$\log(N_f) = \beta(\log(\sigma_b) - \log(\sigma_o))^{\alpha} \tag{3}$$

Comparing the fatigue curves with the fatigue curves in figure 2 and 4 leads to the following conclusions:

- Flaauwe werk dike: The reliability of the original fatigue curve is high and remains unchanged with the adapted approach.
- Hondsbossche seawall: The reliability of the original fatigue curve is low and improves significantly with the adapted approach.
- Hellegatsdam: The reliability of the original fatigue curve is low and remains low with the adapted approach.

In figure 6 the resulting fatigue curves for the three considered revetments are presented.

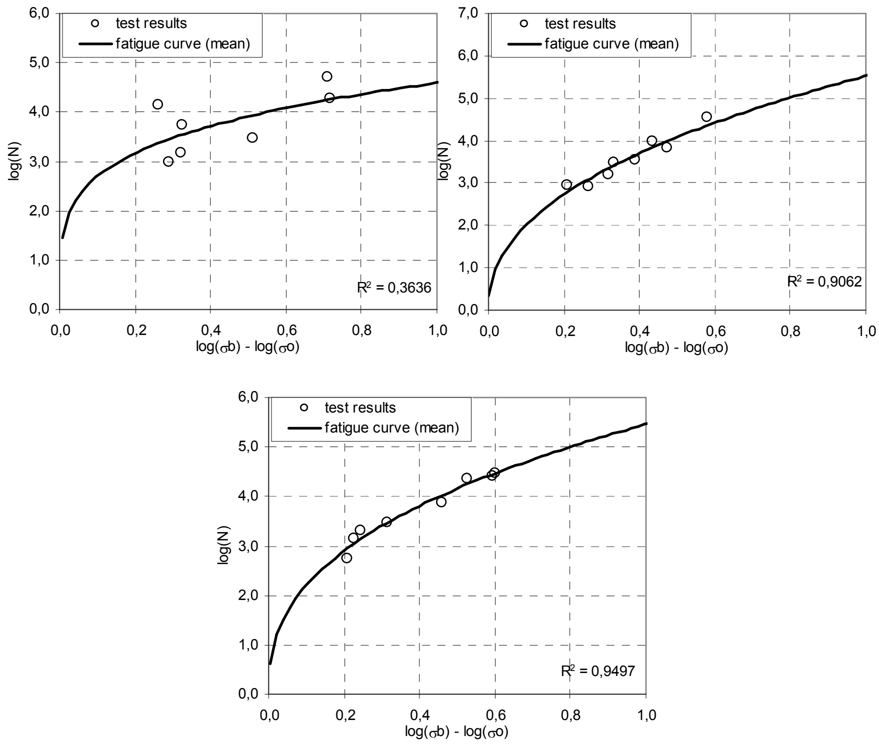

Figure 6. fatigue curves with a log-log scale: Hellegatsdam (upper left), Hondsbossche seawall (upper right) and Flaauwe werk dike (bottom)

Design curves

With the presented method the average strength under repeated loading can be determined. For both design purposes and performing safety assessments a more conservative curve is required. The design curve should represent both a characteristic flexural strength at one load repetition and – for a good asphalt quality - a characteristic curve in the area of the fatigue tests which is approximately equal to the classic linear fatigue curve. For this, several options are developed and compared. The most relevant options are presented in figure 7.

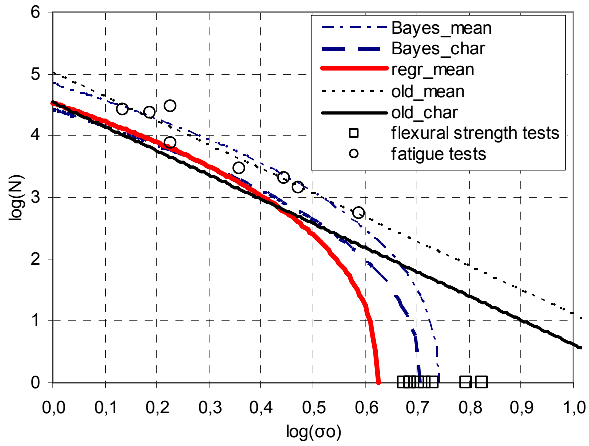

Figure 7. several design curves compared (Flaauwe werk dike)

The presented line regr_mean is a combination of the mean fatigue curve as presented in figure 6 and a 5% characteristic value for the flexural strength at one load repetition. Again this is not an ideal solution from a statistic point of view; the curve does not explicitly take into account variation contained in the fatigue tests. The variation in the flexural strength tests now represent the uncertainty in the results of the fatigue tests as well. In practice the method meets the requirements. In figure 8 the design fatigue curves for the Hellegatsdam and the Hondsbossche seawall are given.

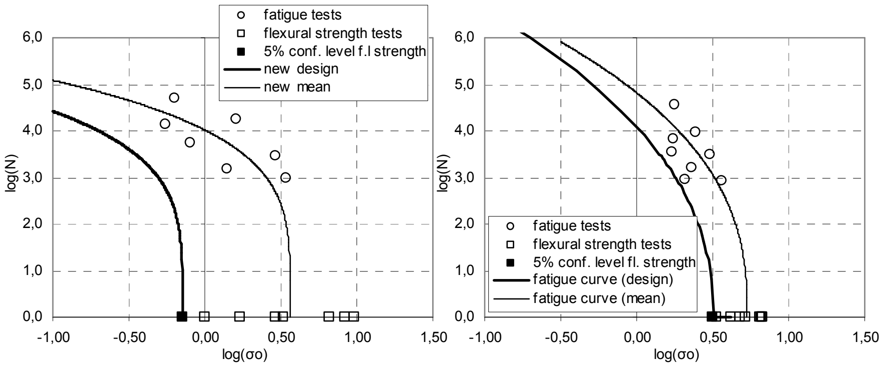

Figure 8. design curves Hellegatsdam (left) and Hondsbossche seawall (right)

The fatigue curves show a decreasing influence of fatigue for poor asphalt quality. The characteristic value of the flexural strength at one load repetition can be used to characterize the strength instead of the fatigue curve. The results of the flexural strength tests and the fatigue tests have equal stress levels.

STRESSES DUE TO WAVE ACTION

The presented material model is implemented in the computer program Golfklap (De Looff et. Al, 2006) making it possible to compare the strength with occurring bending stresses due to wave action. The program calculates a Miner sum:

$$\sum \frac{n_i}{N_{f,i}} \leq 1 \qquad (4)$$

In which: n_i = number of loads at stress level i, $N_{f,i}$ = number of loads to failure at stress level *i*. The revetment will yield if the Miner sum exceeds 1.

The Miner sum is calculated for the three dikes using the input as given in table 4 and the parameters characterizing the fatigue curve as given in table 2. Hydraulic boundary conditions are provided by the Dutch government. Material properties are determined by surveys with falling weight deflectometer (stiffness modulus revetment and bedding value subgrade) and ground penetrating radar (layer thickness) and by laboratory tests (flexural strength and fatigue tests). For material properties conservative values with a 5% confidence interval are used.

Table 4: input for calculations with Golfklap

	Flaauwe werk	Hondsbossche	Hellegatsdam
Stiffness modulus (MPa)	10.150	14.600	10.900
Bedding value subgrade (MPa/m)	275	98	87
Layer thickness (m)	0.24	0.20	0.19
Flexural strength at one load repetition (MPa)	4.1	3.2	0.7
Significant wave height (m)	2.8	3.5	0.8
Mean wave period (s)	9.8	13.6	3.3

The results a given in table 5.

Table 5: results of calculations with Golfklap

	Flaauwe werk	Hondsbossche	Hellegatsdam
Miner sum (-)	0.003	0.17	0.92

In figure 9 for the Hondsbossche seawall the stresses calculated with Golfklap are compared with the fatigue curve.

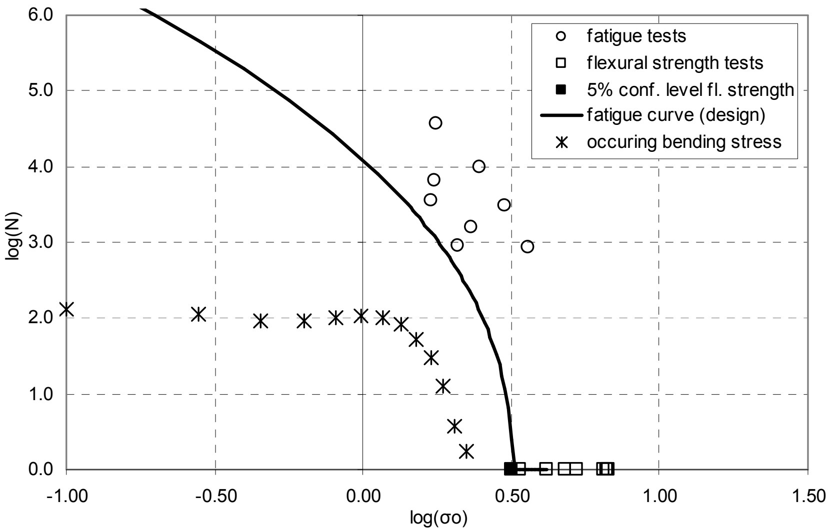

Figure 9. fatigue curve and occurring stresses for the Hondsbossche seawall as calculated by Golfklap.

SIZE EFFECTS

The flexural strength and fatigue tests are carried out on specimens with limited size. Due to heterogeneity of the asphaltic concrete small size of the specimens is preferred; the specimens itself should be as homogeneous as possible.

The minimum specimen size in relation to the maximum aggregate size has been investigated many times by asphalt technologists and by for instance geo engineers. To prevent unnecessary variations in the test results, the maximum aggregate size (D_{max}) must be small compared to the smallest specimen dimension (D_{min}). This requirement is usually set to something between $D_{min} \geq 3D_{max}$ to $5D_{max}$ based on the maximum aggregate size that still gives reasonably reliable test results. More information about this issue can be found in (Head, 1982), (Mier, 1997) and (Transportation Research Board, 1997).

The maximum stone size applied in asphaltic concrete for hydraulic applications is usually 16 mm but incidentally a maximum stone size of 22 mm can be found. This means that a beam with a diameter of 50 mm usually meets the requirements but occasionally it can result in more variation in the test results.

CONCLUSIONS

Recent investigations have been carried out tot determine the strength of several asphaltic concrete dike revetments. Based upon these results a new material model has been developed to describe the flexural strength of asphaltic concrete. This new model has been integrated in the latest version of Golfklap. With this computer model asphalt dike revetments can be designed and evaluated on wave impacts (De Looff et. al., 2006).

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