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Performance of synthetic rubber sheets for surface lining of the upper pond in Yambaru seawater pumped storage power plant

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ABSTRACT: To examine the feasibility of a long-term commercial operation of seawater pumped storage power plant, in 1987, the Ministry of Economy, Trade and Industry of Japan commissioned the Electric Power Development Co., Ltd. to construct and operate the Okinawa Seawater Pumped Storage Power Pilot Plant. This world's first seawater pumped storage power pilot plant with a maximum output capacity of 30 MW has been in test operation since March 1999. For the surface lining of the upper pond of the pilot plant, a synthetic rubber made of the ethylene propylene dien terpolymers (EPDM) sheet has been used, which is the first use of an exposed rubber sheet for the lining of a seawater pond. This paper reports the construction procedure and the results of long-term monitoring at the site and associated laboratory tests.

1 INTRODUCTION

The Ministry of Economy, Trade and Industry commissioned the Electric Power Development Co. Ltd. (EPDC) in 1987 to construct a seawater pumped storage power pilot plant at Yambaru in the Okinawa island, Japan. The plant was designed using the state-of-the-art technology to validate the technical as well as the commercial feasibility of the seawater pumped storage power plant technology. The preliminary work for the pilot plant began in March 1990, the civil engineering and construction work started in June 1991 and the pilot plant was completed in March 1999. Photo 1 shows a general view of the plant.

Photo 1. General view of the plant

The pilot plant uses a rubber sheet for the lining of the upper pond. The sheet is an exposed synthetic rubber sheet consisting of an ethylene propylene dien terpolymers (EPDM), which is a material defined in the ASTM Standards. The lining is underlain by a 50 cm-thick layer of a crusher run gravel, termed the transition layer. The lining sheets were connected to each other with connection parts being embedded in specially designed U-shaped concrete blocks having a number of built-in polyvinyl chloride (PVC) pipes for ventilation and drainage.

In this paper the process and results of the rubber sheet lining work and the long-term performance of the sheet lining after the start of the operation are reported. The detail of the design of the upper pond, including its lining work, was reported (Shimizu & Ikeguchi 1998).

2 RUBBER SHEET LINING SYSTEM

As shown in Figure 1, the rubber sheet lining system consists of; 1) the rubber sheets itself, comprising main sheets, a cushion fabric and cover sheets; 2) sheet connection (including filling concrete); and 3) a transition layer for ventilation and drainage. Figure 2 shows the detail of the sheet connection structure. The lining sheets, each having a width of 8.5 m, were placed on the surface of the slope of the pond. The length of the upper section of the slope is 33 m, whereas the lower section ranges between 32 and 41 m. The surface of the bottom part of the pond was divided into standard sections with an area of 17.0 m x 17.5 m for each section was covered with the lining sheets separately.

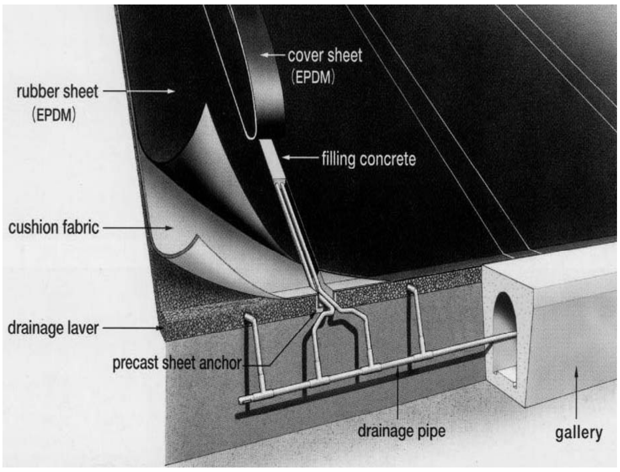


Figure 1. Structure of rubber sheet lining system

Figure 3 illustrates the details of the sheet connection structure The main rubber lining sheets, which function as the water impervious lining, were connected to each other at the respective sheet connection structure. The cushion fabric was used to absorb possible small indentations and protrusions on the surface of the transition layer (i.e., drainage layer) and concrete surface avoiding any possible damage to the rubber sheet. The cover sheet was designed to cover the respective connection section while bonded to the main rubber sheet.

The respective sheet connection structure consists of a number of specially designed U-shaped concrete blocks. Each block contains a pair of 100 mm-diameter PVC water drainage pipes that had been built-in in advance to vent any residual air and to drain percolated water towards a drainage pipe system installed in the inspection gallery (see Figure 1).

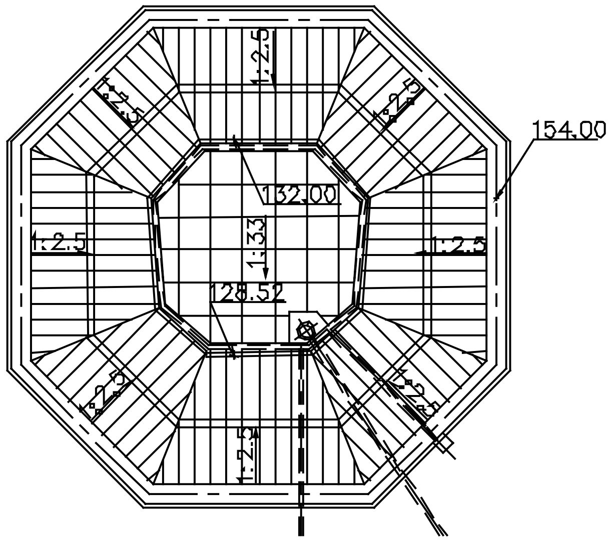


Figure 2. Layout of sheet connection structure

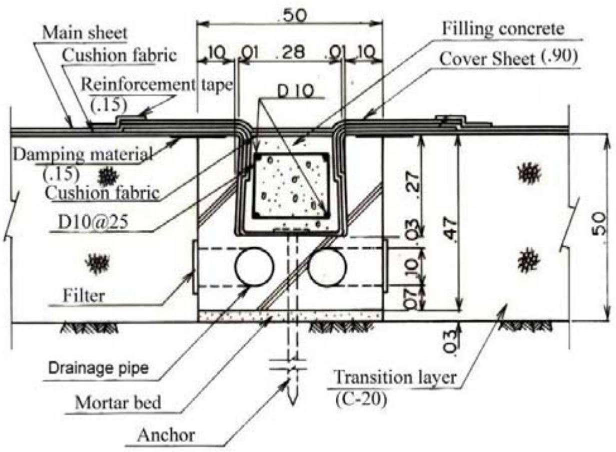


Figure 3. Sheet connection structure

A stiff and firm transition layer was constructed by compacting a crusher run (a C-20 road-base material with a maximum diameter of 26.5 mm, D_{10} = 2.5 mm, D_{50} = 5 mm, D_{60} = 13 mm, a fines content of 5 % ～ 10 % and a coefficient of uniformity of 5.2) to a thickness of 50 cm, according to the JIS A 5001 Standard. The transition layer was designed to have not only a sufficiently high hydraulic conductivity (or permeability) allowing free drainage toward the inspection gallery of possible spring water from the mountains and seawater leaked from the pond as a result of sheet failure, but also a sufficiently high air permeability discharging any residual air that would be caught at the back of the sheet.

3 SHEET CONNECTION WORK

The concrete blocks for the sheet connection structures were produced in not only an outside existing factory but also at the construction site. The standard concrete block has a length of 2.0 m and an approximate weight of 680 kg. Photo 2 shows the installation of a sheet connection structure. Each block was placed on a mortar bed that had been placed to render a flat surface. After confirming perfect fitting to the mortar bed, the block was anchored into the transition layer. Then the filling concrete was cast-in-place inside the recess of the block.

Any offset or misalignment between adjacent concrete blocks could produce a sharp edge acting like a blade, which may seriously damage the rubber sheet and the cushion fabric underneath. To prevent the above, the following measures were taken:


Photo 2. Construction of sheet connection structure

1) A row of concrete blocks was connected to an integral structure by casting-in-place concrete continuously into the recesses of the adjacent concrete blocks while providing steel reinforcement encompassing the adjacent concrete blocks. A possible problem with this measure is that expansion and contraction cracks may develop in the filling concrete by a relatively large temperature change. To prevent the above, joints were provided at the filling concrete at a spacing of 10 m of the unified concrete structure. Additionally, to prevent local bending that may arise as a result of possible differential settlements during seawater storage around the boundaries between the excavation and embankment areas at the dam site, joints were provided at the concrete blocks located at these boundaries.
2) The filling concrete was cast-in-place into the recess of the concrete blocks, where several sheets of rubber lining had been placed in advance, as shown in Figure 3. It was possible that, by this procedure, small triangular sections were formed at the left and right corners of the top of the concrete surface, which could damage the lining sheets. To avoid this problem, triangular EPDM materials were placed at the corners as chamfer strips.

4 TRANSITION LAYER WORK

Figure 4 shows the sequence of the construction work of the transition layer in the slope section, which was established based on the results from installation tests performed before the actual installation work. To compact a crusher run at an optimum water content, water was sprinkled on the crusher run during taking out from the stockpile yard and also during compaction work. To ensure smooth and flat surface of the transition layer without any irregularities, the sloped part was vibration-compacted only while moving a compacting roller upwards. This procedure was also essential to ensure a sufficient high density of crusher run and to prevent the segregation of coarse and fine grain materials. A vibration-compaction roller was moved on the slope by remote control for the safety of workers. As shown in Photo 3, the upward and downward movements of the respective roller was achieved by supporting the roller with a set of wires extending from a crawler crane that was fixed at the top of the slope. The moving speed of the roller was controlled to be constant. In the areas adjacent to the sheet connection structures, this work was carried out all manually to avoid possible damage to the concrete blocks due to contact with construction heavy equipment. The manual compaction was achieved by using vibration steel plates that were supported with wires extending from the top of the slope.

The sequence of the construction work at the bottom section was nearly the same as that in the slope section except that the supporting system of a roller was not used at the bottom section.

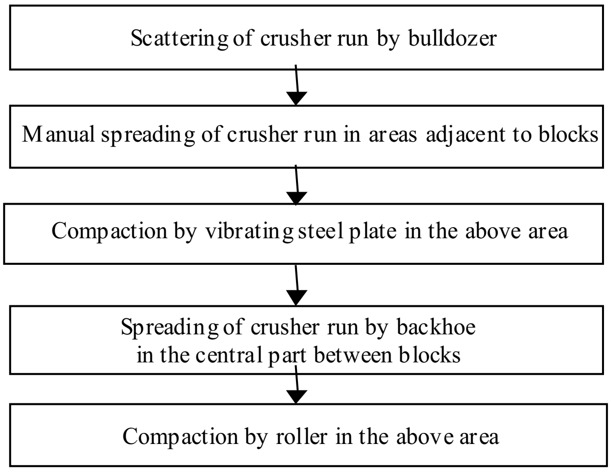


Figure 4. Construction sequence of the transition layer

Photo 3. Compaction of the transition layer

5. INSTALLATION OF RUBBER LINING SHEET AND QUALITY CONTROL

5.1 Installation of Rubber Sheet Lining

Figure 5 shows the installation procedure of the rubber sheet lining around the sheet connection structures.

The lining sheets were transported by using crawler cranes to the site where they were to be placed and the entire installation work at the site was carried out manually. The sheet installation started from one section to another in such a way that different operational steps were performed in several different sections. This installation procedure minimised the total installation time by reducing waiting time before proceeding to the next step of installation in each section. On the other hand, rainwater could damage the surface of the transition layer and could moisten the cushion fabric before placing the main lining sheets, thereby affecting the subsequent adhesion work between the cushion fabric and the main lining sheet. If the above is the case in any section, the entire installation work has to be restarted from the beginning in all the linked sections. Therefore, simultaneous and linked installation work was restricted to only two or three sections.

The installation work was stopped when either of the following conditions appeared, under which an adhesive (either a bonding agent or an adhesive tape) cannot be used:

1) wetting of the sheet surface by rainwater:
2) falling of the ambient temperature or that at the sheet surface to below 5 °C;
3) rising of humidity rising to above 85 %;
4) rising of the wind blow velocity to above 7 m/s; and
5) moving-in of a large number of stones into the inside of the installation zone.

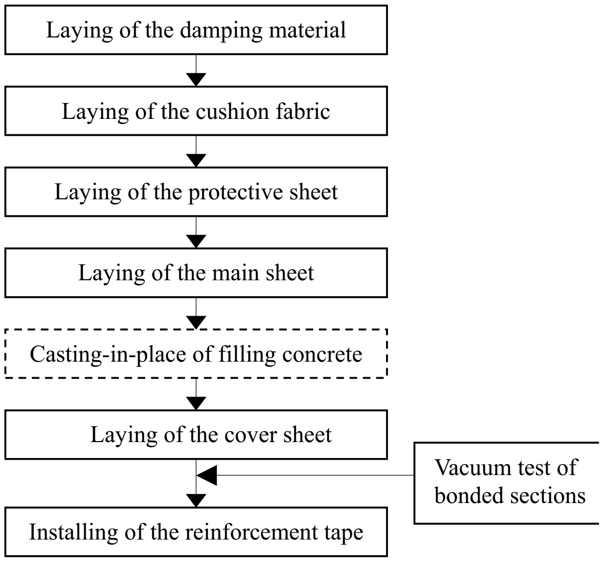


Figure 5. Installation sequence of water impervious sheet

The main rubber lining sheets, cushion fabric, cover sheets and damping materials had been cut to the specified width in the factory. Rubber sheets wound on a steel roll and cushion fabric wound on a cardboard roll were delivered to the construction. As shown in Photo 4, to install the cushion fabric and the rubber lining sheets on the slope sections of the pond, a roll of cushion fabric and rubber lining sheet was placed at the crest of the slope. First the cushion fabric then the rubber sheet was manually pulled out from the respective roll step by step toward the toe of the slope. To install the cushion sheets and rubber sheets on the flat bottom sections of the pond, two thirds of the total rolled length of sheet was first spread out from the roll and then it was arranged at place from left to right. In this installation work, it was essential to prevent undulation, wrinkling and spot formation in the cushion fabric and main lining sheets so that too large residual tensile stress was not introduced in them. It was also necessary to avoid excessive expansion and contraction in the rubber lining sheets as a result of large temperature changes.

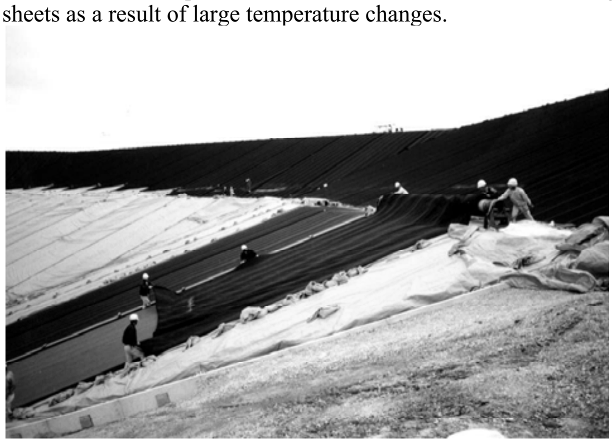


Photo 4. Rubber sheet installation

The cover sheet, which was a piece of the main rubber lining sheets, was bonded to the main rubber lining sheets at the site. As a highly reliable adhesive bonding was essential as the common practice, an adhesive tape that consisted of a naturally vulcanised butyl rubber-type adhesive was used, as shown in Photo 5. The edges of the cover sheet were protected by using a reinforcement tape. At locations where the rubber lining sheets were covered with cover sheets, the surface of the rubber lining sheets was first made as flat as possible and the sealing was made reliable by using a sealing material.

Photo 5. Cover sheet bounding work

To maintain a high quality of the bonding work avoiding poor bonding conditions, the bonded parts between the cover sheets and the main lining sheets were examined first by visual inspection and then by touching with hands. Subsequently, the amount of the gap at the edges of the bonded area was evaluated by using blade-shaped inspection spatula. Finally, a vacuum test was conducted over the total length of the bonded edges (Photo 6). The test was carried out by applying a vacuum with 5 kPa or more for a period of 10 seconds or longer to the inside of a transparent box placed on the part of the bonding edge to be inspected while examining whether bubbles be formed in a soap water layer that had been smeared on that part.

Photo 6. Negative pressure test in the cover sheet

Table 1. Results of the quality control tests of EPDM sheet

	Thickness (mm)	Tensile strength (N/mm^2)		Elongation at rupture (%)		Tear strength (N/mm)	
		Lengthwise direction	Widthwise direction	Lengthwise direction	Widthwise direction	Lengthwise direction	Widthwise direction
Specified value	2.0~2.3	9.8 or more		450 or more		26.0 or more	
Maximum value	2.20	15.9	15.2	557	567	52.5	51.0
Minimum value	2.06	13.0	11.8	484	478	39.3	37.0
Mean value	2.14	14.4	13.5	520	524	45.5	45.1

5.2 Quality Control of Rubber Sheet Lining

The very careful quality control was required for the entire process of the installation of rubber lining sheets, most of which was performed manually, to ensure the high quality of installation work with a highly uniformity. It was therefore necessary to specify relevant quality control standards. Although the rubber sheets were manufactured in a factory, the materials used in this project were subjected to rigorous quality tests with regular evaluations of their properties. In particular, the relevant and accurate control of the mixing proportion of raw materials and the pressure and temperature in the vulcanising process was of critical importance, because even a minor variation in these factors may have significant effects on the quality of produced rubber sheets. The regular quality tests consisted of one test per every 1,000 m² for the particularly important items, such as thickness, tensile strength, elongation at rupture and tear strength, and one test per every 5,000 m² for the other test items, such as temperature dependence, elongation property, elongation capacity (after alkali treatment and heating treatment), as specified in the JIS A 6008 Standard. The results of the quality tests of the main rubber lining sheets are summarised in Table 1, which met fully all of the quality criteria. Shimizu et al. (Shimizu & Ikeguchi 1998) reported the more details of the results of the quality control test of the cover sheet.

The quality of the bonding edges of cover sheet was also controlled by specifying in details the bonding width and relative positions of the different sheet components.

6. OPERATION CONDITIONS AND PERFORMANCE RECORDS

6.1 Seawater Filling and Operation Record

The upper pond was filled with seawater for the first time in August 1998 and the whole plant was put into operation in mid-March 1999. The water level in the pond during the operation of the plant fluctuates generally between altitudes of 135 m and 151 m with design allowable low and high water levels of 132 m and 152 m. According to the operation records as of September 2001, the power generators had been operated for a total of 4,060 hours and the seawater pumping system for a total of 4,340 hours.

6.2 Seawater-Leakage Detection and Recycling System

It was designed that if seawater leaked through the sheet due to sheet failure, leaked water is drained towards the PVC pipes. The pipes were installed not only for water drainage but also for air exhausting from the sheet connection structure in contact with the transition layer having a high hydraulic permeability. The leaked seawater is to be then drained through the water drainage and collection pipe system on the slope of the pond towards a pipe system installed in the inspection gallery (see Figure 1). The leaked seawater is to be finally collected at a water drain pit, which is provided with a water level gauge and a water drainage pump (Figure 6). The system was designed in such a way that whenever the level of the drain seawater exceeds a prescribed value, the drainage pump automatically starts working to return the leaked seawater back to the upper pond.

There has not been any case of water

leakage through the rubber lining sheets so far. The only instances in which the leakage detection and water recycling system operated so far were those when the freshwater flowed into the rubber sheet system under big typhoon conditions.

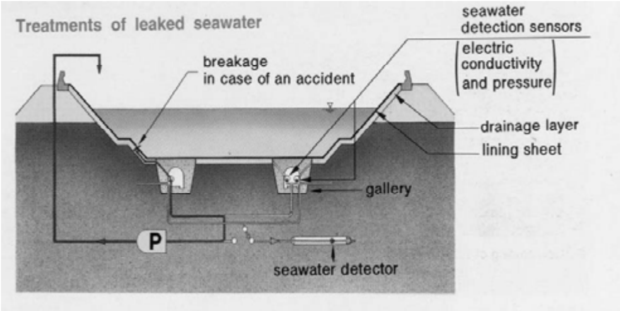


Figure 6. Treatment of leaked seawater

6.3 *Accretion of Marine Life Forms*

As the power generating and pumping turbines have been operated at a full performance rate, the upper pond has been subjected to steady effects of silty materials and algae growth. For this reason, the surface of the rubber sheet lining was gradually covered with a thin silty layer by the end of roughly one year since the start of plant operation.

Until now, the rubber sheet lining system was inspected four times in order to evaluate the accretion level of marine life forms in the system. The inspection performed in June 1999 revealed the presence of barnacles in some parts of the rubber lining sheets. However, this accretion was limited to only some scattered patches. The second inspection, carried out in December 1999, revealed that the extent of shell accretion was still similar to that observed during the first inspection. In the next regular inspection, carried out in June 2000, in addition to the barnacles, a large amount of green limpets was found.

The subsequent inspection performed in October 2000 was a diving survey after the water level of the upper pond was lowered to a level of 132 m. For the fourth inspection, however, the water was totally removed so as to perform a visual survey (see Photo 7).

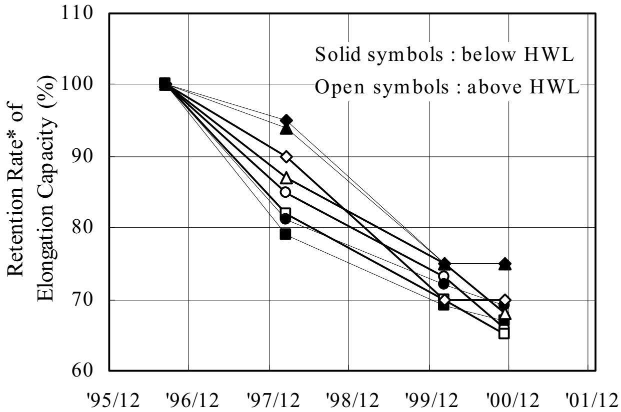
Although the amount of marine life forms tended to increase year after year, there has been no evidence that the surface of the rubber lining sheets had suffered from any damage or deterioration as a result of this marine life form accretion. It was found however that the presence of shell accretion on the sheet surface may raise a particular problem during maintenance and inspection work; i.e., the shells may damage the lining sheets when operators tread on the shells or when equipment is rolled over them. A possible solution would be the use of shoes provided with cushion material soles so as not to damage the lining sheets.

Photo 7. Marine life form accretion

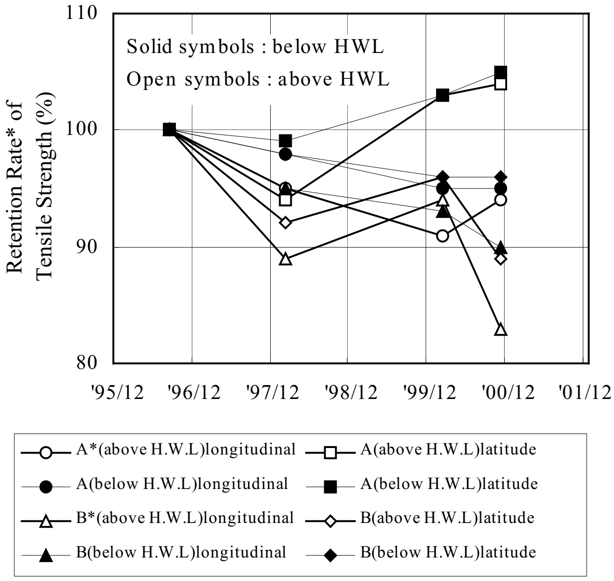
6.4 *Changes with Time in Rubber Sheet Properties*

6.4.1 Changes with Time in Elongation Capacity and Tensile Strength

In order to investigate the possible degradation with time of the physical properties of the rubber lining sheets, a number of sample sheets were placed on the surface of the actual lining sheets, and quality check tests were carried out on these samples at regular intervals. The results are shown below.



(a) Property change in Elongation Capacity



(b) Property change in Tensile Strength

Figure 7. Property changes of the rubber lining sheets
* The letters “A & B” mean the abbreviation of the sheet suppliers.

Figures 7 shows the retention rate of, respectively, the elongation capacity, defined as the tensile strain at failure, and the tensile strength, both in percentage, defined by Equation 1.

$$\mathrm{Re}\,tention\ Rate\ (\%) = \frac{\mathrm{Pr}\,esent\ value\ of\ the\ property}{Initial\ value\ of\ the\ property} \times 100 \qquad (1)$$

The following trends of behaviour can be seen from the figures:

1)The tensile strength decreased at a very low rate, while the elongation capability decreased at a much higher rate.
2)The samples that had been subjected to relatively high temperature rises by being located above the HWL exhibited a similar deterioration rate in the elongation capacity to those located below the HWL.

6.4.2 Prediction of Material Property Change in the Future

When based on a slight deterioration in the tensile strength of the rubber sheets occurred until the inspection conducted in year 2000, it is very likely that the rate of the decrease in the tensile strength will still remain very small in the near future. On the contrary, the elongation capacity of the rubber sheets has deteriorated by about 35 % (Figure 7). Figure 8 compares the retention rate of the elongation capacity of the EPDM rubber sheets in this project with those from other projects in Japan. It may be seen that these data from two different sources are in accordance with each other for a period of five elapsed years. Based on this result, it appears that the retention rate of elongation capacity will converge to a level of around 40 % in the near future. Figure 9 presents the same data as presented in Figure 8, while plotting the reduction rate of elongation capacity, against the logarithm of elapsed year. In Figure 9, straight lines are fitted to the upper and lower bounds and the average of the data. On the other hand, it was estimated that the maximum

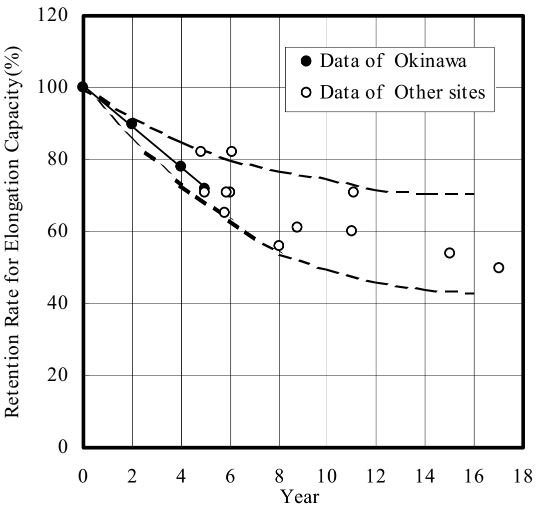


Figure 8. Future Prediction of Elongation Capacity (1)

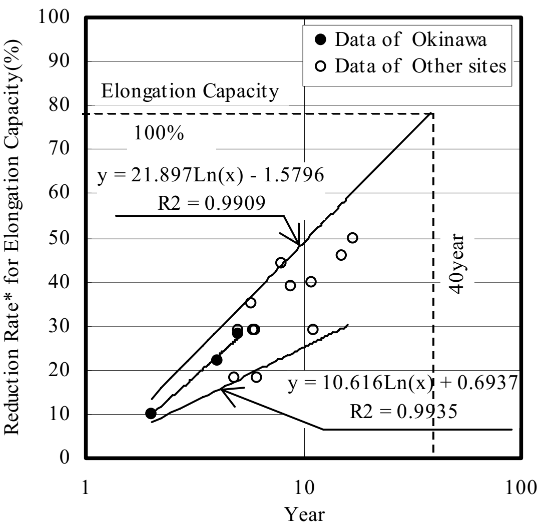


Figure 9. Future Prediction of Elongation Capacity (2)

$$* \quad \text{Reduction Rate}(\%) = 100 - \text{Retention}(\%)$$

elongation due to uneven settlements of the ground supporting the pond would be less than 100 % (Takimoto & Onoi 1997) and the maximum value due to sheet expansion resulting from strong winds and low barometric pressure would be less than 57 % (Shimizu & Ikeguchi 1998). The elongation strain of 100 % at the rupture of sheet is equivalent to a reduction rate of elongation capacity of 78 %, assuming that initial value of elongation strain is 450%. If we assume that the lining sheets will reach its serviceability limit when the elongation capacity drops to 100 %, we can then conclude that the sheet has a service life of about 40 years when based on the results presented in Figure 9.

7. CONCLUSIONS

The following conclusions can be derived:
1) To ensure the designed performance functions of the rubber lining sheets, the detailed control of the installation work, including the followings, was essential:
   a) Adequate quality control tests of the rubber sheets.
   b) Proper procedures of manual installation work of the rubber sheets and others.
   c) Proper bonding between the rubber sheet and the cushion fabric using a proper adhesive.
   d) Adequate design of the sheet connection structure together with proper on-site connections of main rubber lining sheets.
2) It is essential to select a proper low-cost material that is easy to compact while having a high hydraulic permeability for the transition layer for a high cost effectiveness.
3) As this lining system was used for a seawater storage pond, it should be designed and constructed to a reliable level that is much higher than those for fresh-water ponds. This factor increased the cost of this system. More efforts will be necessary for a cost reduction.
4) Despite that the accretion of marine life forms has inevitably increased with time, there has been no evidence of damage to the lining sheets as a result of such marine life form accretion.
5) The tensile strength of the rubber lining sheets decreased only slightly for the first five years after the start of operation. On the other hand, the elongation capacity of the rubber sheets decreased relatively largely. Taking into account the chemical nature of the EPDM sheet while based on the experiences for a longer period with this type of rubber sheets at other places, it could be estimated that the rubber lining sheets will maintain the required elongation performance for around 40 years.

The test operations of this particular pilot plant are scheduled to continue until March 2003 with continuous monitoring of the accretion of marine fauna and flora on the impervious rubber sheet and changes with time of the tensile strength and elongation capacity of the sheet.

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