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Improvement of soft ground using solidified coal ash and its effects on the marine environment

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Abstract

This paper presents some research results pertaining to the application of solidified coal ash (SCA) for improving the stability of soft ground. The results pertain to the physical properties of SCA required for use as an alternative to sand in sand compaction piles (SCPs), and the assessment of possible environmental impacts resulting from construction of SCA piles in marine environments. The results of field tests indicate that the physical properties of SCA (permeability, internal friction angle, and grain-size distribution) are favorable for use in soil improvement applications. Also, the results show that SCA is sufficiently suitable as an alternative to sand in SCPs, although SCA piles cannot be compacted to the same extent as sand piles. Finally, test results showed no adverse environmental impacts on natural benthos resulting from placement of SCA piles in marine environments. Thus, the results of this study confirm that SCA is a viable alternative material to sand in SCPs that are used for ground improvement in marine environments, and that large quantities of SCA may be required for such applications resulting in an alternative use for an otherwise waste material. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Solidified coal ash; Ground improvement; Benthos; Marine impacts

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1. Introduction

The effective utilization of coal ash has been anticipated for a long time in Japan where large quantities of coal ash are produced. For example, about 5.15 million tons of

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coal ash were generated in 1995 in Japan. The main application of the coal ash has been as a raw material for use in cement and in reclaiming ground. However, coal ash is rarely used in other applications in Japan, and the demand for cement in Japan is decreasing. Thus, there is a concern that utilization of coal ash also will decrease resulting in a need to dispose the remaining coal ash at potentially significant cost. This concern has provided the motivation for the current study.

One potential, alternative application for recycling coal ash is as a substitute material for sand in sand compaction piles (SCPs) that commonly are used to improve the stability of soft ground. As a result, a study was undertaken to evaluate the potential use of solidified coal ash (SCA) in SCPs. The study involved both laboratory tests and field application tests performed both in terrestrial and marine environments. Since SCA is manufactured using cement as a binder, the potential adverse effects on the marine environment resulting from the leaching of alkaline components from the cement is a concern. When industrial refuse will be used for construction materials, impact to environment from leaching elements should be considered. M. Carling [1] thought to use coal ash instead of natural resources such as sand and gravel and reported the environment impact when using coal ash as road construction material. Presentation of the results of this study, including an assessment of the potential environmental impact on water and benthos resulting from the use of SCA in SCPs constructed in marine environments, represents the primary purpose of this paper.

2. Basic physical properties of SCA

The manufacturing process for SCA involves continuously supplying coal ash, cement, and water to a pelletizer that mixes the constituents in a tilted rotating pan until the mixture hardens into spherical pellets in sizes ranging from several to tens of millimeters in diameter. This process results in certain basic physical properties for SCA, typical values of which are summarized in Table 1.

The dry unit weight of SCA is about 9.8 kN/cm^3. In the form of pellets, SCA has water content of around 15%, and relatively high percentage (20%) of water absorption. SCA does not exhibit slaking. The permeability of SCA (Table 1) generally is

Table 1
Physical properties of solidified coal ash

Particle size	0% 4.75 mm under, 21% under 9.5 mm
Natural water content (%)	15–18
Bulk specific gravity	1.42–1.46
Amount of water absorption (%)	20–22
Coefficent of permeability (cm/s)	10^{-2}–5×10^{-3}
Slaking ratio (%)	-0.04–-0.7
Crusing strength (4 weeks) (Mpa)	2.1–4.9
Cohesion Cd (KPa)	94.1
Internal friction angle (ϕ d) (°)	40.9

sufficiently high to make SCA a suitable drainage material for certain applications. However, the permeability of SCA is affected by compaction energy, with higher compaction energy resulting in lower permeability. Since, in our experience, an internal friction angle for SCA $\geq 35°$ is required for use in SCPs, the SCA pellet material with an internal friction angle of $\approx 41°$ (Table 1) based on a triaxial compression test is sufficient for this application.

3. Field application tests

To be used as a substitute for sand in SCPs, SCA not only must have suitable material properties but also must be effective in improving the stability of soft ground. M. Kitazume and co-workers [2] showed that the copper slag has high applicability to SCP method for improvement of soft ground. As a result, field application tests were performed to evaluate the ability of SCA to improve the stability of soft ground.

3.1. Field application test at a sandy soil site

A field application test involving an evaluation of the use of SCA as a substitute for sand in SCPs was conducted at a site near a quay in a port. SCP placement was conducted in loose, sandy landfill ground using pellets of SCA. In this field test, 25 piles with diameters of 700 mm and lengths of 10.5 m were placed using a 400-mm-diameter casing. The piles were placed in square patterns at spacings of 1.94 and 2.5 m between pile centers (replacement ratio 7.9%). The results of tests performed on core samples taken after installation of the piles are shown in Table 2.

The results shown in Table 2 indicate that SCA is slightly less effective than sand. However, SCA still possesses sufficient property values to be a useful substitute for sand in SCPs. No adverse effects on the environment were observed. The reduced workability of SCA relative to sand is believed to be due to the adhesion of fine particles generated when crushing the SCA to the casing.

3.2. Field application test at a clayey soil site

An SCP field application test also was conducted at a construction site for a coal storage area. The ground at the site consists of a 7-m-thick clayey fill. Sixteen SCA piles

Table2
Field test results on sandy soil

	Solidified coal ash	Sand
N value of core	17 mean	25 mean
ϕ d of core (°)	37–38	36–38
Permeability (cm/s)	3×10^{-4} $\sim 2\times10^{-3}$	8×10^{-4} $\sim 3\times10^{-3}$

Table 3
Field test (on clayey soil) results of core samples

	Solidified coal ash	Sand
Wet density	1.33–1.45	1.96–2.0
Fine particle content (%)	6–7	3–6
Nvalue of core	16 mean	15 mean
ϕ d of core (°)	37–39.2	38.9–41.2
Cd (KPa)	33.3–50.0	2.9–26.5
Permeability (cm/s)	1.4×10^{-2}–2.1×10^{-2}	4.6×10^{-4}–8.7×10^{-4}

were placed in a square pattern at spacings of 2.0 m between pile centers with a replacement ratio of 9.6%. The results of tests performed on core samples taken after installation of the piles are shown in Table 3.

The standard penetration test (SPT) *N*-value of the pile core was smaller than the value for the test conducted at the sandy soil site, presumably because of the smaller replacement ratio which prevented the SCA piles from restraining each other. No adverse effects on the environment were observed, and favorable values for the permeability coefficient, internal friction angle, and grain-size distribution were measured.

3.3. Field application test in a marine environment

A field application test also was conducted in a clayey soil in a marine environment. The test involved simulating the entire construction process ranging from material transport to pile placement in order to verify the total workability and soil improvement effect.

The SCP ship can place about 1000 m^3 of sand piles per day, which is much more than that placed by onshore machines. The diameters of the casing used and that of the

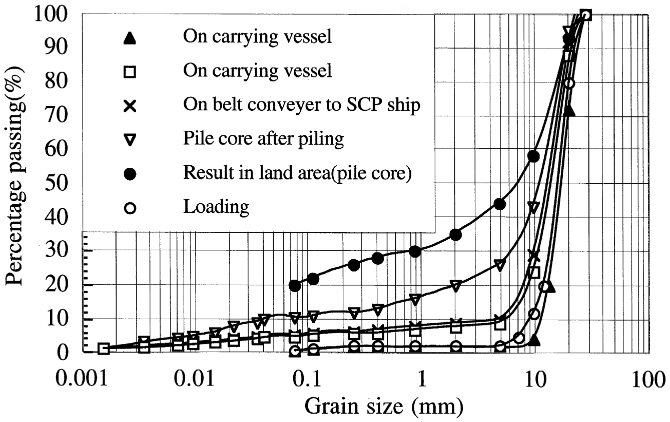

Fig. 1. Change in grain-size distribution during solidified coal ash piling in a marine environment.

Table 4
Field test results in a clayey soil sea bed

	Solidified coal ash	Sand
N value of core	16 min, 20 mean	12 min, 21 mean
ϕ d of core (°)	37.7	not measured
Cd (KPa)	22.6	not measured
Permeability (cm/s)	2.7×10^{-3}	not measured

piles placed are 1200 and 2000 mm, respectively, both of which are larger than those for land applications. Thus, in a marine environment, the replacement ratio typically is higher. In such cases, the piles are expected to serve as a drainage material.

Fourteen SCA piles with lengths of 16–19 m were placed at pitches of 2.1 m with a replacement ratio of 71%. The ground to be improved is soft with an SPT *N*-value of zero at depths ranging from 13 (sea bottom) to 32 m below the sea surface. The natural water content and wet density of the soil were 120% and 13.7 kN/m^3, respectively.

Since SCA is an artificial material that is more fragile than sand or gravel, the grains of the SCA tend to become increasingly smaller as it is handled, as shown in Fig. 1. Nonetheless, the workability of the SCA piles installed in the marine environment was not inferior to that of sand piles, and was better than that observed on land. The whole operation was carried out without hindrance, including material handling. The requirements for soil improvement effect were also satisfied. The results of tests performed on core samples taken after installation of the piles are shown in Table 4.

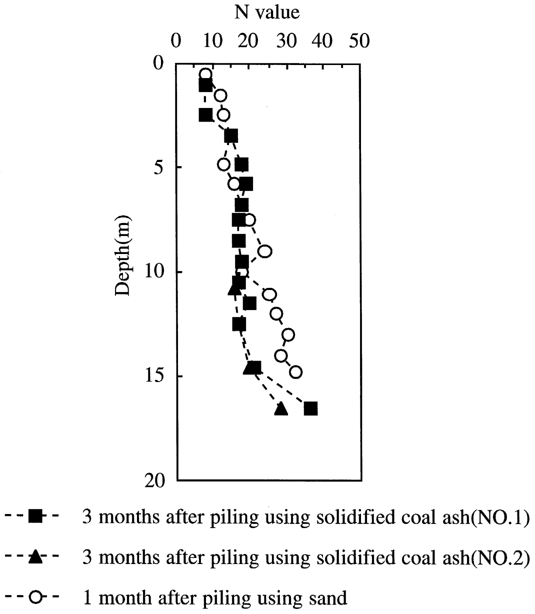

Fig. 2. SPT *N*-values of piling cores placed in a marine environment.

A triaxial compression (CD) test of non stirred pile cores performed 3 months after the placement resulted in an internal friction angle of ≈ 38° and a cohesion of 0.023 MPa, values that are comparable to those previously reported for the same tests performed on the SCPs installed in the sandy and clayey soils on land.

The distribution of SPT *N*-values in the pile cores are shown in Fig. 2. Pile cores checked 3 months after placement had a minimum *N* value of 16 and a mean value of 20. These values compare favorably with those of sand piles (minimum *N* of 12, mean *N* of 21).

4. Adverse effects of SCA on water quality and benthos

When SCA is considered for use in a marine environment, concern arises over the potential for adverse effects caused on the marine environment, particularly on the ecology, resulting from the elution or leaching of cementitious components of the SCA.

The procedure for installation of SCPs in a marine environment and the possible effects on the environment are illustrated in Fig. 3. This procedure may be summarized as consisting of the following steps. First, SCP material is driven into the ground. During this step, the SCA is separated from the environment by the casing (Step 1). After the pile is driven into the ground, the casing is pulled out resulting in residual material being dropped onto the ground surface (Step 2). Once the material has settled, alkaline components elute from the material into the surrounding water (Step 3). After the placement has been completed, the accumulated material is removed and the seabed is leveled to a specified depth (Step 4). Some alkaline components may elute from the SCP piles after installation (Step 5). Finally, structures are installed on the improved ground and the material stabilizes (Step 6).

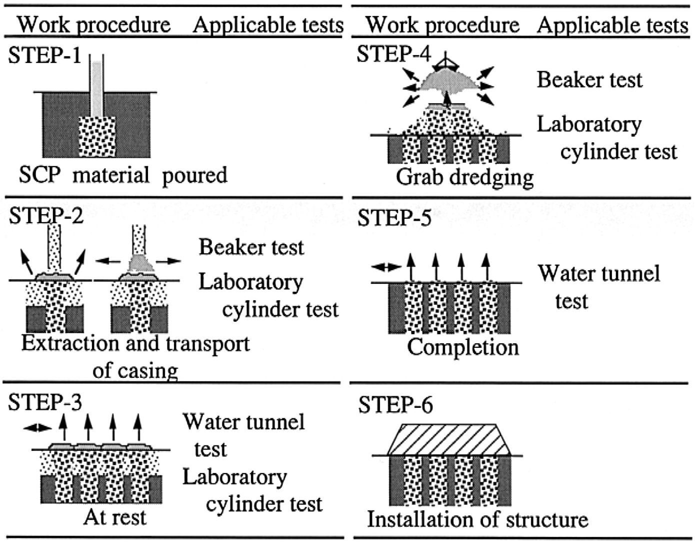

Fig. 3. Marine installation of SCPs and tests to evaluate impact on the environment.

Table 5
Beaker test results

	Sea water	Distilled water
pH	9.4	11.0
Calcium (maximum increase) (mg/l)	280	10
Magnesium (observed) (mg/l)	160	1

4.1. *Tests for evaluating effect of SCA on a marine environment*

4.1.1. *Beaker test*

A study was conducted to measure the elution and diffusion of cementitious components in a mixture of SCA and sea water. The SCA was set and mixed in 500 cm^3 beakers, one containing distilled water and the other filtered sea water at a dilution of 1:100 and 1:500. The results, given in Table 5, show that the pH increased to 11.0 in distilled water, while it was limited to 9.4 in sea water.

4.1.2. *Laboratory cylinder test*

A laboratory cylinder test was performed to simulate the permeation of sea water into piles (Steps 2, 3 and 4 in Fig. 3) to determine how the ratio of permeating water volume to volume of SCA and the change in flow rate of the sea water affects the water quality. The test set-up is illustrated in Fig. 4.

The set-up consists of four 5-l acrylic cylinders filled with SCA or sea sand. The thicknesses of the SCA layers in three of the cylinders were 20, 40 and 60 cm, whereas the sea sand was constructed to a thickness of 40 cm in the fourth cylinder. Sea water was stored in a water reservoir and then supplied from the bottom of the cylinders with fixed delivery pumps, so as to pass through the sample layers and overflow from the top at a constant level. Three flow rates — 5, 15, and 150 l/min — were used in the tests.

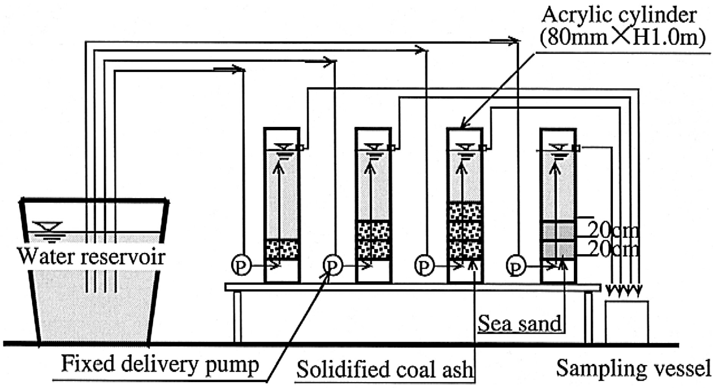

Fig. 4. Set-up of cylinder test.

Table 6
Dilution required for stabilization

	Flow rate (5 l/min)	Flow rate (15 l/min)	Flow rate (150 l/min)
pH	100	5	3
Calcium	10	5	6
Magnesium	3	4	3

After permeation of the cylinders with the three flow rates, almost no change was observed in terms of water temperature, salt content, and conductivity. However, the pH, magnesium, calcium, and alkalinity in the leachate changed depending on the flow rate through the cylinders and the thickness of the SCA layers. Table 6 shows the permeating water volume ratio (i.e., dilution ratio), defined as the total volume of sea water passed through the cylinders divided by the volume of SCA, required to return to the normal quality range of the sea water tested for pH, calcium, and magnesium (i.e., $7.8 \leq \mathrm{pH} \leq 8.4$; Ca ≈ 420 mg/l; Mg ≈ 1500 mg/l).

The test results in Table 6 show that the pH at the lowest flow rate had the greatest influence on the water quality. For example, the volume of sea water passing through the SCA required to decrease the pH to 8.4 was 100 times the volume of the SCA when the flow rate was 5 l/min, five times when the flow rate was 15 l/min, and three times when the flow rate was 150 l/min.

4.1.3. Water tunnel test

After placement of the SCPs, the top of a SCP may be exposed to the surface of the sea bed (Step 3 in Fig 3), or SCA remaining inside the casing may be dropped on the surface of the sea bed (Step 5 in Fig. 3). As a result, a test was conducted to determine the potential effect of elution and diffusion of SCA constitutents into the surrounding sea water under the influence of bottom currents.

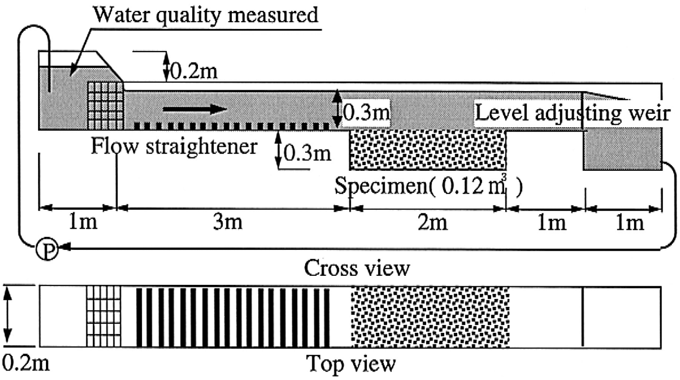

Fig. 5. Set-up for water tunnel test.

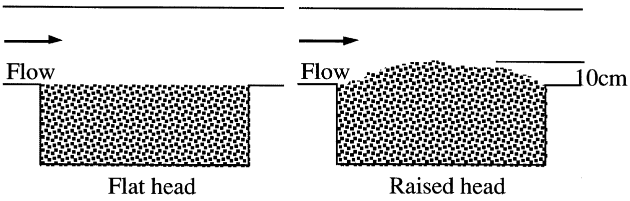

Fig. 6. Schematic profile of sea bed.

When elution and diffusion of alkaline components from SCP material into sea water near the sea bed is considered, the turbulent boundary layers generated near the sea bed also must be taken into account. Thus, a water tunnel that was capable of reproducing turbulent boundary layers over an interval of reduced velocity with relative roughness, i.e., after obtaining a stabilized distribution of flow rates with a flow straightener, was constructed as shown in Fig. 5. Since the shape of the top of the SCP material near the sea bed is assumed to be different before and after dredging to a determined depth (uneven before dredging and even after dredging, as shown in Fig. 6), two cases, one with a flat top and one with a raised top, were tested. The test was conducted using flow rates of 10 and 35 cm/s.

The test results for the water tunnel test are shown in Table 7. The maximum pH value was 8.9, slightly above the quality standard for waste water in Japan (under 8.30). The elution of calcium and the decrease of magnesium caused by such elution was most clearly observed for the raised top and when the velocity was high, but the elution stopped 3 h after the start of the test and stabilized thereafter.

4.1.4. Assessment of impact on benthos

The impact on benthos was assessed by studying primarily the relationship between the content of alkaline compounds eluted from the SCA and the death rate of organisms in the sea area where the SCA was used. The organisms used in the tests were sandworms that are dominant in summer and *Paraprionospio pinnata* that are dominant in winter.

The assessment consisted in breeding sandworms and *P. pinnata* for 48 h in an alkaline solution of SCA diluted to five different ratios, and counting the dead population to determine the pH corresponding to the concentration at which 50% of the population dies (i.e., 50% lethal concentration, or LC_{50}). The alkaline solution was made with SCA and with sea sand. Fig. 7 shows the breeding set-up.

Table 7
Water tunnel results

	10 cm/s		35 cm/s	
	Flat	Raised	Flat	Raised
pH	8.6	8.2	8.45	8.9
Maximum increase of Calcium (mg/l)	50	75	32	90
Minimum decrease of Magnesium (mg/l)	40	23	15	30

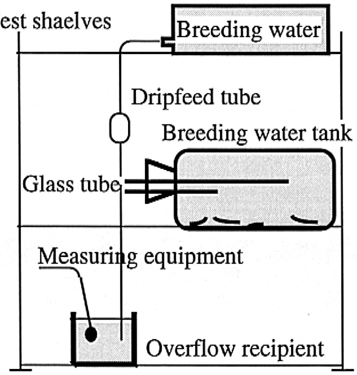

Fig. 7. Breeding set-up.

In the assessment, particular attention was given to the dissolved oxygen (DO) content of the water to ensure a good metabolism for *P. pinnata*. The breeding tanks were filled in advance with an alkaline solution diluted to four different ratios, and the behavior and dead population of *P. pinnata* were observed immediately, as well as at 12, 24, 36 and 48 h after starting the assessment.

4.1.4.1. Results of assessment for P. pinnata dominant in winter. The assessment showed a proportional relationship between the concentration of the alkaline solution and the pH. The higher the concentration of the alkaline solution, the quicker the apparent impact on *P. pinnata*. The dying *P. pinnata* all passed through the same cycle of change in appearance, which went from ‘‘normal’’ to ‘‘congested’’, ‘‘whitened’’, ‘‘softened’’ and ‘‘dead’’, with no exception. The pH of an alkaline solution made with SCA and diluted to a level corresponding to the LC_{50} for *P. pinnata* (i.e., 68%) was determined by linear regression to be 9.9.

4.1.4.2. Results of assessment for sandworms dominant in summer. The assessment showed a proportional relationship between the concentration of the alkaline solution and the pH. As was seen for *P. pinnata*, the higher the concentration of the alkaline solution, the quicker the apparent impact on sandworms is. The pH of an alkaline solution made with SCA and diluted to a level corresponding to the LC_{50} for sandworms (i.e., 93%) was determined by linear regression to be 10.2.

The effects of alkaline solutions made with SCA on sandworms compared to those on *P. pinnata* are summarized in Table 8. The effects on *P. pinnata* were assessed in winter.

Table 8
Effect of alkaline solution

	Sandworms	*P. pinnata*
pH corresponding to 50% lethal concentration	10.2	9.9
pH affecting on appearance or behavior	10.0	8.8

4.2. Outdoor large tank permeation test

The purpose of this test was to assess the impact of the SCP method using SCA on water quality and sea life (attached organisms and bottom fauna). The test was conducted by passing sea water through an outdoor tank filled with SCA which was maintained as far as possible in its natural environmental condition.

4.2.1. Test method

A schematic view of the test set-up is shown in Fig. 8. Sea water was pumped into a reservoir, from where it was sent to cylindrical tanks filled with SCP materials. Water

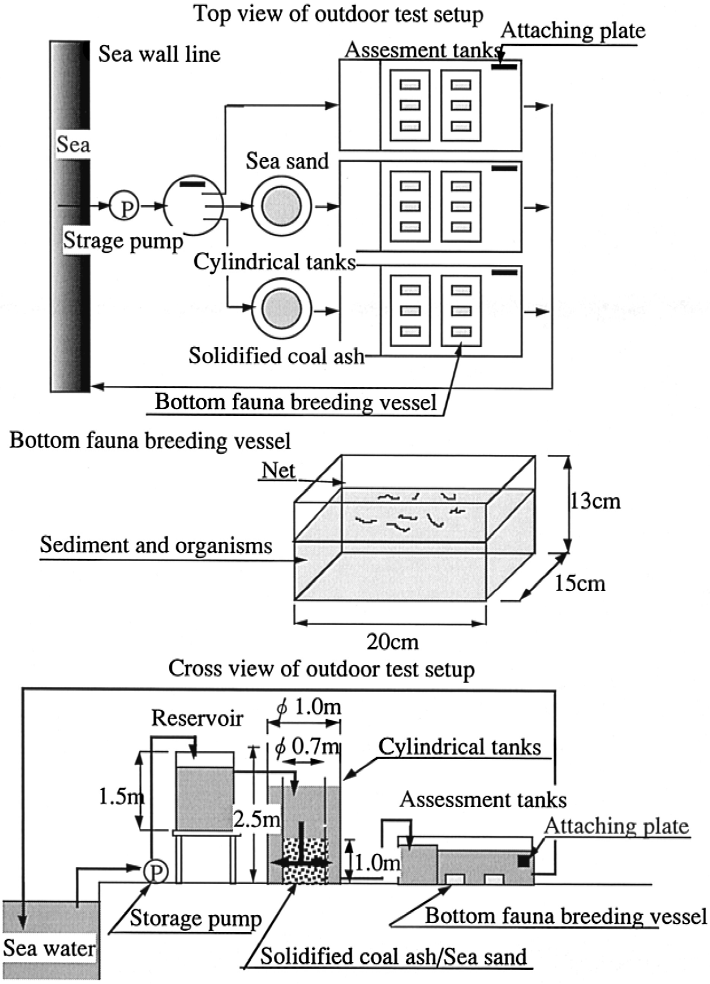

Fig. 8. Set-up of outdoor tank permeation test.

that was passed through the sample layers was extracted from the intermediate bottom of the tanks and sent to the assessment tanks. Sea water was continuously circulated through the test apparatus, and water passed through the sample layers was extracted from the bottom of the tanks and sent to the assessment tanks.

One cylindrical tank was filled with a 1-m-thick SCA and another tank was filled with sea sand. A third tank with no sample layer was assessed for comparison. The tests were conducted in winter (January to February) and summer (July to August), each for a period of 1 month.

4.2.2. Results of assessment impact on water

The assessments conducted in winter and summer showed no difference between water that had been passed through sea sand and through SCA in terms of temperature, salt content, DO, conductivity, COD, nitrate nitrogen, nitrite nitrogen, total nitrogen, and phosphoric acid content. Water that permeated SCA had lower values for SS, TOC, and chlorophyll a, than raw sea water due to filtration.

The results with respect to magnesium, calcium, and pH are shown in Table 9. The magnesium concentration decreased by about 80 mg/l in the first stage because magnesium changed to $Mg(OH)_2$ and precipitated. The magnesium concentration increased to the normal level of sea water after 3 days of permeation, and then showed the same behavior as sea water. In both the winter and summer tests, the value increased by more than 120 mg/l from the normal level of sea water in the early stage of permeation and decreased gradually thereafter to the normal level of sea water (i.e., Mg $\approx$ 1500 mg/l).

The pH value of water passed through SCA increased immediately after starting the test and continued up to 9.4 in winter and up to 8.8 in summer. Thereafter, the pH decreased gradually and stabilized at the upper limit of the range of variation of sea water (i.e., pH $\leq$ 8.4).

The permeating water volume ratio, defined as the total volume of sea water passed divided by the volume of the sample, required for normal level of natural sea water is given in Table 10. The pH and calcium concentration increased in the early stage of permeation, then gradually decreased to the normal level of sea water (i.e., pH = 8.4; Ca $\approx$ 420 mg/l)as permeation continued. The magnesium concentration decreased in the early stage of permeation, but gradually increased to the normal level of sea water (i.e., Mg $\approx$ 1500 mg/l) as permeation continued. The permeating water volume ratio was 210 times the volume of the sample for pH.

Table 9
results of outdoor large tank permeation test

	Winter test	Summer test
pH	9.4	8.8
Maximum increase of Calcium (mg/l)	80	80
Minimum decrease of Magnesium (mg/l)	120	140

Table 10
Permeating water volume ratio required for normal sea level

	Winter test	Summer test
pH	210 times	210 times
Calcium (maximum increase)	160 times	20 times
Magnesium (minimum increase)	20 times	30 times

4.2.3. Results of assessment of impact on benthos

The results of the winter test in terms of the remaining population of *P. pinnata* are shown in Fig. 9. For the population of *P. pinnata* that was tested immediately after starting the water circulation, the survival rate was 100% for case 1 in which they were exposed to the flow for 24 h, and 80% for case 3 in which they were exposed for 3 days to sea water permeating sea sand.

The survival rate was similar for case 2 where the test organisms were counted on the first day and then placed into the flow again to be exposed for 2 days. The survival rate was 90% for case 4 where they were placed into the flow of sea water on the third day of circulation to be exposed for 2 days. The survival rate was 100% for all the cases where they were placed into the test on the third day and exposed to the flow for 7 consecutive days. On the other hand, the survival rate was 100% for all the cases using

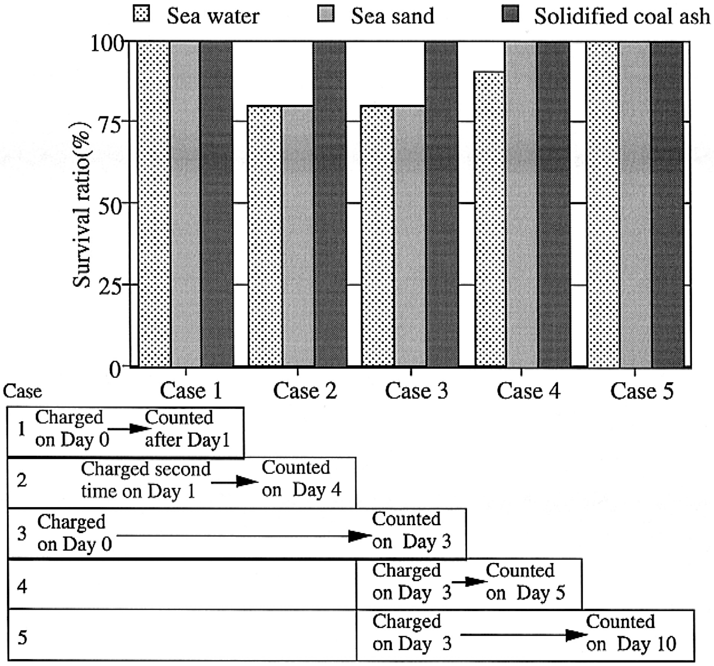

Fig. 9. Results of counting the remaining population of *P. pinnata* for the winter test.

Table 11
Amount of attaching organisms (g/400 cm^2)

Place of installation	Blank	Sea sand	Solidified coal ash
Winter test	3.19	5.47	3.09
Summer test	57.11	33.59	31.59

the SCA tank in which *P. pinnata* was bred in water passing through SCA. The test results for the summer test using sandworms were similar to those for the winter test case using *P. pinnata*.

The amount of organisms found on the attaching plates are given in Table 11. For the winter test, large attaching organisms such as sandworms, acorn shells, and blue mussels were not found. However, for the summer test, the amount of attaching organisms was nearly 10 times that found in winter due to the development of biological activity.

A large amount of attaching organisms was found in the sea sand tank exposed to water that was permeated through sea sand in the winter test. For the SCA tank that contained water that had permeated SCA, the wet weight of attaching organisms observed was almost the same as in the blank tank. For the summer test, the greatest amount of attaching organisms was found in the blank tank, while the amount of attaching organisms was similar for tanks containing either sea sand or SCA. In the summer, when biological activity is more abundant, the amount of attaching organisms exposed to water that had permeated sea sand was similar to the amount of attaching organisms exposed to water that had permeated SCA (i.e., about 31–33 g per plate), suggesting that SCA has virtually no impact on these organisms.

4.3. Change in pH measured in field test

The model experiments described above suggested that SCA has virtually no impact on sea life. However, the most reliable data is obtained by observation in a field application. For this reason, a survey was conducted to study the impact of SCA on water quality and benthos at a SCP work site in a marine environment.

A survey was conducted during the SCP work to study the change in pH and the effect of diffusion on the surrounding turbidity of the sea water. The pH was measured every 15 min for 24 h starting before the SCP work with multipurpose water quality monitoring systems installed at a depth of 0.5 m below sea level and 1 m above the sea bed near the SCP work points. Water was also sampled and checked for pH five times in total before commencement of work until 7 days after completion of the work at five points in nearby areas. Furthermore, the turbidity of water was measured in the area around the SCP work site to study the potential effects of diffusion on the turbidity in sea water during the piling work.

The results of the continuous measurement of pH showed a slight change within the range of 7.9–8.0. As for benthos, the survival of sandworms suspended in sea water was confirmed and no impact of the SCP work was observed in terms of number of species, population, or wet weight, although the circumstances of their appearance differed depending on the location.

5. Conclusion

The conclusions to be drawn from the results reported in this study are as follows:

- The strength, permeability, and grain-size properties of SCA are all suitable for use in soft ground improvement applications.
- From the results of field tests, the use of SCA as a substitute for sand in SCPs for improvement of soft ground results in an equally good performance and therefore, represents a viable alternative to sand.
- An impact on benthos for SCPs installed using either sand or SCA in marine environments was observed only when the pH value was higher than 10.0 for sandworms and 8.8 for *P. pinnata*.
- No impact of the elution from SCA on the survival of *P. pinnata* and sandworms was observed.

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