PRELIMINARY STUDY OF PUR-REVETMENT'S APPLICATION

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Abstract: PUR-revetment is a newly developed method for hydraulic application. Its structure is similar to that of open stone asphalt revetment, but the crushed stones are glued by polyurethane (PUR) instead of bitumen. To study the feasibility of applying PUR-revetment, a research based on the comparisons between PUR-revetment and open stone asphalt revetment was carried out, for which, a standard four-point bending frequency sweep test, a standard monotonic three-point bending strength test, a porosity test, a stability on slope test, a wave run-up test, an interface permeability test, a relative resistance to abrasive action test and some calculations in GOLFKLAP were done. It suggests PUR-revetment is applicable in practice.

Keywords: PUR-revetment, PUR-stone, polyurethane, open stone asphalt revetment, bank protection

INTRODUCTION

During these years more and more attentions have been paid to the protections of coastal and riverine areas due to the global warming and climate change; the appearance of PUR-revetment is one of the results of these attentions. This research is a preliminary study of the feasibility of PUR-revetment's application.

Nowadays, various protection methods such as sediment supply, groynes, breakwaters and revetments have been applied to prevent bank and shore from erosions caused by waves and currents. A very simple example of a revetment is one layer of geotextile with crushed stones on top; besides loose rocks, other materials such as placed blocks, asphalt, grass and rigid structures are also popularly applied for revetments; they can be not only applied individually but also combined together. Recently polyurethane has been involved in the application of revetments as well.

Polyurethane (PUR) is a very well known material in plastic industry and applied for example in automotive, constructions, electronic segments as well as offshore oil and gas pipe coating industry. A special hydrophobic PUR-system (Elastocoast 6551/100) has been developed for revetment constructions in coastal protection: gravels of 20-60 mm are coated in a standard concrete mixer with about 1.8 % (by weight and depending on stone size) PUR; this PUR-stone mixture is then distributed on the slope as a 15-30 cm thick top layer of a revetment and starts to cure; one day later the PUR-stone is resilient and achieves its final strength after 2 days, namely a PUR-revetment is ready.

A PUR-revetment has a similar structure with that of open stone asphalt revetment (OSA revetment). Moreover, the structure of PUR-stone mixture is similar to that of open stone asphalt (OSA) as well. So this research is mainly based on the comparisons of PUR-stone to OSA and PUR-revetment to OSA revetment.

Some popular criterions of revetments and the comparisons of different applied materials are given in Table 1. In the column of PUR-stone, 'part of study' indicates the studied aspects in this research; the question mark means the aspect was not studied in this research. Seven experiments have been done in this study; they were (standard) four-point bending frequency sweep test, (standard) monotonic three-point bending strength test, porosity of PUR-stone test, stability of unhardened PUR-stone on slope test, permeability of interface between PUR-stone and geotextile test, wave run-up test and relative resistance of PUR-stone and other materials to abrasive action test; additionally, some calculations were made in computer program GOLFKLAP with the results of four-point frequency sweep test and three-point bending strength test to compare the minimum required layer thickness of PUR-revetment and OSA revetment at various wave impacts. At last, the final conclusions about the application of PUR-revetment were made.

METHODS

Among the seven experiments carried out in the study, the four-point bending frequency sweep test and monotonic three-point bending strength test were standard material property experiments; and the test results were applied in a computer program GOLFKLAP. The other 5 experiments were designed testes to study the performances of PUR-stone and PUR-revetment in hydraulic applications. In Table 2 a summary of the experiments done in the study is given.

Four-point Bending Frequency Sweep Test

The standard four-point bending frequency sweep test was carried out to obtain the stiffness of PUR-stone, which was necessary for the calculations in GOLFKLAP. The test set-up and applied apparatus are shown in Fig. 1 (in which the specimen on the apparatus was not PUR-stone).

The major set-up parameters of the test are given in Table 3; in which, 23 °C was chosen according to DIN EN ISO 291 (Normklima) for the convenience of comparison with

Table 1 Comparisons of different materials applied for revetments

Criterion Type	Loose rock	Placed block	Grass	Rigid structure	Asphalt	PUR-stone
Accessibility	-	+	+	-	+	part of study
Construction and maintenance	++	0	+	0	-	part of study
Costs	depends	depends	depends	depends	depends	depends
Flexibility for subsidence	++	+	++	-	+	?
Heavy loads	+	+	-	++	++	part of study
Landscape	depends	depends	depends	depends	depends	depends
Space required	0	0	-	++	0	0

Table 2 Summary of the 7 experiments carried out in the study

Experiment Type	Main Task	Main Apparatus	Specimens
Four-point bending frequency sweep test	Measured stiffness of PUR-stone at 5, 23, 35 and 50 °C, with frequencies of 0.5, 1, 2, 4, 8 and 10 Hz	A 4-point bending beam fatigue testing equipment, computer	Three 50x50x400 mm beams made of 10/14 mm black limestone and three 50x50x400 mm beams made of 8/11 mm yellow limestone
Monotonic three-point bending strength test	Measured tensile bending strength of PUR-stone at loads of 0.5 mm/min and 50 mm/min	A universal testing machine (UTM), computer	Six 50x50x400 mm beams made of 10/14 mm black limestone and six 50x50x400 mm beams made of 8/11 mm yellow limestone
Porosity test	Measured voids ratio of PUR-stone made of two different grading stones	Sealed wooden mould, scale	Three 25x25x25 cm PUR-stone samples made of 16/32 mm yellow limestone and three 25x25x25 cm PUR-stone samples made of 8/11 mm yellow limestone
Permeability test	Measured and compared the permeability of the interface between PUR-stone and geotextile under water pressure of 1, 2 and 3 m	Pump, steel pipes, basin, hydraulic pressure gauge and computer	20x20x10 cm, 20x20x20 cm and 20x20x30 cm PUR-stone samples made of 16/32 mm yellow limestone; 20x20x10 cm, 20x20x20 cm and 20x20x30 cm PUR-stone samples made of 8/11 mm yellow limestone
Wave run-up test	Measured the roughness factor of PUR-revetment at regular wave impacts	Flume, wave gauges and computers	A 1:3 slope of PUR-revetment made of 8/11 mm yellow limestone; A 1:3 slope of PUR-revetment made of 16/32 mm yellow limestone; A 1:3 smooth cement slope
Relative resistance to abrasive action test	Compared the resistance of several different materials against abrasive action	An concrete mixer, cement and abrasive materials (two sizes of granite)	2 PUR-stone specimens made of 8/11 mm yellow limestone, 2 PUR-stone specimens made of 16/32 mm yellow limestone, 3 aged open stone asphalt specimens, 3 artificial basalt specimens and a colloidal concrete specimen
Stability on a slope test	Measured the critical slope angles causing unhardened PUR-stone unstable on both woven and non-woven geotextile	A trolley, wood plate, crane, woven and non-woven geotextile and camera	Some bulk unhardened PUR-stone of 16/32 mm yellow limestone

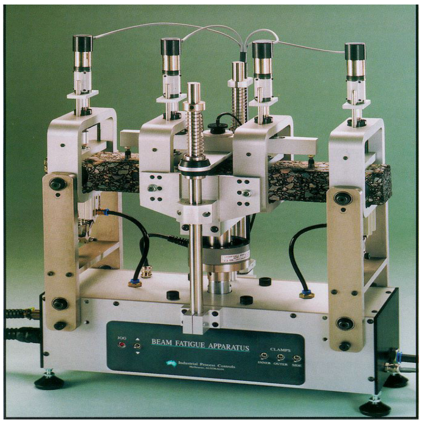

Figure 1 The 4-point bending frequency sweep test apparatus

the tests of polyurethane. The test procedure at a certain temperature of 5 °C is given as an example:

1. First all the beams were stored at 5 °C for at least 3 hours to assure the beams' temperature were stable.
2. After conditioning, one beam was fixed on the fatigue test equipment, of which the temperature was also set at 5 °C, and kept for at least half-hour to assure the whole system including the closed environment of the equipment and the tested beam itself stayed at 5 °C stably.
3. Then the test was carried out with a frequency sweep in the order of 10, 8, 4, 2, 1, 0.5 and 10 Hz again; the last measurement of 10 Hz was done for checking the reliability of the test.
4. After this beam was tested at all the 6 frequencies, it was taken out and put at room temperature; then another beam was tested.
5. After all the beams had been tested at 5 °C, the experiment was repeated at 23, 35 and 50 °C.

The test results are shown in Fig. 2 and Fig. 3; in which, 'B' indicates specimens made of 10/14 mm black limestone, 'Y' indicates specimens made of 8/11 mm yellow limestone.

Table 3 Major parameters of 4-point bending frequency sweep test

Temperatures	5, 23, 35 and 50 °C
Frequencies	0.5, 1, 2, 4, 8 and 10 Hz
Peak micro-strain	150
Conditioning cycles	100
Stop test after	100

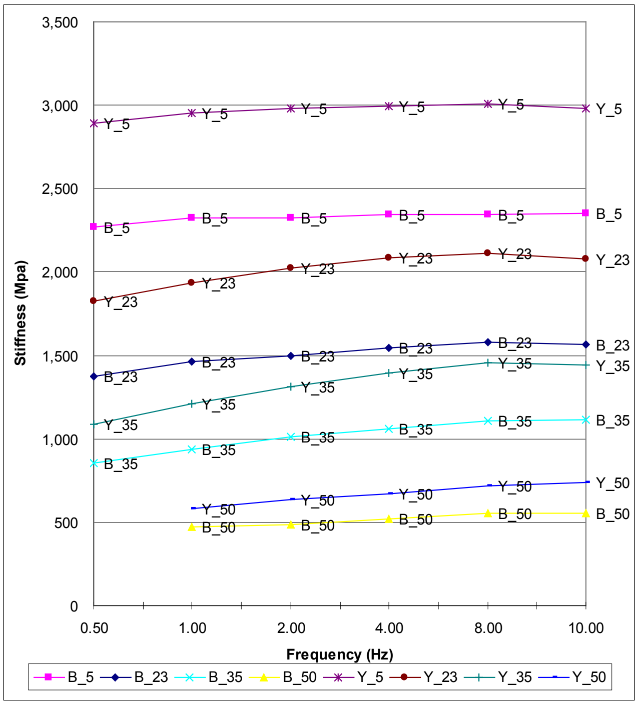

Figure 2 Stiffness results chart of 4-point bending frequency sweep test

The number after ‘B’ or ‘Y’ indicates the temperature (°C).

The graph in Fig. 2 suggested that the stiffness of PUR-stone was somehow independent of frequency at a certain temperature. However, the influence of temperature was considerable; the stiffness values varied between 500 Mpa and 3000 Mpa from 5 °C to 50 °C. Moreover, the stiffness decreased with the increase of the temperature; and the difference of stiffness between 23 °C and 35 °C was similar to that between 35 °C and 50 °C; while the difference of stiffness between 5 °C and 23 °C was obviously larger.

Additionally the stiffness of PUR-stone also varied with type of stone. In general, the stiffness of PUR-stone made of 8/11 mm yellow limestone was higher than that of the PUR-stone made of 10/14 mm black limestone; it perhaps was a result of the different quality or grading width of these two types of stones (the density of 8/11 mm yellow limestone was about 1464 kg/m^3 and that of the 10/14 mm black limestone was about 1380 kg/m^3). Further studies need to be done to understand how the stiffness of PUR-stone is influenced by different stone qualities and sizes.

It was also found the differences of stiffness between these two types of PUR-stone became smaller at higher temperatures. It perhaps indicated that at higher temperatures, the influence of stone types was smaller.

The other test result was phase angle which was defined in the test program as Φ=360fs, in which,

f=load frequency (Hz)
s=time lag between peak force and peak deflection at centre of beam (seconds)

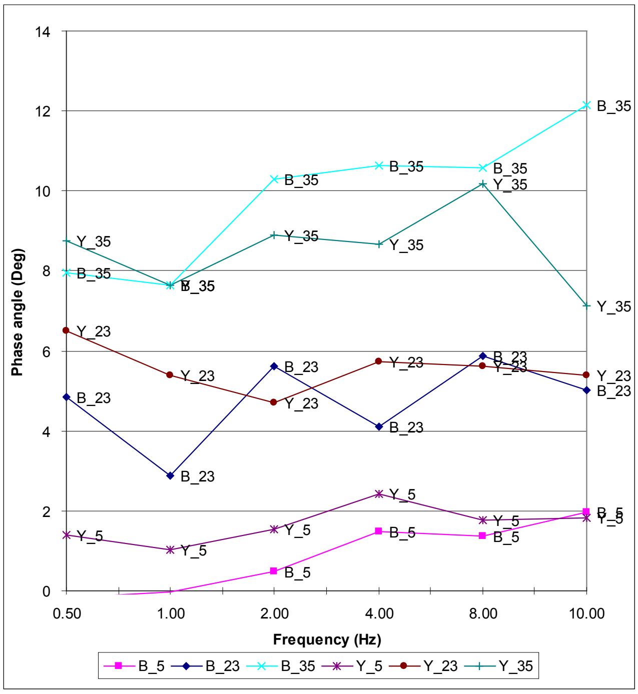

Figure 3 Phase angle results chart of 4-point bending frequency sweep test

Normally when the phase angle equals to zero degrees, the material has elastic behaviours; when it is between 0 and 90 degrees, the material is visco-elastic; when it is 90 degrees, the material is viscous.

In Fig. 3, the phase angles of two types of PUR-stone were close to each other. At 5, 23 and 35 °C both of their phase angles respectively remained stable basically around 1, 5 and 9 degrees with the margins of 2, 3 and 4 degrees. The results suggested PUR-stone was approximately a kind of elastic material at lower or normal temperatures. At 50 °C, the test results were neglected due to the error of measurements. The unreliable results at 50 °C were caused by the applied small forces which led to unsmooth force signals; consequently it was difficult for the program to derive reliable values of phase angle based on these scattering signals.

On the other hand, the increasing phase angles with increasing temperatures might also suggest that PUR-stone became more visco-elastic at higher temperatures.

The main results of the four-point frequency sweep test were: the stiffness of PUR-stone depended on the temperature, stone size and quality; at low temperature (5 °C), the stiffness of PUR-stone was lower than that of aged OSA (around 5000 Mpa); PUR-stone was more or less elastic.

Monotonic Three-point Bending Strength Test

The standard monotonic three-point bending strength test was a failure test carried out at room temperature (20-25 °C) to obtain the tensile strength (and other data such as tangent stiffness). Four 10/14 mm black limestone beams and four 8/11 mm yellow limestone beams were tested at 50 mm/minute; two 10/14 mm black limestone beams and two 8/11 mm yellow limestone beams were tested at 0.5 mm/minute.

The tested beam was located in a universal testing machine (UTM); the fixture included two cylindrical supports combined with two metal plates and one load roller combined with one metal plate (See Fig. 4). The metal plates were used as the contact interfaces between the beam and the supports or load cell; because the surfaces of the beams were too rough for the cylindrical supports and load cell.

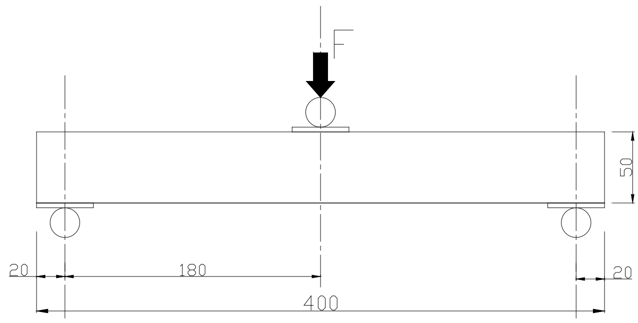

Figure 4 Sketch of the monotonic three-point bending strength test set-up

Table 4 Records of the monotonic three-point bending strength test

Samples	10/14 mm black limestone beams		8/11 mm yellow limestone beams	
	Placement	Broke in the middle	Placement	Broke in the middle
Sample 1	Top surface upward	No	Top surface lateral	Yes
Sample 2	Top surface lateral	Yes	Top surface lateral	No
Sample 3	Top surface lateral	No	Top surface lateral	No
Sample 4	Top surface lateral	Yes	Top surface lateral	No
Sample 5	Top surface lateral	Yes	Top surface lateral	Yes
Sample 6	Top surface lateral	Yes	Top surface lateral	Yes

Table 5 Results of the monotonic three-point bending strength test

Samples and loads	Max. load [kN]	Displacement [mm]	Sum Energy [J]	$E_{tangent}$ [Mpa]	σ [Mpa]
Black, 10/14 mm, 50 mm/min, average of 4 beams	0.31	0.85	0.95	800.43	2.66
Black, 10/14 mm, 0.5 mm/min, average of 2 beams	0.26	1.27	0.94	615.77	2.23
Yellow, 8/11 mm, 50 mm/min, average of 4 beams	0.36	1.12	0.86	934.75	3.15
Yellow, 8/11 mm, 0.5 mm/min, average of 2 beams	0.26	1.45	1.11	686.78	2.24
Black, 10/14 mm, average of all 6 beams	0.29	0.99	0.95	738.88	2.51
Yellow, 8/11 mm, average of all 6 beams	0.33	1.23	0.95	852.09	2.84

In the progress of the test, the beams were numbered and their performances were recorded by words and photos; the photos of broken cross sections and broken positions were also taken. At the load of 50 mm/min, the beams bent a little at first and then broke suddenly after less than 20 seconds; at the load of 0.5 mm/min, the beams broke suddenly as well after about 20 minutes since the beginning of the tests. The details are shown in Table 4.

The test results are given in Table 5. Generally, the strength of 8/11 mm yellow limestone beams was larger than that of 10/14 mm black limestone beams; besides, the strength at higher loading speed was larger than that at lower loading speed.

Moreover, it was found during the test that sometimes the strength of PUR-stone did not depend merely on the bonding force of polyurethane between stones. In the test, yellow beam 6 was protected particularly from being damaged by the underneath metal part of the equipment frame when the beam was broke and fell down; then the cross section was observed and several stones were found broken into two parts with intact bonding points (see Fig. 5). So it was concluded that the strength of bonding points sometimes was even bigger than the strength of stones.

Figure 5 Broken stones at the broken cross section of yellow beam 6 in the monotonic three-point bending strength test

The results of monotonic three-point bending strength test suggested that the strength of PUR-stone depended on the stone size and quality; the different bonding connections (structures) perhaps influenced the performance of PUR-stone. But the strength of PUR-stone was certainly higher than that of OSA which was around or less than 1 Mpa.

Porosity Test

Voids ratio influences the resistance to abrasion, the durability and other properties of a material. So a porosity test was done with 6 PUR-stone specimens and the volume of pores, namely the voids ratio, VIM was given by,

$VIM=100(d_m-d_a)/d_m$ vol %

In which,

d_m=density of the mixture without voids (kg/m^3)
d_a=density of the mixure with voids (kg/m^3)

(The weight of polyurethane can be neglected)

In the test, in order to obtain the density of PUR-stone specimens without voids, the specimens were put into the water to get the volume of the specimens without voids by measuring the differences of weights.

The results were calculated by average values of the test data. According to the test results, there was no obvious difference of porosity between the PUR-stone specimens made of 16/32 mm yellow limestone and the PUR-stone specimens made of 8/11 mm yellow limestone (see Table 6). In another word, the porosity of PUR-stone was not quite relevant with the stone size and grading width, at least for grading width of 8/11 mm and 16/32 mm. This conclusion was an useful reference for making conclusions of permeability test.

Table 6 Results of the porosity test

Specimens	B_1	B_2	B_3	S_1	S_2	S_3
D_d (kg/m^3)	1463	1427	1475	1425	1382	1393
D_w (kg/m^3)	1912	1889	1919	1878	1852	1858
Porosity (-)	0.45	0.46	0.44	0.45	0.47	0.47

B_{number}=the symbol of 16/32 mm yellow limestone specimen
S_{number}=the symbol of 8/11 mm yellow limestone specimen
D_d=dry bulk density
D_w=wet bulk density

The Stability of bulk Unhardened PUR-stone On Slope Test

The stability on slope test was designed to know how stable a pile of bulk unhardened PUR-stone was on a slope with a certain angle; because the major way of constructing PUR-revetment was tumbling the mixture and spreading it onto the slope. The interface applied in the test between PUR-stone and the wooden plate slope was two different types of geotextile—woven and non-woven. After the unhardened PUR-stone had been put onto the slope, the incline was adjusted gradually and smoothly in less than one minute so as to avoid the influence of different hard extents (started at 0 degrees at a speed of one degree per two seconds). The test set-up is shown in Fig. 6, in which, the camera was used to record the slope angles and time periods.

In the first test, a pile of bulk PUR-stone was tested on a piece of woven geotextile first and then tested again on a piece of non-woven geotextile; and this applied PUR-stone was tested about 10-15 minutes after being produced. To avoid the error due to the different hard extents of PUR-stone on the first tested geotextile and the second tested geotextile, the test was repeated by testing on the non-woven geotextile first and on the woven geotextile second; besides, the PUR-stone was tested directly after being produced in the second test to check whether there was obvi-

Figure 6 Stability of unhardened PUR-stone on slope test set-up

ous influence of different hard extent. In these two tests, when the bulk PUR-stone started to move, it was considered as 'begin failure'; when the bulk PUR-stone spread completely on the slope, it was considered as 'completely failure'.

The test results are given in Table 7. It indicated that on the woven geotextile, the bulk PUR-stone started failure at about 15 degrees slope and completely failed at about 20 degrees slope; on the non-woven geotextile, the bulk PUR-stone started failure at about 27 degrees incline and completely failed at about 34 degrees incline.

Table 7 Results of stability on slope test

First test			
Woven	Start	Begin failure	Completely failure
Time	16:15:40	16:16:14	16:16:30
Angle (deg.)	0.0	14.8	18.9
Non-woven	Start	Begin failure	Completely failure
Time	16:21:54	16:22:56	16:23:38
Angle (deg.)	0.0	27.2	34.7
Second test			
Woven	Start	Begin failure	Completely failure
Time	17:53:58	17:54:32	17:54:46
Angle (deg.)	0.0	15.6	21.1
Non-woven	Start	Begin failure	Completely failure
Time	17:45:34	17:46:30	17:46:50
Angle (deg.)	0.0	27.2	33.0

The tests results suggested the types of geotextile influenced the stability of bulk unhardened PUR-stone on a slope; and bulk unhardened PUR-stone stayed more stable on a non-woven geotextile. Additionally, there was almost no difference between the first test results and the second test results, it indicated that a short delay between the production and the application had less influence as long as the interval was less than the requirement period (about 20 minutes). Considering the angles of 1:3 slope and 1:4 slope, which are popular slope angles of revetments, are about 18 degrees and 14 degrees, no big problem would be expected in the application of PUR-stone on revetments.

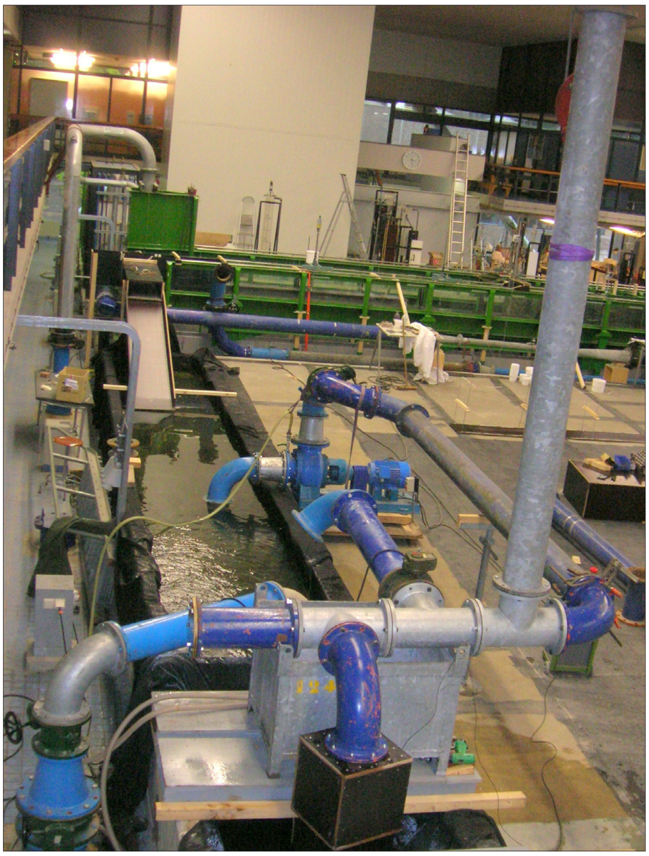

Figure 7 Permeability test set-up

Permeability of the Interface Between PUR-stone and Geotextile

Although the permeability of PUR-stone had already been proved to be significantly high, the extra polyurethane flowing onto the geotextile during producing should still be concerned since it might block the interface to some extent and then consequently influenced the permeability as well as stability of the whole structure. So this permeability test was designed to study the permeability of the interface between PUR-stone and geotextile. This experiment was carried out with different thick specimens made of two sizes' stones at various water pressures. The permeability coefficient in this study was defined as,

K=Q/A (m/s)

In which,

K=the permeability coefficient,
Q=the water discharge,
A=the cross section area of flow path

Six different specimens were produced with PUR-stone, woven geotextile and wooden moulds. Every specimen was produced in a wooden mould with a piece of geotextile at bottom and was tested together with that geotextile. The test system shown in Fig. 7 was set up to measure the permeability of PUR-stone with geotextile at three different water pressures of 1, 2 and 3 m. The water pressure was generated by a pump and a vertical steel pipe. Various water pressures from 0.8 m to more than 3 m could be obtained by pumping different amounts of water into the vertical pipe; the amount of the water passing through a specimen could be calculated by measuring the variance of water volume in a basin of 21.9x1.35 m^2. For each specimen and water head, one test was done twice.

It was obviously shown in Fig. 8 the blocking situation of specimens made of 16/32 mm yellow limestone was much more serious than those made of 8/11 mm yellow limestone. It was probably due to the more contact points and surfaces between stones and polyurethane for the

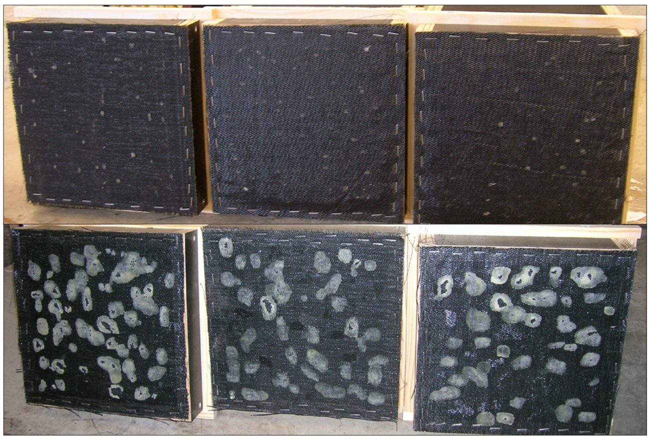

Figure 8 Blocking extents of 8/11 mm stone specimens (up) and 16/32 mm stone specimens (down)

specimens made of 8/11 mm limestone; and the flow path of polyurethane in a specimen made of smaller stones was believed to be much longer than that in a specimen made of larger stones.

The summary graph of test results is shown in Fig. 9; in which, '8/11 mm, 10 cm' meant 10 cm specimen made of 8/11 mm yellow limestone; the rest were analogically defined.

Fig. 9 suggests:

1. For 10 cm thickness, the permeability of the specimen made of 8/11 mm yellow limestone was similar with that of the specimen made of 16/32 mm yellow limestone.
2. For 20 cm and 30 cm thickness, the permeability of the specimens made of 16/32 mm yellow limestone was much bigger than that of the specimens made of 8/11 mm yellow limestone.
3. The differences of permeability between small stone specimens of various thickness were big than those of the different thick big stone specimens. So it was believed that small stone specimens were more sensitive to the changes of thickness.
4. For small stones, the permeability of 20 cm specimen was bigger than that of 30 cm specimen, it was reasonable. However for big stones, the permeability of 20 cm specimen was a little bit smaller than that of 30 cm specimen.

There were several possible reasons of the phenomenon described in item 4. On one hand, when the specimens were produced, some polyurethanes flow down to the surface of geotextile and block the geotextile to some extent; so the permeability could be considerably influenced by these blocking points; moreover, this kind of situation of the big stone specimen was much more severe than the situation of the small stone specimen, and might cause the permeability of 20 cm big stone specimen to be obviously bigger than that of 30 cm big stone specimen. But on the other hand, the geotextile of the three big stone specimens were peeled off and compared together after the test; it was found that the polyurethane's amount on the geotextile of 20 cm specimen almost equalled to that on the geotextile of 30 cm specimen. Besides, it was also possible that when the thickness was larger than 20 cm, the permeability of the specimens made of bigger stones perhaps maintained stable or namely reached the limitation. Furthermore, the measuring error might also influence the test results especially for the big stone specimens; because the water discharge was bigger and so the waves in the basin were bigger which caused bigger measuring errors. In a word, it was hard to judge the influence extent of the extra polyurethanes based on the results obtained from this test.

The conclusions of the permeability test were: for different

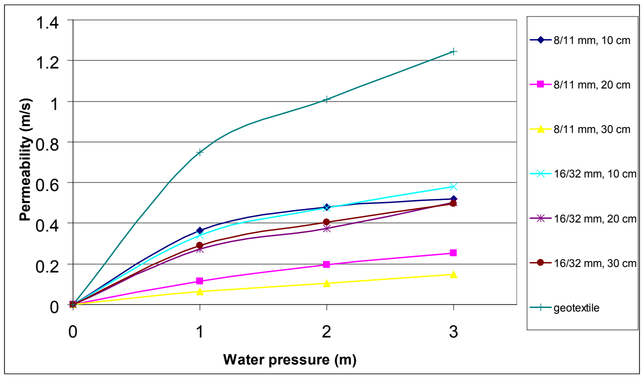

Figure 9 Summary graph of permeability test results

thickness, the permeability of the interface between PUR-stone and geotextile was sensitive to the stone size; but the influence of the extra polyurethane on geotextile should be further studied.

Wave Run-up Test

The high permeability of PUR-stone can probably reduce the wave run-up (wave loads) on the revetment and this can be helpful to decrease the cost of the structure. So it is meaningful to design an experiment to make a quantitative analysis of the reductive effect. For that purpose, two experiments were done with two PUR-stone slopes, and one test was done with a smooth slope in a flume. The wave run-up was measured; then the roughness factor was obtained and evaluated by comparison with the roughness factor of other materials such as open stone asphalt.

The first test was carried out on an existing smooth cement slope in the flume, the second test with PUR-stone made of 16/32 mm yellow limestone and the third test with PUR-stone made of 8/11 mm yellow limestone were done in a wooden slope mould filled with sands, on which a piece of geotextile was placed and the top layer on the geotextile was PUR-stone; the sizes of the PUR-stone specimens were

Figure 10 Specimens applied for wave run-up test

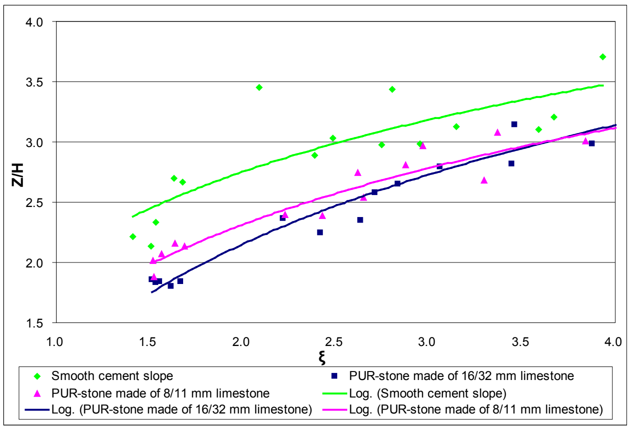

Figure 11 Results of wave run-up test (Z/H- ξ)

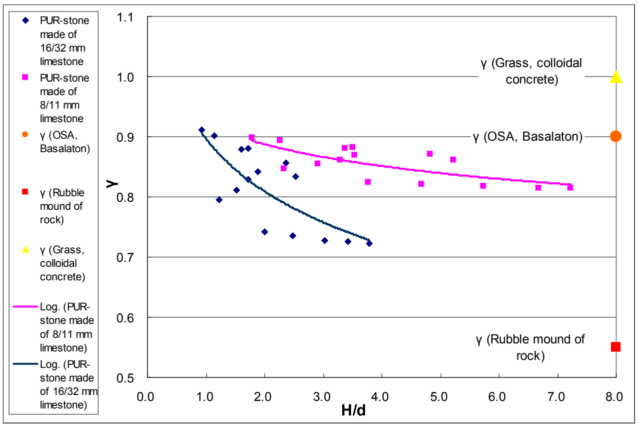

Figure 12 Results of wave run-up test (γ-H/d)

about 210 x 75 x 10 cm (for 8/11 mm yellow limestone) and about 210 x 75 x 15 cm (for 16/32 mm yellow limestone) (see Fig. 10). Different regular wave loads (ξ=1.5-4, H/L=0.004-0.03; $\xi=\tan(\alpha)/\mathrm{sqrt}(H/L_0)$, in which α=slope angle) were applied and the wave run-up was recorded by counting the run-up heights of ten continuous waves on the slope; for instance, if the highest point of one wave reached the middle area between the sixth line and the seventh line, 65 cm was recorded. At last, the results of these three tests were combined to obtain the reduction coefficients and roughness factor of PUR-stone.

The test results are shown in Fig. 11; in which, the horizontal axis is breaker parameter (ξ) and the vertical axis is the ratio between wave run-up height (Z) and wave height (H). Then the reduction coefficients of PUR-stone were obtained by comparing the values of Z/H between smooth slope and PUR-stone slopes. At last the roughness factor (γ) was calculated; the roughness factor of PUR-stone specimen made of 16/32 mm yellow limestone varied from about 0.7 to 0.9; the roughness factor of PUR-stone specimen made of 8/11 mm yellow limestone varied from about 0.8 to 0.9 (see Fig. 12).

In the test, it was also found under impacts of plunging waves (ξ=1.5-3), the reductive effects of PUR-stone specimen made of 16/32 mm yellow limestone was better than that of PUR-stone specimen made of 8/11 mm yellow limestone (see Fig. 11). This phenomenon was perhaps due to the higher permeability of PUR-stone specimen made of 16/32 mm yellow limestone (see Fig. 9); because the type of plunging wave was different from that of surging wave, it led to different impacting effect and so the permeability of the top layer probably had bigger positive influence to the wave run-up reductive effect at impacts of plunging waves compared to the situation of surging waves. This point might also explain why the blue trendline of PUR-stone made of 16/32 mm limestone dropped rapidly than the pink trendline of PUR-stone made of 8/11 mm limestone in Fig. 11 considering most of the applied higher waves were plunging waves.

Considering the roughness factor of open stone asphalt is about 0.9, the wave run-up reduction ability of PUR-stone is better than that of open stone asphalt; in Fig. 11, the roughness factors of grass, colloidal concrete, open stone asphalt, basalaton and rubble mound of rock are included for reference. By comparisons, the test results suggested the roughness factor of PUR-stone was more or less lower than all the other materials except rubble mound of rock.

Relative Resistance to Abrasive Action Test

Since the strength of PUR-stone is much higher than that of open stone asphalt, the erosion of wave impacts is probably not a major issue for PUR-stone. Nevertheless, the influences of sands and rocks in the currents should be concerned since the crash and abrasion may lead to failures.

A relative comparison method was chosen because it fit the target of this project and could provide intuitional results. The test was done in a concrete mixer, of which the inboard surface of container was covered with different specimens, which were two PUR-stone discs made of 16/32 mm yellow limestone, two PUR-stone discs made of 8/11 mm limestone, three artificial basalt discs, one colloidal concrete disc and three open stone asphalt discs; the thickness of all these discs was about 10 cm. By rotating the container filled with water and two sizes of granite stones which were applied as abrasive materials, the relative abraded extents of the specimens were observed after two days' testing (see Fig. 13).

Figure 13 Set-up of relative resistance to abrasive action test

- Artificial basalt specimens

There was almost no obvious abraded situation observed on the surface of all the three artificial basalt specimens; only few cement was eroded, some parts of the small stones on top were exposed and round; a corner of one specimen had a small abraded hole.

- Colloidal concrete specimen

The colloidal cement on the surface of the specimen was completely moved away; the aggregates on the top were exposed, round and slick; but the whole surface of the specimen still kept almost flat and no obvious hole was observed. In another word, only few stones was lost. On the surface, the distance between the lowest point and highest point was less than 1 cm. Most of the gaps among the aggregates on the surface were filled by the small abrasive materials; due to the strength of granite, it might reduce the abrasive effect to some extent.

- PUR-stone specimens made of 8/11 mm yellow limestone

Some stones were moved away from the specimens and mixed with the abrasive materials in the water; the surfaces of two specimens were uneven, the stones on top were round and slick; lots of abrasive materials were found in the gaps as well; besides, by the feeling of touch, it was believed there was almost no polyurethane covering around the stones on surface. The deepest holes of the two specimens were about -3.5 cm, ('-' means below the surface level of basalt specimens, hereinafter the same), the rest points varied from -0.5 to -2.5 cm, the average surface level was about -1.5 cm.

- PUR-stone specimens made of 16/32 mm yellow limestone

Some stones were stripped off and mixed with the abrasive materials; the surfaces were quite uneven and the stones on top were round and slick, which is similar to the situations of specimens made of 8/11 mm yellow limestone. Some abrasive stones were found in the gaps; there was almost no polyurethane covering around the top stones. The deepest holes of the two specimens were about -3.5 cm, the rest points varied from 0 to -3 cm, the average surface level was about -2 cm.

- Open stone asphalt specimens

Lots of aggregates were stripped off and mixed with the abrasive materials in the water; the surfaces of the specimens were considerably uneven, the exposed stones on top were slick and round; there were still a little bit asphalt left but not many abrasive materials were found among the stones due to the big gaps. Two deepest holes of -4.5 cm and -5 cm were observed, even the cement and wood plate at the bottom were exposed and visible. The rest points varied from -4 to -1 cm.

The test results suggested the artificial basalt specimens were strongest. The abraded degrees of PUR-stone specimens were between those of colloidal concrete specimen and open stone asphalt specimens (see Fig. 14, 15). The surfaces of all the four PUR-stone specimens were rough and uneven; some stones were stripped off and mixed with the abrasive materials. Many abrasive materials were found in the gaps; besides, by the feeling of touch, it was believed there was no polyurethane around the stones on the surface of the specimens. The open stone asphalt specimens were abraded most seriously. A lot of asphalt and aggregates were moved away and two of the three specimens were considerably damaged; even the white wooden plate at bottom could be observed in one of them. Besides, only a few small abrasive materials were found probably due to the bigger gaps. One of the three OSA specimens had less erosion and more abrasive materials among the gaps. It was probably because it was located between the artificial basalt specimen and the colloidal concrete specimen which were both relatively much stronger than open stone asphalt; so the abrasive action on this OSA specimen was more or less weakened.

Figure 14 Abrasive test results of OSA, basalt and PUR-stone discs

Figure 15 Abrasive test results of PUR-stone specimens made of 8/11 mm limestone and 16/32 mm limestone

One point should be concerned when comparing PUR-stone specimens and open stone asphalt specimens. The PUR-stone specimens were tested directly at about 50 days after the production; but the open stone asphalt specimens were sawed from the samples collected from a dike which was constructed at least 20 years ago which means the properties of the tested OSA specimens were certainly different with the properties of fresh OSA.

The Application of GOLFKLAP

According to 'Dutch Guidelines for the Assessment of the Safety of Dikes 2004', the investigation of asphalt revetments in respect of mechanism consists of a comparison between the actual layer thickness and required layer thickness. Two methods have been developed for obtaining the required layer thickness (a simplified and a more detailed method); the simplified one is to determine the required thickness from the graph shown in Fig. 16 which was derived by previous computer programs and relative data; the more detailed one is carried out using the computer program GOLFKLAP of which the latest version is 1.2. Table 9 shows for what combinations of age and mortar percentage the simplified method is applicable (Step 3) and

Table 9 Applicability's requirement of aged open stone asphalt

Negative deviation relative to mortar content agreed when laying [percentage by mass]	Age (years) 0 - 5	6 - 10	11 - 15	16 - 20	> 20
0 - 0,5	3	3	3	3	4
0,6 - 1,0	3	3	3	4	4
1,1 - 1,5	3	3	4	4	4
1,6 - 2,0	3	4	4	4	4
> 2,0	4	4	4	4	4

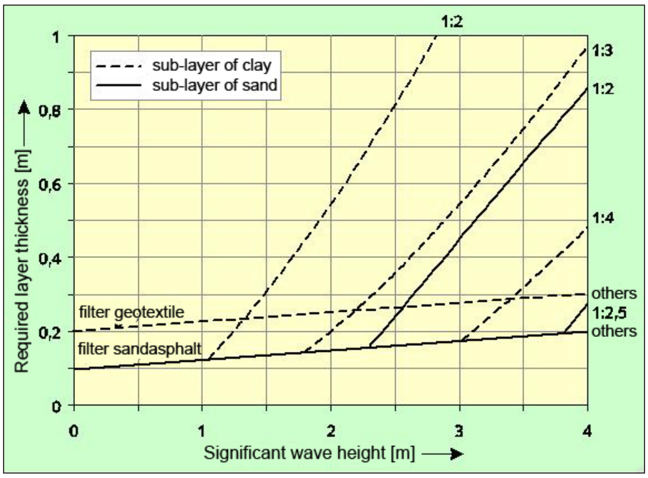

Figure 16 Design graph of asphalt revetment

for what combinations the detailed method must be applied straightaway (Step 4); in which, the quantity of asphalt mortar used is taken as an indicator of the quality of open stone asphalt, because this determines how thick and durably the stones are enclosed.

In this project, fresh OSA and aged OSA were compared to fresh PUR-stone respectively. According to Table 9, step 3 was applied to fresh OSA and step 4 was applied to aged OSA (in operation for more than 20 years) based on the test data provided by Road and Railway Engineering Section, TU Delft.

Considering the similar structure of PUR-stone and OSA as well as the same structure of PUR-revetment and OSA revetment, it was believed to be feasible to apply GOLFKLAP to PUR-revetment; besides, most of the necessary mechanical data of PUR-stone for the calculations in GOLFKLAP had already been obtained from the previous four-point bending frequency sweep test and three-point bending strength test. So step 4 was decided to apply to PUR-revetment. Additionally, the calculations of GOLFKLAP needs fatigue line, but at that moment the fatigue property and the fatigue line of PUR-stone was still unknown. So in this study, the fatigue line of PUR-stone was assumed based on the fatigue line of aged OSA; and this assumption was believed to be very conservative because from the four-point bending frequency sweep test results it was known already PUR-stone was more or less elastic.

GOLFKLAP is a computer program for the design and evaluation of an asphalt revetment at wave impacts. It calculates the bending stress in the revetment due to wave loads and compares it with the failure stress to verify whether the construction will yield. To calculate this bending stress in GOLFKLAP, the revetment is schematized as an elastic beam supported by small springs; so the structure can be characterized by the layer thickness, the stiffness modulus, the fatigue strength of the material and the modulus of subgrade reaction; the wave impacts are schematized as a series of triangular loads on the layer (see Fig. 17).

In this study, the minimum required layer thickness of the

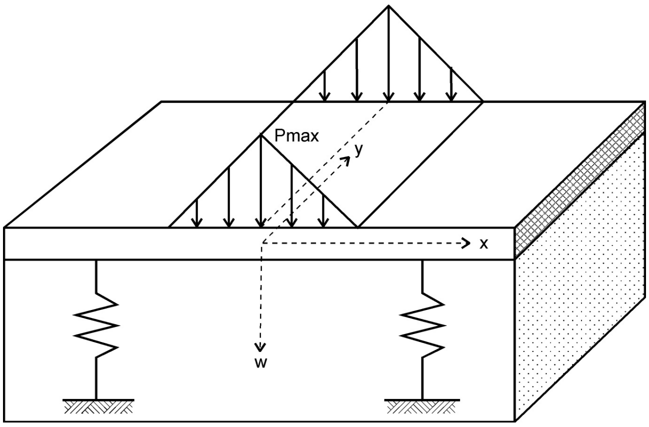

Figure 17 Schematization of the revetment in GOLFKLAP

Table 10 Major input parameters in GOLFKLAP

	Fresh PUR-stone	Aged OSA
Slope inclination	0.33	0.33
Bearing capacity of sub-layer (Mpa/m)	30 (clay)	30 (clay)
Stiffness (Mpa)	3000	4500
Poisson	0.35	0.35
Water depth (m-NAP)	10	10
a	6	6
log(k)	3.3	1

Table 11 Summary of the layer thickness comparison results

H_s	T_g	Thickness (m)		
(m)	(s)	Fresh PUR-stone	Fresh OSA	Aged OSA
2.5	5.53	0.21	0.36	0.98
3	6.06	0.31	0.54	1.35
3.5	6.55	0.43	0.75	1.77
4	7	0.56	0.97	2.2

revetment was considered as the parameter for comparison. The minimum required thickness meant the minimum practical layer thickness or the layer thickness when the value of miner sum, which was the output data of GOLFKLAP, was equal to 1; because the revetment would probably fail when the value of miner sum was larger than 1.

In Fig. 16, the horizontal axis indicates the significant wave heights, the vertical axis indicates the thickness of OSA layer. Two kinds of sub-layer are available for reference, sand and clay; for each sub-layer, several inclination curves or lines are provided for getting the minimum required layer thickness based on a certain significant wave height. In this study, only one sub-layer (clay) and one inclination (1:3) were applied. The results obtained from Fig. 16 are included in Table 11.

The minimum required thicknesses of PUR-stone and aged OSA were calculated in GOLFKLAP 1.2. The major input parameters are provided in Table 10; in which, the stiffness of aged OSA was obtained from the previous test results carried out in the Road and Railway Engineering lab of TU Delft, 'a' and 'log(k)' are coefficient and intercept of the fatigue curve.

In Table 11, a summary of the minimum required layer thicknesses of fresh PUR-stone, fresh OSA and aged OSA at various wave impacts (significant wave heights) are given. Lower wave heights were neglected in Table 11 because the minimum required layer thickness was determined by the practical value at small wave impacts; in another word, the differences of the results were not obvious for comparisons. In conclusion, it was found that at the same significant wave heights, PUR-stone requires the smallest layer thickness compare to fresh OSA and aged OSA.

CONCLUSIONS

Based on the results of all the experiments and the calculations in GOLFKLAP, the conclusions of this study are given:

- The stiffness of PUR-stone is lower than that of aged OSA at low temperature. It varies with different temperature, stone size and quality; the higher the temperature is, the lower the stiffness is; but the stiffness of PUR-stone remains almost constant at a certain temperature with different frequencies of load.
- The strength of PUR-stone is higher than that of open stone asphalt. It is basically constant but sometimes varies due to its particular open structure; furthermore, the strength is not always determined by the bonding force because sometimes the bonding connections can be stronger than the stones themselves.
- For PUR-stone specimens produced by stones of 8/11 mm and stones of 16/32 mm, the porosity of them is similar to each other.
- PUR-stone stays more stable on the non-woven geotextile compared with woven geotextile; a short delay between the production and the application makes no influence as long as it is in the range of the required application period. Considering the usual angle of a revetment is 1/3 or 1/4, it is feasible to apply PUR-stone to the real construction on site.
- For PUR-stone of small thickness, the influences of

stone sizes and blocking points can both be neglected; however, for PUR- stone of big thickness, these influences should be considered; moreover, the influence of stones sizes is bigger than that of blocking points regarding the porosity of PUR-stone made of 8/11 mm yellow limestone and that of PUR-stone made of 16/32 mm yellow limestone are similar. In another word, for larger thickness, the grading width of stones decides the permeability of the interface between PUR-stone and geotextile despite of the blocking points.

- The roughness factor of PUR-stone slope made of 16/32 mm yellow limestone varies from about 0.7 to 0.9; the roughness factor of PUR-stone slope made of 8/11 mm yellow limestone varies from about 0.8 to 0.9. Both of them have smaller roughness factor than grass, colloidal concrete, basalaton and open stone asphalt; but larger than rubble mound of rock. The different permeable extents of two different PUR-stone slope probably cause their different roughness factors at impacts of plunging waves.
- The artificial basalt blocks are strongest. The resistance of PUR-stone to abrasive action is better than that of open stone asphalt but worse than that of colloidal concrete.
- At same wave loads the required minimum layer thickness of PUR-revetment is smaller than that of open stone asphalt revetment.

In conclusion, compared to open stone asphalt (see Table 12), PUR-stone is a kind of strong and permeable material; PUR-revetment is relatively easy to be constructed and maintained as well. It is expected to be a suitable material for applications of revetments.

Table 12 Comparisons between OSA revetment and PUR-revetment

Criterion Type	OSA revetment	PUR-revetment
Accessibility	+	+
Construction & maintenance	-	+
Costs	depends	depends
Flexibility for subsidence	+	?
Heavy loads	+	++
Landscape	depends	depends (+)
Space required	0	0

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REFERENCES

Anongmous. 2004. De Veiligheid van de Primaire Waterkeringen in Nederland, Voorschrift Toetsen op Veiligheid voor Detweede Toetsronde 2001-2006 (VTV). Den Haag: Ministerie van Verkeer en Waterstaat. 303-310.

Anongmous. 2005. Standaard RAW Bepalingen 2005. CROW. 1084 p.

De Looff, A., Hart, R., Montauban, K., and Van de Ven, M. GOLFKLAP a model to determine the impact of waves on dike structures with an asphaltic concrete layer.

Evertz, T. 2007. Elastomeric revetments–a new way of coastline protection. PhD thesis, Hamburger Wasserbauschriften, Technical University of Hamburg-Harburg, Germany. (not published yet)

Gu, D. 2007a. Some important mechanical properties of Elastocoast for safety investigation of dikes (VTV 2004). Minor Msc. thesis, Department of Civil Engineering, Delft University of Technology, Delft, The Netherlands.

Gu, D. 2007b. Hydraulic properties of PUR-revetments compared to those of open stone asphalt revetments. Msc thesis, Department of Civil Engineering, Delft University of Technology, Delft, The Netherlands.

K. d'Angremond and F.C. van Roode. 2001. Breakwaters and closure dams. Delft: Delft University Press.

Pilarczyk, K. 1998. Dikes and revetments. Lisse: A.A. Balkema.

Pilarczyk, K. Design of revetments.

Schiereck, G.J. 2001. Introduction to bed, bank and shore protection. Delft: Delft University Press.

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