Determination of mechanical properties of hydraulic asphaltic concrete by means of a three-point bending test.

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DETERMINATION OF MECHANICAL PROPERTIES OF HYDRAULIC ASPHALTIC CONCRETE BY MEANS OF A THREE-POINT BENDING TEST

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Research - The Netherlands

1. INTRODUCTION.

Asphalt is used as a protective revetment in many sea walls. It is therefore an important material for protecting the Netherlands against flooding. There are many different applications such as asphaltic concrete, open stone asphalt and asphalt grouting mortars.

Asphaltic concrete is the most widely known of these because it is commonly used in the most severe attacked zone during extreme storm conditions. It forms an impervious and flexible slope protection.

Asphaltic concrete exhibits plastic and viscous as well as elastic behaviour. One advantage of this is that the revetment can follow irregular settlements in the subsoil. Cracking is rare owing to the high bitumen content. Under rapid loads like wave impacts, the asphaltic concrete behaves as an elastic, relatively stiff material which ensures good spreading of the load.

The fact that asphalt is commonly used has led to the material for many years being given special attention in the research conducted in the context of the Technical Advisory Committee on Waterdefences in the area of slope protection. This research is concerned for example with:

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- the mechanical behaviour of asphalt revetments
- the service life of the revetments

The design method for asphaltic concrete revetments is described in the "Guidelines for the use of asphalt in hydraulic engineering" [ref. 1].

The mechanical properties of hydraulic asphaltic concrete play an important role in the determination of the required thickness for the asphalt layer. This paper describes a method for assessing the required/present thickness of the asphalt structure both for the design of sea walls and for existing sea walls.

The aim of this study was to develop a standard method for determining the bending tensile strength under dynamic stresses. The test must be suitable for testing new asphalt mixtures and existing sea wall structures. An important factor was the possibility to take samples in a simple and representative way.

2. MECHANICAL TESTING OF ASPHALT.

Building materials are generally characterised by their "strength" and "stiffness". Strength can be established in many different ways, depending on the nature of the material and the application. Bending tensile strength is determined as the most relevant property for timber, and compressive strength in the case of concrete. Stiffness is generally expressed as the E modulus (Young's modulus), which indicates the linear relationship between stress and strain.

The situation is more complicated in the case of asphalt. In this material, strength and stiffness are not only dependent on the composition and nature of the basic materials but also depend heavily on the temperature and time of loading.

We therefore cannot refer simply to the "strength" and "stiffness" of asphalt. These properties are determined as a

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function of temperature and time of loading. Strength and stiffness will generally decrease as the temperature and period of loading increase. So it is important to know the loading conditions of the structure.

In Dutch road engineering, this had led to asphalt mixtures being studied under specific conditions:

For example creep and wheel-trackings tests at 40°C and fatigue tests at 0°C and 20°C.

The method of testing is thus governed by the desired functional properties. When asphaltic concrete is used as a sea wall revetment, the functional properties and therefore the test conditions are different. Under normal circumstances, the asphalt layer must be stiff, so it does not noticeably creep on the slope. In addition, the material must be flexible, so irregular settlements in the subsoil can be followed without cracking. Under extreme conditions (super-storm), the asphalt must resist a particular number of wave impacts and water pressures. Resistance to wave impacts is increasingly regarded as the most relevant criterion. This has also resulted in extensive analysis of this aspect in the "Guidelines" [ref. 1].

3. MECHANICAL BEHAVIOUR OF HYDRAULIC ASPHALTIC CONCRETE.

Unlike in road engineering, a sea wall is designed to withstand failure with a limited number of load repetitions due to wave forces. In a super-storm there are a maximum of a few thousand load repetitions in a period of 36 hours. Super-storms statistically occur very rarely. The super-storm will occur between 0 and 10°C, the load frequency of the wave impact being between 1 and 10 Hz. [ref. 2].

There is little data in the literature on this specific fatigue behaviour ($N<10^4$). In order to simulate this behaviour to some extent in practice, force-controlled repetitive

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loading can be adopted in order to achieve genuine failure of the testspecimen. In addition, it is possible to obtain a good impression of the deformation of the various asphaltmixes.
The dynamic strength of hydraulic asphaltic concrete (as a measure of the resistance to failure) is an essential component in the design of asphaltic concrete revetments as described in the "Guidelines" [ref. 1]. A formula is derived for calculating the layer thickness on the basis of wave impact value and aphaltproperties:

$$h=0{,}75\cdot\sqrt[5]{\frac{27}{16}\cdot\frac{1}{(1-\nu^2)}\cdot\left(\frac{P}{\sigma_b}\right)^4\cdot\left(\frac{S}{c}\right)} \qquad (1)$$

The dominant influence of the bending tensile strength is evident. This strength depends on the number of times the material is loaded. The relationship is linear on double-logarithmic scales and is written as:

$$\mathrm{Log}(N_{fracture}) = \mathrm{Log}(k) - a*\mathrm{Log}(\sigma) \qquad (2)$$

The relationship between N and σ is thus determined by k and a.
For calculating a layer thickness under more than one wave impact, the wave-impact formula has been re-written as:

$$h=\sqrt[5]{\left[\frac{\sum_{i=1}^{j} n_i P_i^a}{k}\right]^{4/a} A} \qquad A=\frac{27S}{16(1-\upsilon^2)c} \qquad (3)$$

where the stress is represented by N, k and a.
No standard method for determining the bending tensile strength as stated in this formula is given. In the absence of better information, use has been made of results of fatigue testing as obtained in road engineering (for example the design nomographs from Shell). These fatigue results have

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mostly been obtained through standard four-point bending fatigue test. In the Netherlands, this test is carried out with long beams (450 mm), strain-controlled alternating stress being imposed. However, the long beams make simple sampling difficult, and a different method has therefore being sought. A three-point bending test was chosen as a starting point for research, as performed by Paulmann and Grätz at the Technical Institute of Darmstadt (Germany) [ref. 3]. The method consists in dynamic loading of a short beam in a simple three-point bending equipment.

4. DEVELOPMENT OF A THREE-POINT BENDING TEST (TPB-test).

4.1. Three-point bending test versus four-point bending test (FPB-test).

There is a preference for FPB-tests to study mechanical properties of asphalt, because of the constant moment and the zero transverse forcelevel in the middle-section of the beam, see figure 1.

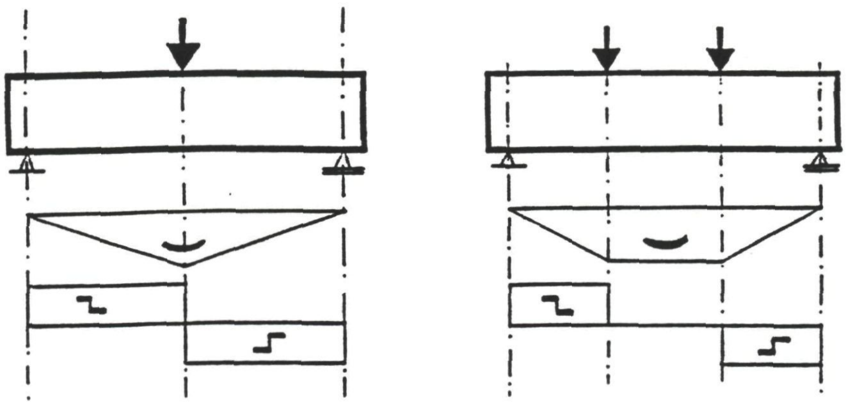

Fig. 1 Transverse force and moment lines

It has been found in studies on cement-bound materials [ref. 5] that the TPB-test results in a higher strength. The reason for this is thought to be that in the FPB-test approximately one third of the beam is available for the weakest point.

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However, the TPB-test has been chosen because of simple and representative sampling. This can only be achieved with core drilling. Because the dimensions of drilled cores are limited, a TPB-test, with short beams is a solution.
Because of the dominant influence of bending tensile strength in the design method, the TPB-test is carried out in a force-controlled manner with a non zero mean stress level (figure 3, 4). It is then possible to cause the beam to fail within a limited number of load repetitions (10^2 to 10^4), so that the relationship $N_{fracture}$ - σ can be determined. It is not possible to make a direct comparison with the standard FPB-test.

4.2 Experimental phase

The following were to be determined:

- the fatigue properties under repeated loading up to a number of $N=10^4$ at failure
- the stiffness modulus expressed as E_{dyn}
- the deformation during the fatigue test

It was decided to start with the same dimensions as in ref. 3. The dimensions of the testspecimen are 160*50*50 mm^3 and can be sawn out of drilled cores of dia. 200 mm (see fig. 2). The test was initally kept as simple as possible (see fig. 3 and 4).

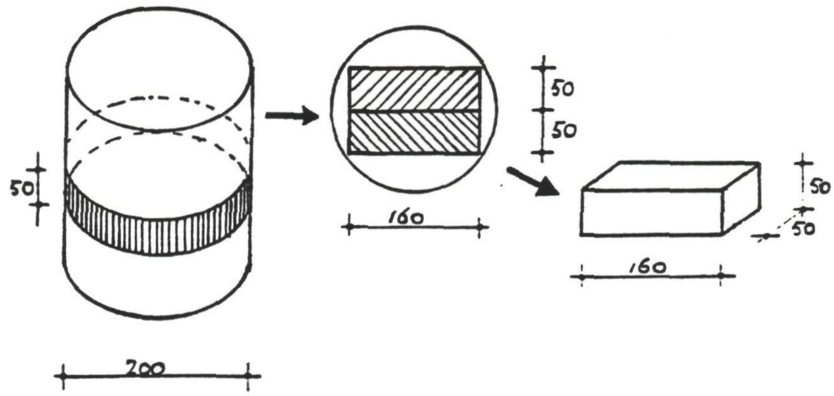
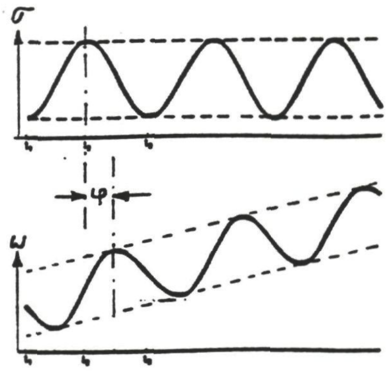


Fig. 2 Drilled core, slice and beam



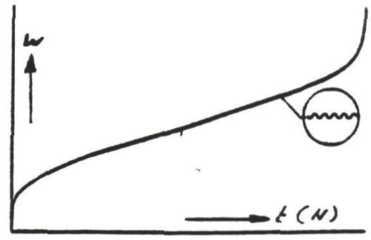


Fig.3 TPB-test load signal   Fig.4 TPB-test, bendingcurve

In a first series of tests the temperature was varied between 0 and 20°C and the frequency between 1 and 10 Hz. These tests (Figure 5) showed that it is possible to achieve a good relationship between bending stress and the number of load repetitions [ref. 6].

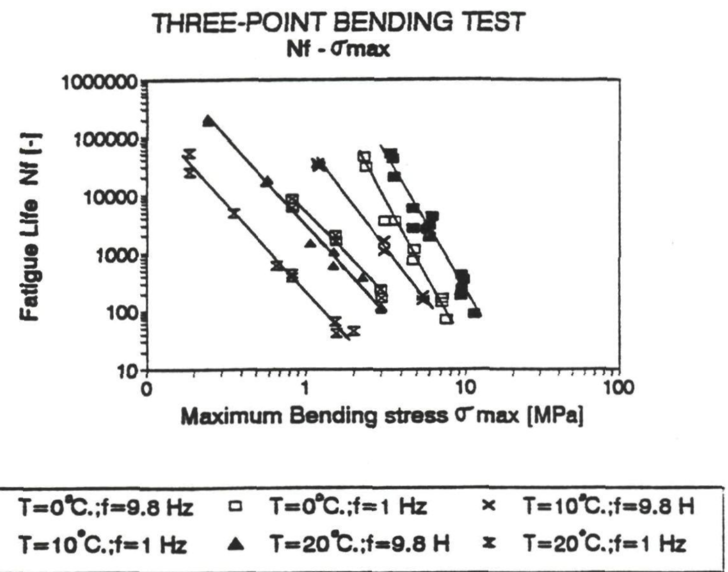


Fig. 5 N-σ relationship of short beams of hydraulic asphaltic concrete

The stiffness modulus was also calculated from the automatically recorded force and deflection signals. The theory of the FPB-test [ref. 7] was used for this purpose, the derived formulae having been adapted to a three-point bending system [ref. 8]. The stiffnesses obtained in this way were found to differ greatly from stiffnesses determined by the FPB-test on similar material. The reason may have been the dimensions of the testbeam, but also the fact that the deflection of the beam is a combination of increasing permanent deflection and a deflection amplitude (Figure 4). Because both signals are measured with one LVDT (set to a wide range for the total deflection), it is found that the deflection amplitude cannot be measured accurately.

4.3 Calibration testing

Because of the problems associated with stiffness, a limited calibration study was carried out [ref. 9]. This study consists of comparative measurements with FPB-tests and TPB-tests, examining in particular the effect of the test equipment, the beam length and the LVDT. Aluminium beams were used in the study and the stiffness was determined and compared with $E_{al} \approx 70{,}000$ MPa.

The mean conclusions are:

- the accuracy of the LVDT plays a major role.
- the way in which the beam is supported and how the force is applied are very influential.
- in the case of short beams (effective length = 100 mm) E_{al} is considerably lower than in the FPB-beams (effective length = 400 mm).

It should be noted that E_{al} is far higher than $E_{asphalt}$ and that the deflections were very small. In 1993 a calibration study will be carried out with epoxy beams with a stiffness comparable to asphaltic concrete. In addition, it will be examined through a theoretical study whether the use of the adapted FPB-formulae is correct or needs to be adjusted.

4.4 Final method

A final method was provisionally developed from the

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experimental phase and the calibration study.
Because the effective length of 100 mm in relation to the minimum dimension (50 mm) was very small, it was decided to take longer testspecimens. It was found possible to drill cores with a diameter of 250 mm. From one layer (= slice 50 mm in height), see fig. 2, it is possible to saw two testbeams 220 mm in length. In this way reasonably slender testbeams were obtained (220*50*50 mm^3), which are tested with an effective length of 200 mm. The effect of the transverse force then will be small [ref. 4]. It was decided that stiffness would only be measured at the start of the test with an accurate LVDT (small range). A small force amplitude is set which is maintained over a limited number of load repetitions. The fatigue is measured with a wide range LVDT. It will soon be possible to combine two LVDT's, so the variation in stiffness can also be measured during fatigue.

4.5 Provisional test specifications

Extensive test specifications were compiled to ensure that in future the tests are performed according to agreed procedures [ref. 10].
The specifications include:

- preparation of the testbeams
- the test equipment
- the test procedure
- data processing (with the formulae used)
- a detailed example

In this way an attempt is made to contribute towards a clear interpretation of test results.

5. TEST RESULTS

5.1 Locations

A number of hydraulic asphaltic revetments coverings were

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tested in order to examine their quality. The results of two revetments are presented here.

First of all a newly constructed revetment was studied. This was a test slope in the Delta Flume of the Voorst Hydraulics Laboratory (Figure 6). The test slope was constructed in 1991 to examine the effect of heavy wave impact on a sea wall body covered with asphalt [ref. 2].

A layer of asphaltic concrete was applied to a slope of 1:4 and compacted with vibrating rollers. In order to interpret the measured results of the construction (stresses, strains and displacements) it is important to know the mechanical properties of the asphalt.

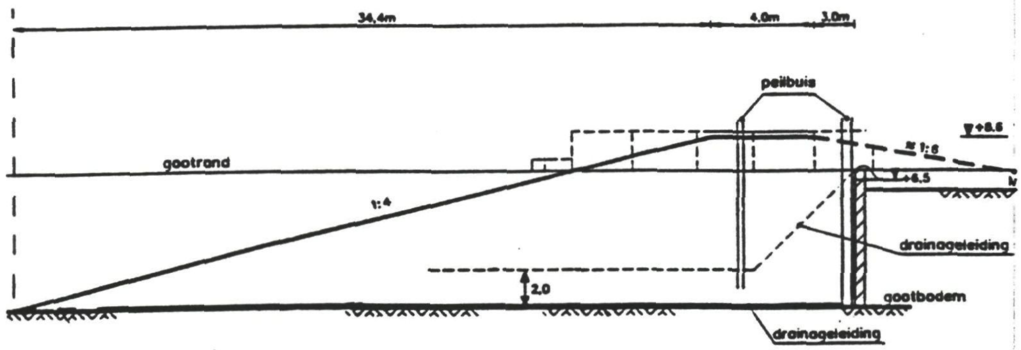

Fig. 6 Asphalt revetment of test slope in Delta Flume

The sea wall of the Boulevard in Vlissingen was protected in 1957 with an asphalt revetment consisting of two layers of asphaltic concrete (Figure 7). After more than 30 years service the mechanical quality needs to be established. An assessment can then be made on the safety, remaining service life and durability of the revetment.

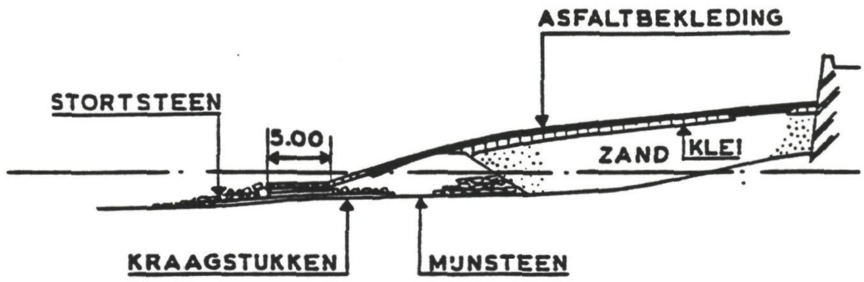

Fig. 7 Asphalt revetment on Boulevard de Ruyter in Vlissingen

Cores of 250 mm diameter were drilled from the two revetments. After the beams were wawn, the remaining parts of the slices were used to determine the standard properties:

Location		Delta Flume		Vlissingen top layer	
		av.	(s)	av.	(s)
Compo-sition:	stone fraction	49.1	0.7	46.5	3.6
	sand fraction	42.3	0.5	46.7	2.4
	filler fraction	8.6	0.3	6.8	2.0
	bitumen	6.6	0.1	7.5	0.7
Density:	specific density	2345	7	2287	84
	voids ratio	3.1	0.3	4.3	3.7
Bitumen quality:	penetration	74	6	74	16
	softening point	50.0	1.1	49.5	2.0
	penetration index	-0.3	0.1	-0.4	0.4

These results show that there are wide differences between the new and old revetment. Although the asphalt of Vlissingen is more than 30 years old, the mean binder quality is found to agree with new asphalt. More detailed research is needed to examine whether the method of recovery for these old types of

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asphalt is adequate and what the chemical/physical changes have been.

5.2 Stiffness modulus and phase angle

Four test conditions were chosen for testing the beams in the FPB-test:

	Temperature:	0	5	5	10	(°C)
	Frequency:	9.8	9.8	1.0	1.0	(Hz)

First of all the initial stiffness moduli and associated phase angles were measured by imposing a small load signal. The force amplitude was limited to a maximum of 400 N. The force and deflection signal was sampled five times over a total maximum number of load repetitions of 250, from which the average stiffness modulus and phase angle was calculated using Fourier transformation.

In order to examine whether the results of the Delta Flume are realistic, a comparison was made with similar results obtained with the standard FPB-test (Figures 8 and 9). This related to new hydraulic asphaltic concrete of a test segment of the West-Kapelle sea wall on which the E-dyn and ϕ were determined as a function of temperature and frequency [ref. 13].

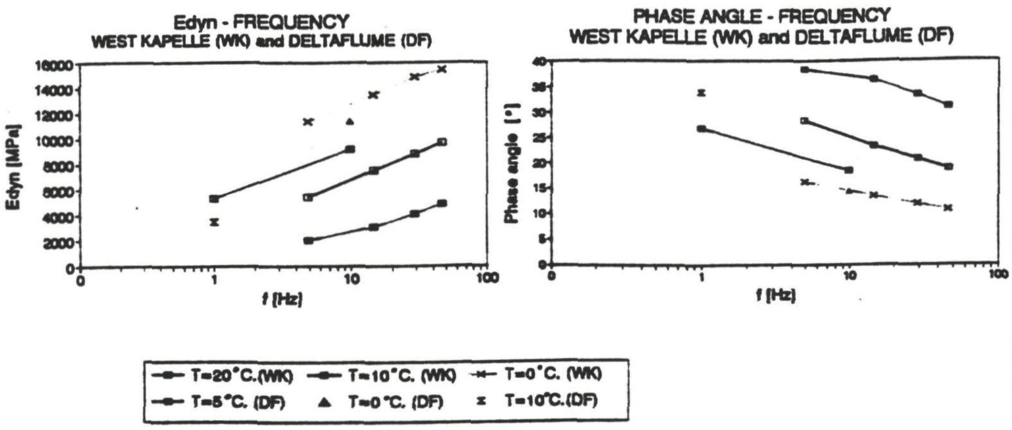

Fig. 8 Fig. 9

The measurements show that both test methods supply comparable results on new hydraulic asphaltic concrete. The data quoted above can now be used as reference values to test the results

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of older structures. Only the results of the top layer are given for the Vlissingen revetment because this mixture, like hydraulic asphaltic concrete, is a dense asphaltic concrete with crushed stone (Figures 10 and 11).

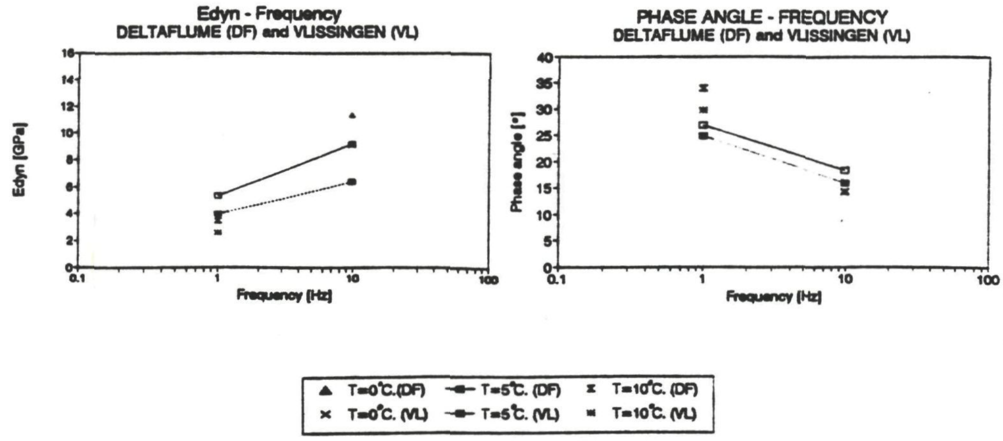
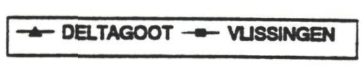


Fig. 10 Fig. 11

The results show that the old asphalt has a lower stiffness. It is not clear whether this is solely attributable to the higher bitumen content or also to a certain degree of stripping. The expected higher phase angle was not found but appears to be slightly lower. Detailed study of recovered binder (mechanical and chemical) is required in order to find an explanation. Another way of comparing the data is given in Figure 12, where the phase angle is plotted against the E modulus, so that all observations can be contained in one curve. The difference between the old and new asphalt, is very clear.



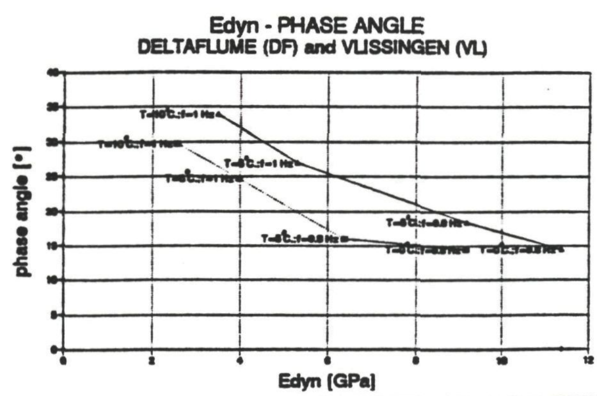


Figure 12.

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5.3 Dynamic strength

The same test conditions are retained for determining the dynamic strength. The force level (amplitude) is set so that the beams preferably fail after approx. 10^2, 10^3 and 10^4 load repetitions. In reality this proves difficult to manage, particularly in the case of old material.

Tests on the Delta Flume material provided the following results:

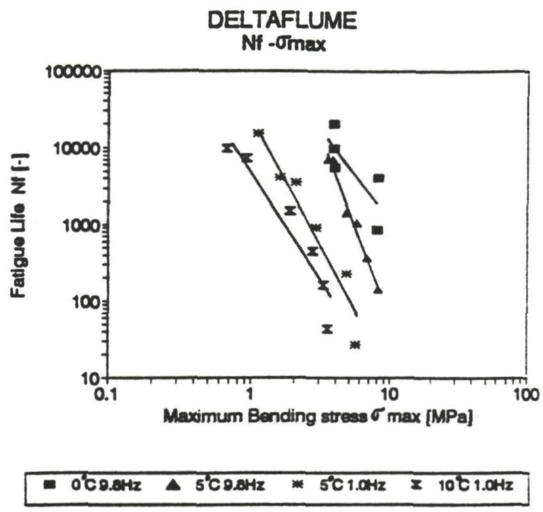

Fig. 13: N-σ relationship of hydraulic asphaltic concrete of Delta Channel

The regression and correlation coefficients were calculated in each test condition:

Temp.	Freq.	Log(k)	a	c.c.
0	9.8	5.4	2.3	0.80
5	9.8	6.4	4.7	0.99
5	1.0	4.4	3.5	0.97
10	1.0	3.7	3.0	0.96

A strong relationship is found in three out of four conditions (c.c. $\geq$ 0.96). It must be borne in mind that all the regressions have been calculated with a maximum of six results. One deviating result thus has a great effect.

Testing the old asphalt of Vlissingen is found to pose a number of problems. The quality sometimes proves to be so poor that a beam even can not be sawn. It is also found that beams are so weak that one load cycle already leads to failure.
In the beams that could be tested, the quality was found to be so variable (see table in 5.1) that it was pointless to determine the regression lines. The following results were obtained:

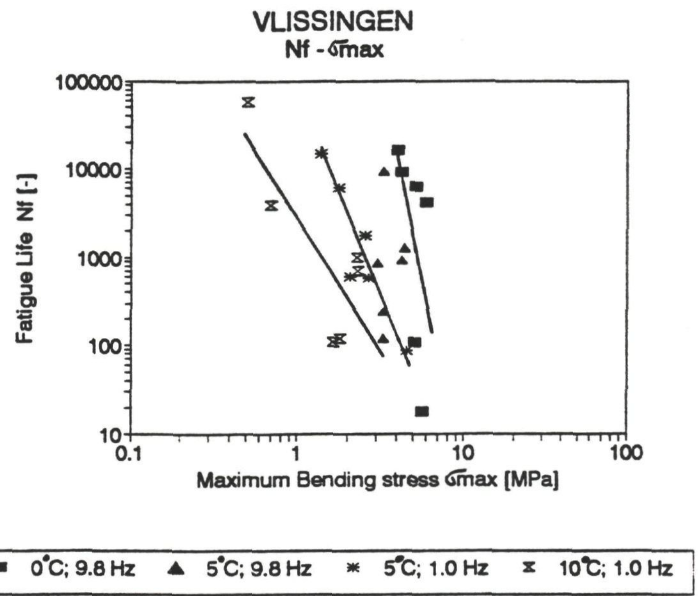

Fig. 14

The calculation of the regression lines provided the following results:

Temp.	Freq.	Log(k)	a	c.c.	n
0	9.8	9.6	9.9	0.54	6
5	9.8	-1.4	2.2	0.15	6
5	1.0	4.2	4.7	0.92	6
10	1.0	2.9	3.5	0.80	6

It is found from the correlation coefficients (and the negative value of Log(k)) that there is virtually no connection here. Each observation will in itself form part of a possible regression line; however, there will be several regression lines which depend (for example) on the density. Instead of statistically testing the coefficients of the old and new asphalt, the testing of the "old" data against the mean level of the "new" data is a possibility. This can be done by setting up a confidence interval of the "new" data for the regression line and examine what "old" data lie within this interval. Another advantage of this method is that observations at N = 0 (i.e. no beam to be tested) and N = 1 (i.e. fracture after one load repetition) can be included.

In Figure 15 the results of Vlissingen (Boulevard De Ruyter) are compared with the confidence interval of the regression line of the Delta Flume study. Out of 27 observations, six are found to lie outside the interval, indicating that the old asphalt is significantly poorer.

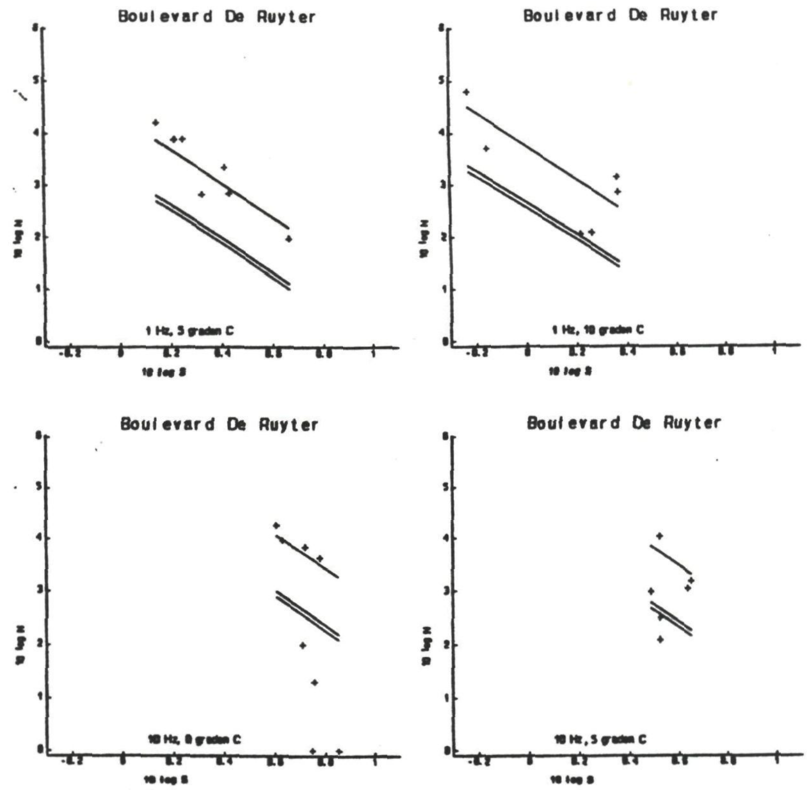

Fig. 15 Testing of old asphalt against regression interval of new asphalt (S = maximum bending stress)

6. CALCULATION OF STRUCTURAL VALUE.

A comparison of old and new materials alone does not lead to a statement on the residual value of the construction. It is necessary to examine what load an old revetment can withstand before failure occurs.

A possible procedure is indicated below in diagrammatic form (Figure 16):

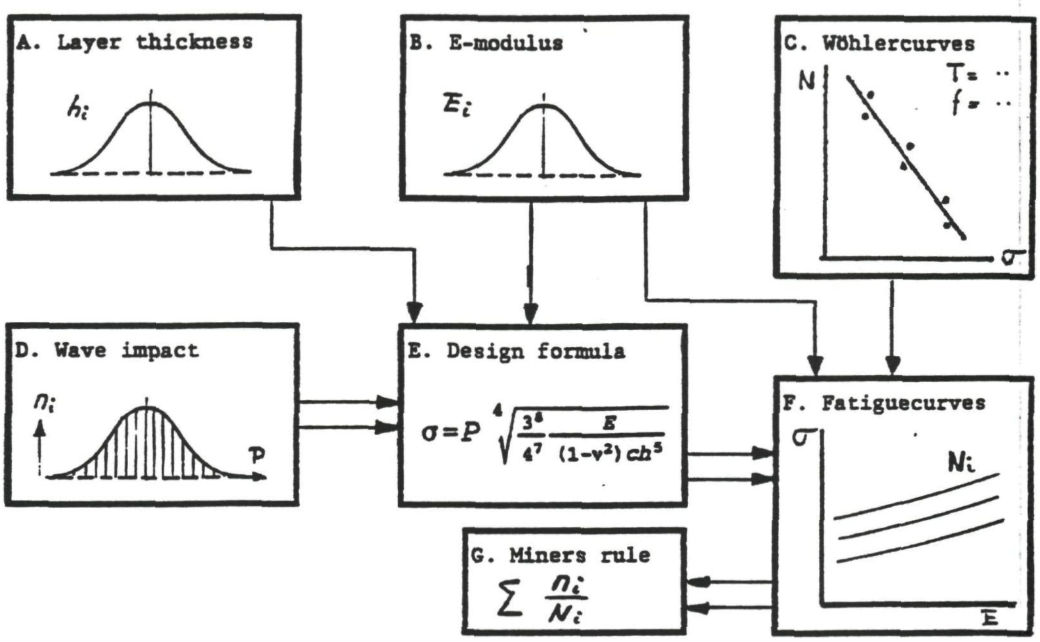

Fig. 16: Diagram for calculation of structural value.

Results have been obtained from testing the drilled cores on layer thickness (Fig. 16A), the E modulus (Fig. 16B) and the fatigue behaviour (Fig. 16C).

From the fatigue data (N-σ), known as the Wöhler curves, and the initial E moduli, F curves are derived (Fig. 16F).

With wave force distributions (Fig. 16D), design formula (Fig. 16E) from the Guidelines and layer thickness/E modulus data, the total scale of stress alternations can then be calculated. With this scale of stresses and E moduli as input in F curves, it is possible to determine the distributions of the permissible numbers of load repetitions (N_i). These numbers

can statistically be tested against the wave force spectrum (n_i) using Miner's rule.
By applying Miner's rule, the partial fatigue damage of each part of the stress spectrum can be calculated. Summation of the damage then leads to the Miner's sum, which can be tested against a standard to be specified.

7. CONCLUSIONS AND RECOMMENDATIONS

It seems to be possible to determine the quality of an asphaltic concrete revetment by drilling large (250 mm dia.) cylinders, sawing short beams and subjecting the beams to dynamic bending. Drilling cores have the great advantage that samples can be taken simply and non-selectively from the revetment.

The short beams can be dynamically tested in a simple three-point bending set-up, force-controlled repeated loading being found to be suitable for causing the fatigue failure of the testspecimens without creep having a great effect on fatigue. This conclusion applies to a number of load repetitions $< 10^4$.

Using this method it is possible to determine both stiffness modulus, phase angle and the relationship between stress and number of load repetitions as a function of temperature and frequency.

As a result of the absence of adequate measuring instruments and software, however, E and ϕ have to be measured separately from fatigue. Soon it will be possible to measure the variation in E/ϕ during fatigue.

Both with E/ϕ and with the fatigue data (N-σ), it is possible to test old material technologically, although a statistical model needs to be developed with which the "old" data can be tested against a confidence interval of the "new" data. For better interpretation it will be necessary to make

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a closer study of the quality of the binder during lifetime. This applies both to the recovery method and the chemical/physical change in the binder.

It is in principle possible from the total results of drilled cores (layer thickness, E/ϕ, N-σ) to calculate a structural value. For this purpose the load spectrum should be known and Miner's rule should be applied. It should then be calculated whether a revetment can still withstand a superstorm without failing.

Finally it is recommended that the test results should be linked to visual inspections, to be able to examine to what extent damage can be explained on the basis of materials testing.

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