ACCELERATED TEST FOR EVALUATING THE DURABILITY OF GEOSYNTHETICS ON COASTS

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To stablish the method evaluating the durability of geosynthetic structures on coast, field observations of concrete blocks and field exposure of geosynthetic test pieces were carried out on Japanese coasts. We analyzed the depths of erosion measured on coasts using multivariate statistical analysis, and investigated the effectiveness of the duration of settlement, elevation, wave conditions and size of coastal sediments on the degree of abrasion. Two types of accelerated tests for imitating gravel abrasion and a weathering test were developed, and the applicability of these tests were assessed by comparing the results to the results from field exposure tests. Based on these tests, we proposed the methods for estimating the remaining tensile strength of geosynthetic materials after settlement.

Keywords: geosynthetics, gravel, multivariate statistics, test method

INTRODUCTION

Geosynthetics have recently gained considerable attention for their application in coastal engineering (Pilarczyk 2000). However, geosynthetic structures have not been constructed on the Japanese coast, except in a few test cases, because such materials may not be capable of withstanding frequent typhoon attacks and the severe abrasion caused by gravel-mixed sand.

In 2010, the National Institute for Land and Infrastructure Management (NILIM) launched a research project to promote the use of geosynthetics in coastal areas. Three geosynthetics companies joined this project and constructed test pieces of geosynthetic coastal structures on the Seisho (Suwa et al., 2013) and Miyazaki coasts of Japan. Based on the findings from these field experiments, we published a manual addressing the performance evaluation, construction, and maintenance of geosynthetic sand dune scarp control works (NILIM et al., 2014).

During preparation of this manual, we discussed the necessary strength for geosynthetics to withstand the severe abrasion caused by gravel-mixed sand and degradation from the typical weather conditions typical of the Japanese coast. Lawson (2008) proposed that the ultimate strength requirements of geosynthetic tubes should be calculated by considering the global factor and recommended values 4.0–5.0. Although most geosynthetic coastal structures have been designed using this method, the degrading factors needed to be precisely evaluated to assess the applicability of geosynthetic structures in various potential situations for the Japanese coast. Thus, we started this study because such a detailed evaluation would help promote technical developments by geosynthetics companies.

In this paper, we present the evaluation of the durability of geosynthetic materials against abrasion stress and weather factors on coastal areas. Two types of accelerated tests were performed, and methods were developed for evaluating the endurance of geosynthetic coastal structures.

MATERIAL AND METHODS

First, we measured the degrees of abrasion stress and degradation by weather factors on the coast to evaluate the durability of geosynthetic coastal structures. Then, we developed accelerated tests to simulate degradation due to coastal abrasion and weathering in the laboratory. We investigated the applicability of the results through a comparison with the field test results.

Field Observation of Abrasion Stress on Coast

To evaluate the degree of abrasion stress on the coast, we measured the depths of erosion visible on the surface of 47 and 35 concrete blocks from the Suruga-Fuji and Shimoniikawa coasts,

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respectively (Fig. 1). The depths of erosion were measured to a resolution of 0.1 mm using a scale. We also measured the ground levels where the block settled and the grain sizes of the coastal gravel to investigate the difference in physical conditions around the blocks. We collected data on the wave conditions over a 10-year period (2001–2010) and the duration of settlement of each concrete block after the field observations.

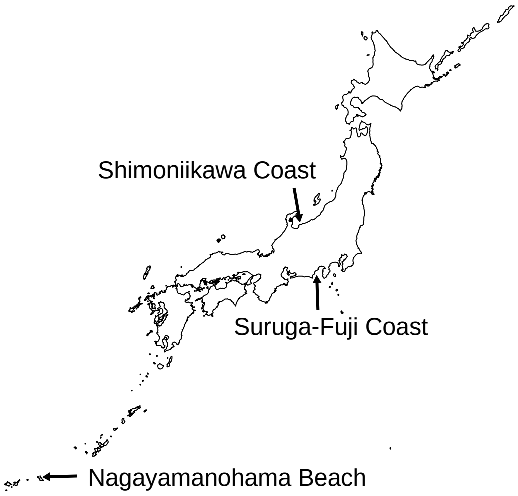

Figure 1. Beaches where degree of abrasion stress was surveyed

Development of Accelerated Test

We developed a new accelerated test using a rotating drum to imitate gravel abrasion in the laboratory over a short period of time (Fig. 2) because the standard test method (D4886 in ASTM) does not cover this type of damage.

Five pieces of concrete blocks were placed inside a drum containing 70 L of water and 10 kg of coastal sediments from the Suruga coast. The drum was rotated at a rate of 20 rpm. The coastal sediments were lifted up by the rotating drum and dropped on the concrete blocks at lower positions. This sediment action was believed to be analogous with the sediment impact on the coastal structures. In this test, the number of rotations was expected to correlate with the exposed period of materials near the shoreline.

The median grain size (D_{50}) of the coastal sediment used was 13 mm. Three of the five test pieces were concrete blocks, and the other two blocks were covered with geosynthetic sheets (Table 1). The water/cement ratios of the concrete blocks were differentiated for the three blocks in order to assess the effect of compressive strength on the durability against abrasion. We measured the depths of erosion on the concrete blocks after the rotation and compared them with those measured in field observations on the Suruga-Fuji coast.

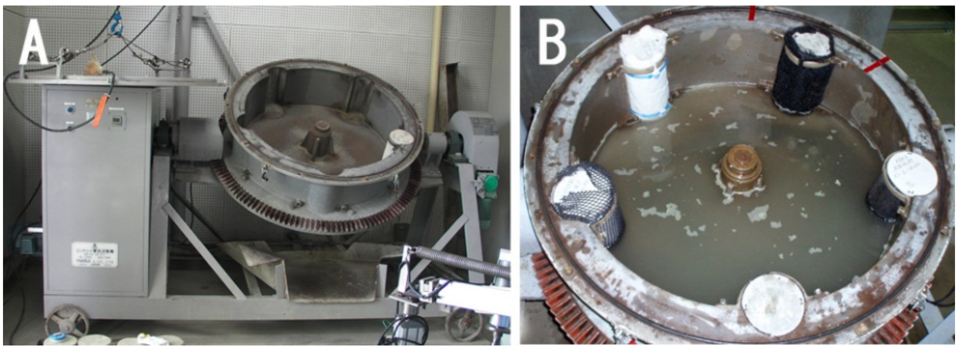

Figure 2. (A) Rotating drum used for accelerated abrasion test. (B) Five test pieces were placed inside the rotating drum with water and coastal sediments.

Table 1. Water/cement ratio and compressive strength of test pieces

		Water/Cement Ratio (%)	Compressive Strength (N/mm^3)
1	Standard Cement Ratio	50	27.1
2	Rich Cement Ratio	45	29.0
3	Poor Cement Ratio	55	24.4
4	Standard Cement Ratio + Geosynthetic sheet 1	-	-
5	Standard Cement Ratio + Geosynthetic sheet 2	-	-

Field Exposure Test of Geosynthetics

We conducted field exposure tests of geosynthetic materials on the above two coasts as well as Nagayamanohama beach (Fig. 1). We used polyester sheets containing black carbon (T-500, Maeda Kosen Co., Ltd.) as the test pieces of geosynthetic materials; these were cut and processed into panels with a height of 60 cm and width of 40 cm.

To investigate the degradation by gravel attack and abrasion on shore, we attached 31 test panels onto the surface of concrete blocks positioned near the shoreline of the Suruga coast (Fig. 3). The duration of exposure ranged from 14 days to 275 days.

Figure 3. Test pieces of geosynthetic materials attached on the surface of concrete block.

To investigate the degradation by weather factors, we also conducted field exposure tests on the back shores of the Shimoniikawa coast and Nagayamanohama beach (Fig. 4). Test panels with a height of 60 cm and width of 40 cm were attached to places inland that would not be affected by abrasion caused by waves. The duration of exposure ranged from 38 days to 897 days. Nagayamanohama beach is located in a subtropical zone, and degradation due to ultraviolet light was considered to be severe on this beach.

After exposure, all of the test pieces were cut into strips with widths of 5 cm width, and their tensile strengths were measured.

Figure 4. Test pieces of geosynthetic exposed on backshore of Nagayamanohama beach.

Accelerated Test for Geosynthetics

We tested the durability of the geosynthetic materials to abrasion stress by using the rotating drum mentioned above. The same type of polyester sheets used in the field exposure tests was used for the test pieces. First, we performed the rotating test until the specimens ruptured to determine the upper limit for the number of rotations. Then, we conducted accelerated tests for nine levels of rotations. All test pieces were cut into 5 cm after the rotation, and their tensile strengths were measured.

In order to test the degradation from weathering factors, we used apparatus that can emit ultraviolet light and spray water (open-flame carbon-arc type). The temperature of the black panel was kept at 63±3 °C, and we carried out the test using a two-step condition cycle. Each cycle involved 102 min of UV irradiation (step 1) followed 18 min of UV irradiation with spray (step 2). The testing periods ranged from 75 h to 1500 h. We measured the tensile strengths of all test pieces in the same manner as for the specimens of the other tests.

RESULTS

Field Observation of Abrasion Stress on Coast

The concrete blocks were heavily eroded near the beach surface, and erosion was also observed on blocks settled at higher elevations (Fig. 5). The depth of erosion reached 500 mm on the most eroded blocks. Fig. 6 plots the relationship between the maximum depth of erosion on each concrete block and the duration of settlement. The maximum erosion depth was higher in older blocks and was higher on the Suruga-Fuji coast on than the Shimoniikawa coast (Table 2).

When we considered the blocks whose duration of settlement exceeded 20 years, the depths of erosion tended to be smaller at high elevations. However, there was a high variance in measured values, and those relationships were not so clear compared to the relationship between the erosion and duration of settlement (Fig. 7).

Figure 5. Erosion of concrete blocks settled on Suruga coast.

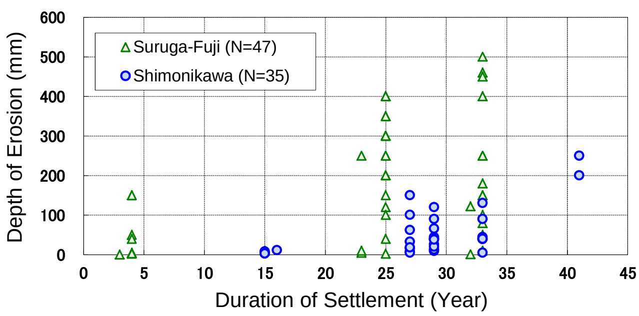

Figure 6. Relationship between duration of settlement and maximum depth of erosion.

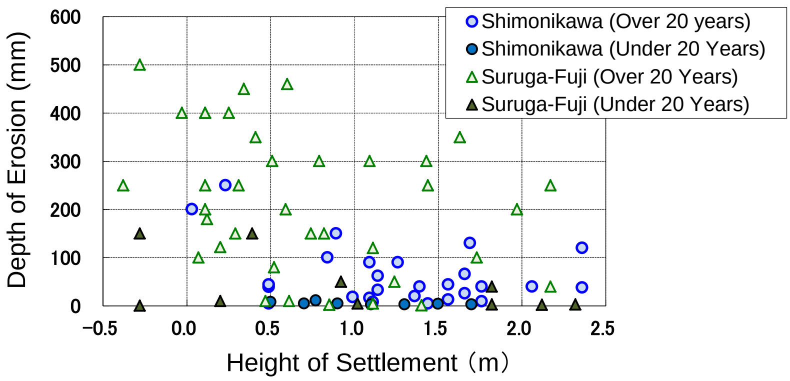

Figure 7. Relationship between elevation of settlement and maximum depth of erosion.

Table 2. Summary of observed erosion depth of concrete blocks on the coast. The values are the mean ± standard deviation, and the ranges of values are represented in parentheses.

	Suruga-Fuji Coast	Shimoniikawa Coast
Number of Location	7	6
Medium Grain Size of Coastal Sediment (mm)	6.3 ± 5.9 (0.35–15)	31.5 ± 39.8 (0.5–115)
Significant Wave Height $H_{1/3}$ (m)	0.70 ± 0.06 (0.65–0.78)	0.62
Number of Blocks Measured	47	35
Duration of Settlement	23 ± 10 (3–33)	27 ± 7 (15–41)
Maximum Depth of Erosion	180 ± 148 (0–500)	50 ± 58 (3–200)
Elevation of Most Eroded Part	0.82 ± 0.70 (-0.38–2.32)	1.21 ± 0.55 (0.03–2.36)

Development of Accelerated Abrasion Test

We inspect the applicability of the newly developed accelerated abrasion test by performing the test using concrete blocks. The concrete test pieces gradually eroded during drum rotation, and the inner aggregates of the test pieces were exposed on the surface after the pieces experienced 2000 rotations. When the pieces were rotated 120,000 times, the erosion became so deep that some aggregates dropped off from the test pieces (Fig. 8). The appearance of the pieces with exposed inner aggregates was almost the same as that observed on the coast where we carried out field measurement.

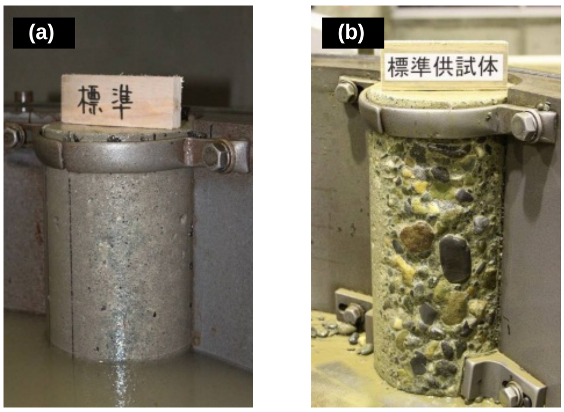

Figure 8. Appearances of test pieces after accelerated test. The pieces were rotated (a) 1000 and (b) 120,000 times.

The maximum depth of erosion of each test piece rapidly increased up to 40,000 rotations. However, the rate of increase slowed down after 40,000 rotations (Fig. 9). The erosion depth throughout the entire experiment was greater in test pieces with a rich cement ratio and least in the standard test piece.

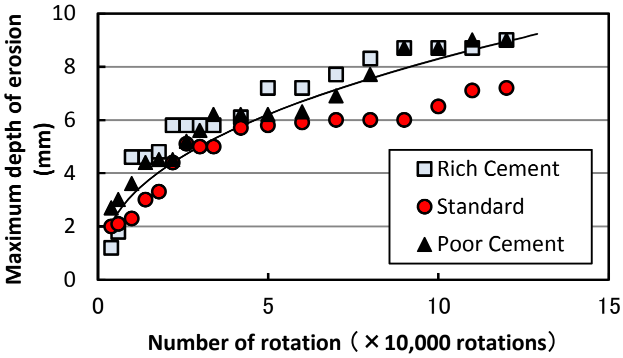

Figure 9. Relationship between number of rotations and maximum depth of erosion.

Field Exposure Test of Geosynthetics

During the testing period, we collected 21 of the 31 geosynthetic test pieces on the Suruga coast and investigated the remaining tensile strength for 20 pieces. The tensile strengths of the test pieces gradually decreased with the duration of exposure down to 29.4 % of the strength of the untreated virgin pieces after 275 days of exposure (Table 3).

Table 3. Duration of exposure and remaining tensile strength of geosynthetic pieces. The values are the mean ± standard deviation, and the ranges of values are represented in parentheses.

Duration of Exposure (days)	Number of Specimens	Tensile Strength (kN/5cm)
Untreated (Virgin)	5	8.47 ± 0.16 (8.17–8.63)
14	5	5.38 ±1.24(3.35–7.10)
58	5	3.73 ± 0.92 (2.20–4.70)
94	5	3.75 ± 1.08 (2.20–5.57)
156	2	2.80 ± 0.34 (2.46–3.14)
275	3	2.49 ± 0.83 (1.82–3.91)
Heavily Damaged	1 (exposed 275 days)	-
Covered by Sediments	3	-
Undiscovered	7	-

Accelerated Abrasion Test for Geosynthetics

A slight rupture of fibers appeared on the surface of the geosynthetic test pieces when the testing drum was rotated 8000 times. The range of ruptured fibers gradually expanded with more rotations, and a small hole began to form on the center part of the test piece. Most of the test pieces ruptured, and the inner concrete was exposed to abrasion by coastal sediments after 40,000 rotations (Fig. 10). In the accelerated abrasion test of concrete blocks, the concrete blocks eroded to a depth of 5.7 mm after 40,000 drum rotations. These results indicate that the tested geosynthetic material could not withstand the abrasion to which they would be subjected to at coastal locations where the erosion of concrete blocks exceeded a depth of 5.7mm.

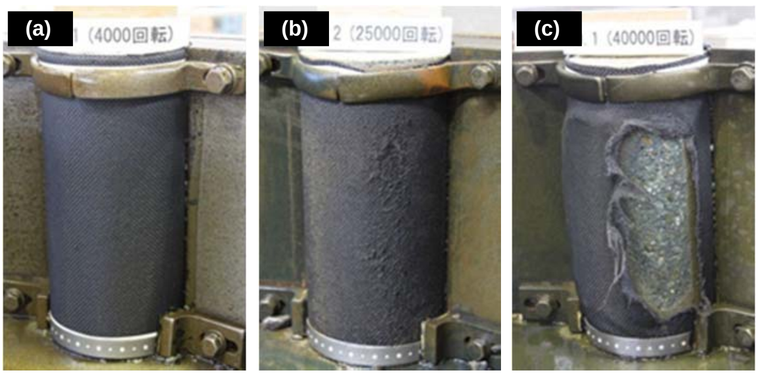

Figure 10. Appearances of geosynthetic test pieces after accelerated abrasion test. The specimens were rotated (a) 4000, (b) 25,000, and (c) 40,000 times.

The tensile strengths of the degraded test pieces decreased to 2.44 kN/5 cm on average after 4000 rotations (Table 4). This strength was almost the same as the remaining strength (2.49 kN/5cm) in the field exposure test after 275 days (Table 3). This suggests that the accelerated test conditions with 5300 rotations were equivalent to the field exposure conditions on the Suruga coast.

The tensile strength fell below 0.1 kN/5 cm, indicating the loss of performance, after 24,000 rotations.

Table 4. Tensile strength of geosynthetic test pieces and number of rotations performed in accelerated abrasion test.

Number of Rotations	Number of Specimens	Tensile Strength (kN/5 cm)
4,000	3	2.44 ± 0.13 (2.33–2.62)
8,000	7	0.91 ± 0.45 (0.10–1.66)
9,000	1	0.70
12,000	2	0.58 ± 0.11 (0.47–0.68)
16,000	4	0.24 ± 0.08 (0.14–0.37)
17,000	2	0.15 ± 0.07 (0.08–0.22)
24,000	3	0.06 ± 0.02 (0.04–0.08)
25,000	2	0.06 ± 0.00 (0.06–0.07)
32,000	2	0.04 ± 0.00 (0.04–0.04)

Field Exposure Test and Accelerated Test for Weathering

Fig. 11 shows the results of the field exposure test on the degradation by weather factors. The tensile strengths rapidly decreased during the first 300 days, and the rates of decrease then gradually slowed down on both coasts. The degree of degradation was higher on the Nagayamanohama beach than on the Shimoniikawa coast.

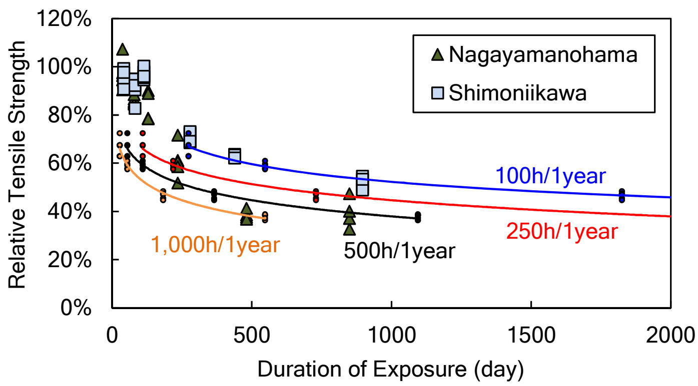

Figure 11. Decrease in tensile strength of geosynthetic test pieces in exposure test on back shore. The lines on the graph were obtained by converting the durations of the accelerated tests to durations of exposure on the coast.

A rapid decrease was also observed at the beginning of the accelerated weathering test (Table 5). The remaining tensile strength showed little variance in both the field exposure test and accelerated test compared with the abrasion test.

The results of the field test at the Nagayamanohama beach correlated with the results of the accelerated test when 500 h of accelerated testing was assumed to be equivalent to 1 year of field exposure (Fig. 11). On the other hand, 100 h of accelerated testing was equivalent to 1 year of field exposure on the Shimoniikawa coast. These results demonstrate that the weather factors had a stronger effect on the Nagayamanohama beach than on the Shimoniikawa coast.

Table 5. Tensile strength of geosynthetic test pieces and duration of accelerated weathering test.

Duration of Test	Number of Specimens	Tensile Strength (kN/5 cm)
Untreated (Virgin)	5	8.47 ± 0.16 (8.17–8.63)
75	5	5.64 ± 0.30 (5.32–6.13)
150	5	5.00 ± 0.10 (4.87–5.16)
500	5	3.95 ± 0.12 (3.78–4.10)
1500	5	3.20 ± 0.08 (3.08–3.28)

DISCUSSION

Factors Affecting Degree of Abrasion Stress on Coast

Although the observed depth of erosion on the coastal concrete blocks was related to the duration and elevation of settlement, those relationships contained a large amount of variance. This suggests the existence of other factors that affect the degree of abrasion stress on the coast. In order to investigate the effectiveness of each factor, we conducted multivariate statistical analysis to consider the duration of settlement, elevation, wave conditions, and size of coastal sediments.

First, we defined the depth of erosion y (mm) as follows:

$$\mathrm{y} = f(x_2, x_3, x_4)x_1 \qquad (1)$$

x_1, x_2, x_3, and x_4 represent the duration of settlement (year), elevation of settlement (m), wave height (m), and median grain size (mm) respectively. If the abrasion stress is determined by the amount of energy that is generated by the impact of gravel attack on a concrete block, the abrasion stress for 1 year $f(x_2, x_3, x_4)$ should correlate with the elevation (x_2) and wave height (x_3) squared and grain size (x_4) cubed. Assuming these effects are combined linearly, $f(x_2, x_3, x_4)$ can be represented as follows:

$$f(x_2, x_3, x_4)^{1/2} = C_2 x_2^{1/2} + C_3 x_3 + C_4 x_4^{3/2} + \varepsilon \qquad (2)$$

C_2, C_3, and C_4 are the coefficients determining the effectiveness of each factor, and ε represents the error function including the effect of unknown factors. The variable $f(x_2, x_3, x_4)$ is square-rooted in order to diminish the statistical bias caused by the small sample size of data obtained on the coast, proposed by Grafen and Hails (2000).

We analyzed the depths of erosion measured on the Suruga-Fuji and the Shimoniikawa coasts using this linear model. The elevation (x_2) was defined as the height above the mean highest monthly water level on the Suruga coast. The significant wave height ($H_{1/3}$) observed near each coast was used as the wave height (x_3). The median grain size of the coastal sediments (x_4) was measured on the shoreline of each coast (Table 2.).

The results of the multivariate analysis showed that the wave height had a significant effect ($p < 0.001$) and had the most influence on the depth of erosion over 1 year (Table 6). The also showed a significant effect ($p = 0.002$). However, the grain size was not significant ($p = 0.353$). The coefficient of the elevation factor was negative and coincided well with the tendency represented in Fig. 7. This result suggests that geosynthetic structures are applicable on coasts with high abrasion stress if structures are settled at positions of higher elevation.

In generally, larger grains generate higher energy when they attack the surface of a concrete block. On the other hand, the frequency of the gravel attack may decrease if the grain size becomes too large. The results of the multivariate analysis suggest that the relationship between grain size and abrasion is not a simple correlation as modeled in the analysis. Moreover, the difference in grain size between the two coasts was too small to assess its effect. Drawing the conclusion that the grain size has no effect on abrasion would be premature.

Table 6. Results of multivariate analysis. $R_{adj}^2 = 0.389$, ***: $p < 0.001$, **: $p < 0.01$, *: $p < 0.05$

Factors	Cn	Standard Error	*t* Value	*p*
Elevation	-1.719	0.537	-3.20	0.002**
Wave Height	12.77	2.11	6.06	<0.001***
Grain Size	3.058×10^{-4}	3.276×10^{-4}	0.93	0.353
ε	-4.250	1.626	-2.61	0.011*

Relationship between Abrasion on Coast and Results of Accelerated Test

The results of the accelerated abrasion test using concrete test pieces showed no correlation between the cement ratio and depth of erosion. Although we cannot conclude that the compressive strength of concrete blocks does not affect the durability against abrasion based solely on this result, three types of concrete test pieces were considered, as discussed below.

The progress of erosion on the concrete test piece gradually decreased corresponding to the number of drum rotations (Fig. 9.). The coastal sediments were suspected to also be damaged by impact with the concrete block; this decreased the grain sizes of the sediments and weakened the abrasion stress of each gravel attack during the test. The erosion of the standard test pieces tended to slow down after 50,000 rotations and increased again after 100,000 rotations. Based on these results, the exposure of inner aggregate may have also affected the progress of erosion.

Based on these results, the relationship between the maximum depth of erosion (y_{abr}) and number of rotations (x_{rot}) should be represented as follows. In this equation, we can express the decrease in the speed of erosion adopting a value of less than 1 for the coefficient b.

$$y_{abr} = a x_{rot}^{b} \quad (3)$$

The coefficients a and b were estimated to be 0.0674 and 0.418, respectively, based on the results for the three test pieces. Fig. 9 shows the calculated fitting curve using this equation; the R_2 of the curve was 0.846. Using this equation and equation (1), we can correlate the observed erosion on the coast with the results of the accelerated test and imitate the abrasion stress in a laboratory.

Fig. 12 shows the relationship between the results of the field exposure and accelerated abrasion tests. The degree of abrasion stress was defined in terms of the depth of erosion of the concrete blocks. The result of the laboratory tests tended to be somewhat more severe than the field exposure test when the abrasion stress was high. However, the results of the field and laboratory tests were generally in good agreement.

In the accelerated test, geosynthetic test specimens were attached directly onto the concrete test piece; thus, the gravel impacted the test specimens with no reduction. On the other hand, there was some buffering space between the test panel and concrete block in the field exposure test, which may have softened the impact of the gravel attack.

Note that the field exposure results also included chemical degradation by ultraviolet rays and rain. Based on the results of the field exposure test conducted on the backshore, the ultraviolet rays and rain decreased the tensile strength by about 1 kN/5 cm over 100 days. Exposure to ultraviolet rays was considered to be infrequent where seawater washed the surfaces of the test pieces. Thus ultraviolet rays should have little effect on the above field exposure test, which was intended to evaluate the abrasion stress. The accelerated abrasion test developed in this study was judged to be applicable for evaluating the durability of geosynthetic materials on a gravel coast.

However, this abrasion test should not be applied on sandy beaches because the mechanism for the degradation of geosynthetic materials caused by sand is suspected to be different from that caused by gravel. To evaluate the durability with respect to abrasion on sandy beaches, another accelerated test should be developed.

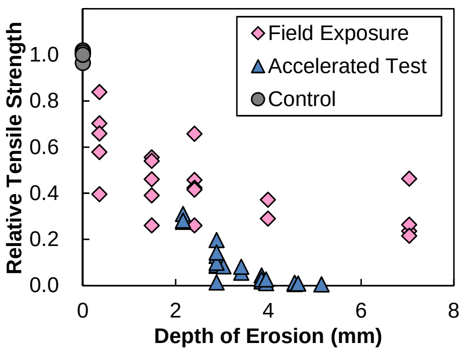

Figure 12. Relationship between results of field exposure and accelerated tests for geosynthetic test pieces.

Method for Evaluating the Durability on Coast

Based on the above results, we propose the following method for evaluating the durability of a geosynthetic coastal structure. $\alpha_a(t)$ and $\alpha_w(t)$ are reduction factors that represent the degrees of degradation caused by abrasion and weather factors respectively, over t years. The remaining tensile strength of geosynthetic materials after t years $T_d(t)$ can be estimated by using the following formula:

$$T_d(t) = Min\{T_m \times \alpha_a(t) \times \alpha_w(t), T_{st} \times \alpha_a(t) \times \alpha_w(t)\} \quad (4)$$

where T_m and T_{st} are the initial tensile strengths of the geosynthetic material and seams that connect two geosynthetic sheets, respectively. $T_d(t)$ must sufficiently exceed the designed tensile strength to maintain the shape of the geosynthetic structure. The designed tensile strength of geosynthetic tubes should be calculated in the following manner proposed by Namias (1985) or Palmerton (2002). To estimate the reduction factor for abrasion $\alpha_a(t)$, the expected depth of erosion on concrete blocks during the design period has been proposed as an index to represent the abrasion stress, as shown in Fig. 12. The reduction factor for weathering $\alpha_w(t)$ must be estimated by the accelerated test as presented in this paper, and 250 h of accelerated weathering was defined as equivalent to 1year of field exposure. Based on the results that 100 and 500 h of testing are equivalent to 1 year of field exposure on the Shimoniikawa coast and Nagayamanohama beach respectively, 300 h may be adequate on average. However, considering the fact that 250 h of testing has already been used for geosynthetic materials in other fields, this value was determined to also be the standard for coastal structures.

We designed the strength of geosynthetic materials used for sand dune control works on the Miyazaki coast. If we expect 10 years of durability, the abrasion test must be carried out under conditions that can erode a concrete block to a depth of 2.5 mm. In addition, 2500 h of accelerated weathering testing must be conducted. The remaining tensile strength estimated using the reduction factors $\alpha_a(t)$ and $\alpha_w(t)$ as determined from these tests must exceed a design strength of 91.5 kN/m.

CONCLUSION

In this paper, we present the results from field observation, field exposure tests and the newly developed accelerated tests. We also propose methods for evaluating the durability of geosynthetic structures. These methods are not sufficiently established and should be revised based on empirical data from Japanese coasts in the future.

For the evaluation of abrasion stress, we only presented a method applicable to gravel coasts. We also developed a test method for sandy beaches during our project and presented it in a manual (NILIM et al., 2014); we will present its detail in a later paper. The published Japanese manual addresses not only the presented evaluation method, but also the construction and maintenance of geosynthetic structures and the concept of dune scarp control works. At present, we are preparing an English version of this manual.

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