Use of Respiration in the Sandy Beach or on the Tidal Flat: 1. Permeable Sandy Beach

ICHITARO SAKAMOTO
Shin Nippon METOCEAN Consultant Co., Ltd, Edobori 3-2-23, Nishi-ku, Osaka, 550 Japan

There are two types of respiration of the marine beaches. One is the sandy beach type, where air and sea-water shift each other in the porous space of the permeable soil. The other is the tidal flat type, where air and sea-water shift each other on the surface of nonpermeable soil.
Both types are noted distinguished function of aerobic decomposition rapidly mineralizing organic materials brought in by water of flood tide in the natural system. The former is especially effective for removal of organic load in dissolved form, while the latter is effective in suspended particulate form. This is because in the former type performed by microorganisms adhered on sand particles, while in the latter type the same function is performed by burrowed macrobenthos.

The function of beaches for disposition of heavy organic loads flowing along the shoreline, silently in pure natural system, has been utilized by the laver farm in coastal waters through introduction of the floating net-rafts. Appraisal of the respiratory function of the beaches has been further accelerated in view of conservation of coastal water quality, supported by the trend of water intimacy and growing recognition of amenities. This has led to construction of beaches not only conservation but also imitated man-made beaches in the 1980's.

Based on the continued observation since 1953, an outline of quantitative estimates and characteristics of respiratory functions of sandy beaches is presented for choice the skill of beach innovation projects and improvement of such construction works.
In view of growing concern to deal with the chaotic conditions along coast brought by occasional oil spills, practical application method of sands and respiratory function of sandy beaches is also presented.

1. The Median Diameter of Beach Soils and Shift Porosity of the Sandy Beach

The sandy beach is a space filled with well sorted grains of sand. Fig. 1 shows an example of vertical construction of the sandy beach on a volume basis, which is composed of sand particles classified by diameters, captured water, shift pore space for air and water, and of bubbles. It is mostly dried up down to 5 to 10 cm underground, since the captured water is lost with break in capillary water due to evaporation from the ground surface. There is a capillary rise layer 2 to 5 cm thick near the free ground water head rising and falling with variation of tide level. The respiratory moving volume of water per cycle of the tide is equal with the total amount of shift porosity corresponding to the difference in free water head.

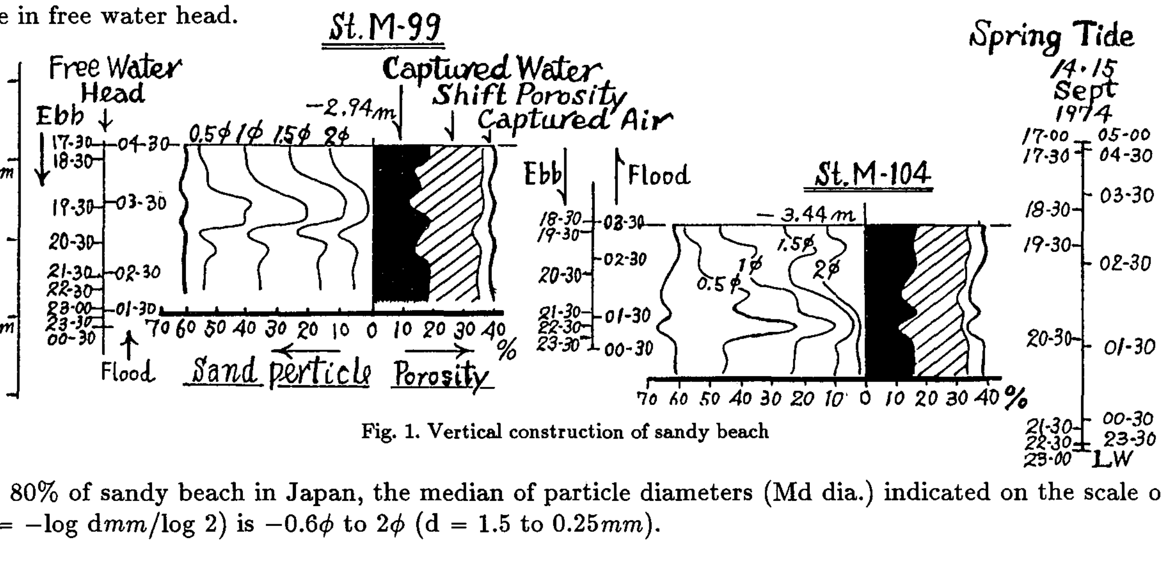

Fig. 1. Vertical construction of sandy beach

For 80% of sandy beach in Japan, the median of particle diameters (Md dia.) indicated on the scale of ϕ (= $-\log d mm/\log 2$) is -0.6ϕ to 2ϕ ($d = 1.5$ to $0.25 mm$).

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From many samples, the following empirical formula has been obtained as a correlation of porosity (**n**), captured water porosity ($\mathbf{n}_{\mathrm{Lmin.}}$) and Md$\phi$:

$$\mathbf{n} = (9.8+\mathrm{Md}\phi)/27$$

$$\mathbf{n}_{\mathrm{Lmin}} = (1.11+\mathrm{Md}\phi)/12 \qquad \text{eq. 1}$$

$$\textit{Shift porosity} \leqq \mathbf{n}-\mathbf{n}_{\mathrm{Lmin}} = 0.27-0.0463\cdot\mathrm{Md}\phi$$

A relation between the porosity and Mdϕ is shown in Fig. 2 where the hydraulic pore depth computed as **porosity/total surface area of particles** is also indicated.

If a space is filled with a single diameter of spherical particles, the porosity (**n**) will lie between 0.26 in dense filling and 0.48 in rough filling.

No shift porosity exists for fine silt and clay with Mdϕ of particles more than 6ϕ, and once they are saturated with water, there is no means of volume restoration but drying. For particles more than 4ϕ, the thickness of shift porosity reduces to less than 2 micron and water permeability is lost. On the other hand, with particles less than -1ϕ (pebble), the capability of capturing water is lost.

The "sand" defined by Wentworth (1922) for the range from -1ϕ to 4ϕ, insures in its character both the capability of capturing water and permeability.

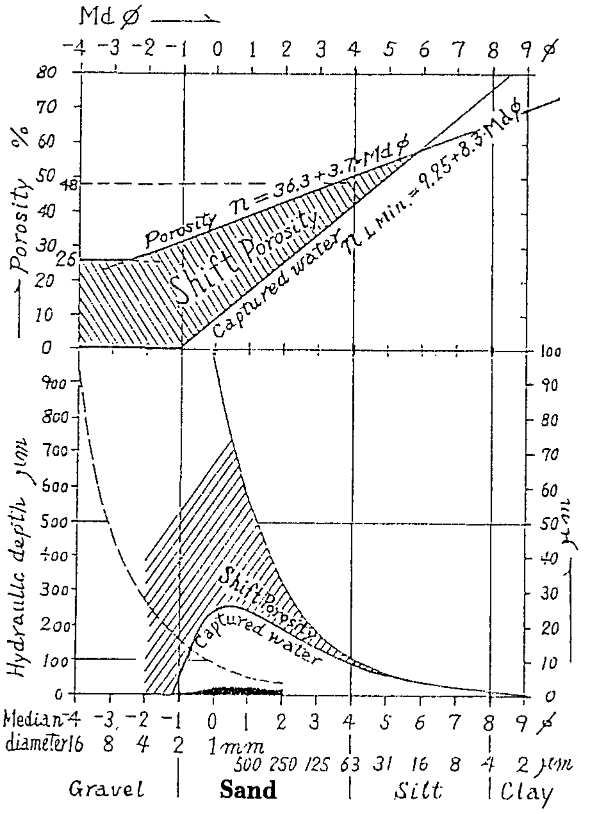

Fig. 2. Porosity and Hydraulic Depth of beach soil related to the Median Diameter.

2. Moving Volume of Pore Water

The difference in water head between the free water head in the sandy beach and the sea level serves as a power source to cause intrusion of water into the shift porosity and discharge of air from it on the flood tide, and when saturated with water, a gloss appears on the ground surface. The gloss disappears with discharge of water and intake of air on the ebb.

From a low water level of the neap tide, the oozedout-water on the ebb tide turns into surface water and runs out grooving the ground surface on the lower slope of the tidal zone.

From the measurement of shift porosity the result of which, is shown in Fig. 1 and the intertidal observation of corresponding free water head, the intertidal lapse time change of free ground water head and of moving volume can be estimated as shown in Fig. 3.

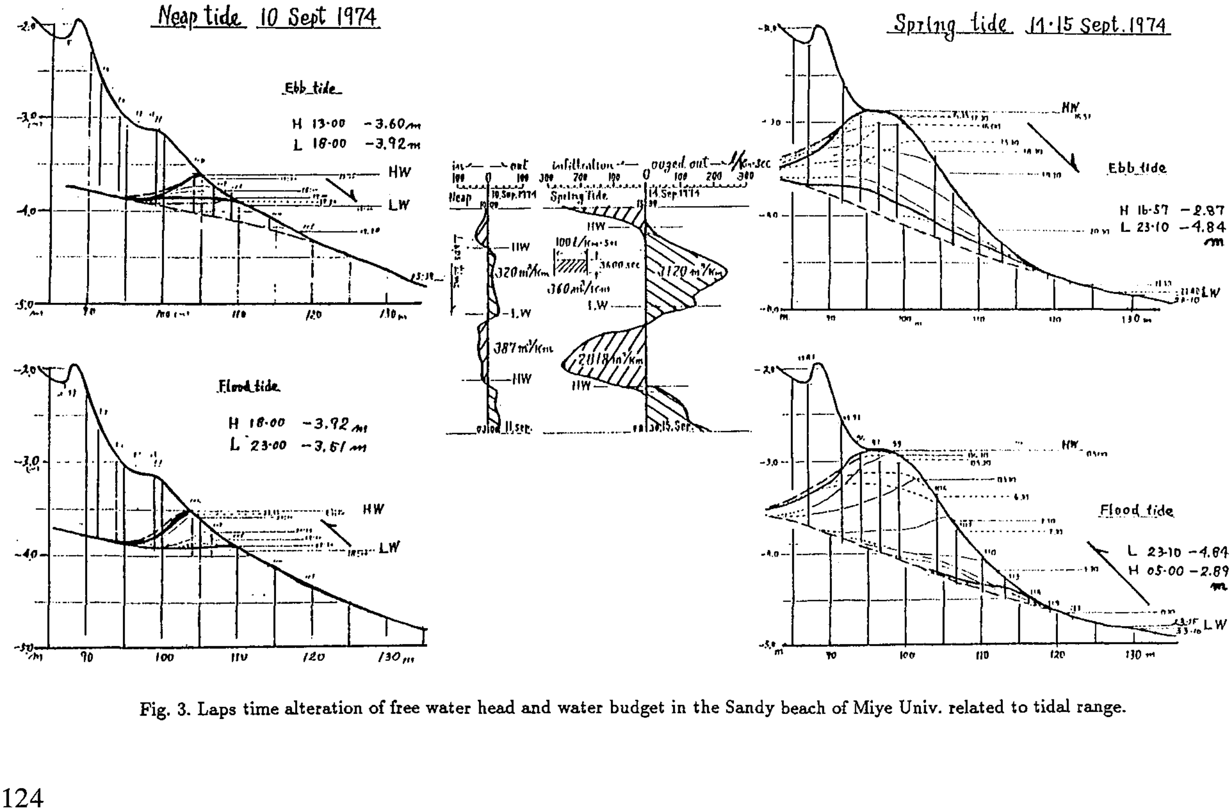

Fig. 3. Laps time alteration of free water head and water budget in the Sandy beach of Miye Univ. related to tidal range.

In this frontal beach M of Miye University, the volume of the water flowing in and out of the sandy beach per cycle of tide was about $3000m^3/km$ at a spring tide with $195cm$ of tidal range, while it was about 350 m^3/km at a neap tide with $31cm$ of tidal range. This shows the distance of tidal intrusion into the sandy beach at the mean sea level was only about 65% of that at the spring tide.

3. Structure of Soil Temperature of the Sandy Beach

Surface temperature of a dry sandy beach sometimes exceeds 50° C in the afternoon in summer, and sometimes results in appearance of **freezing sand scales** before sunrise in winter even in Ise Bay. Though its variation by day and night is very wide, the temperature of wet sand in a layer about $20cm$ underground is much moderated.

Calculated values of thermal characteristics for unit volume of beach sand, corresponding to dryness, wetness and saturation with water, are indicated in Table 1. Since sand grains contact together with points touch, **Dry** heat conductivity is smaller in reality than shown in the table and they form adiabatic layer.

Table 1. Thermal Character of Beach Sand for Volume Base

	Sand	Water	Air	Density	Specific heat	Heat capacity	Heat conductivity	Reflectance
Air				0.0012	0.24	0.0003	0.003	
Water				1.02	1.00	1.0	0.06	
Sand				2.65	0.19	0.51	0.18	
Dry Sand	60	–	40	1.590	0.19	0.51	(0.109)	18~28%
Wet Sand	60	20	20	1.794	0.253	0.57	0.121	ca. 10%
Water saturated Sand	60	40	–	1.998	0.355	0.61	0.132	

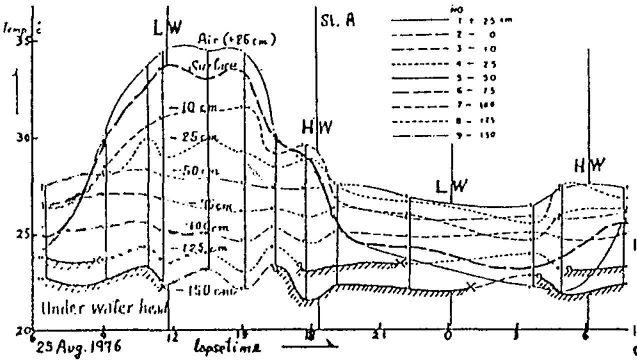

Fig. 4. Laps time temperature in the **Beach of Miye Univ.**

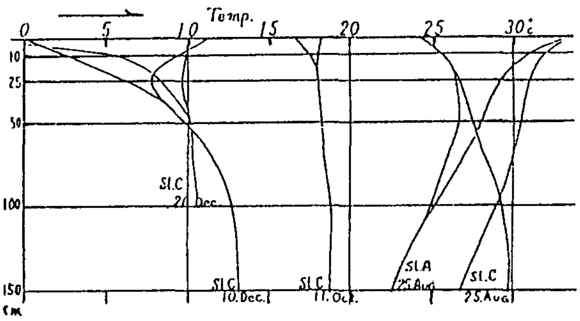

Fig. 5. Vertical distribution of daily Max. and Min. temp.

An example of the lapse time change of soil temperature in each layer which was recorded continuously with thermister chained drill in summer of 1976, is shown in Fig. 4. A day-and-night inversion layer had been formed by the part upper than about $-25cm$. On a clear night, the vertical distribution of temperature turns to have a pattern of **"Head Cooler with Leg Warmer"**. Saturated water vapor is conveyed through the air pore to the surface layer of the sandy beach, condensed into water-drops, and results underground rainfall formed on the ground surface into the sandy beach. This mechanism of conveyance of water to the ground surface at night led to a means of restoration of pine woods on the sandy beach which has been utilized by Dr.M.Umebayashi (1986), my cooperator in this research.

An example of the vertical distribution of soil temperature including its seasonal variation, is shown in Fig. 5. Depth of the day-and-night inversion layer sometimes reaches $-100cm$, and the gradient in the pattern of **"Head Cooler with Leg Warmer"** at night is more notable in winter.

In the backmost part of the tidal sphere in the sandy beach including offshore sand-banks, there are always **pore ponds of fresh water** drifting.

The range of the change of soil temperature in uncovered sandy beaches is remarkably wider than that of the change of sea water temperature on the beach-line. Fig. 6 shows the result of the investigation by my cooperator, Dr. K. Hayashi (1979) in which the influence of temperature on phosphatase activities of microorganisms adhering to sand particles, was examined from the organic phosphorous compound (paranitrophenyl phosphate) decomposing activity per liter of beach sand. For the sand in summer, Q_{10} is about 2 in the range up to 35° C and drops at a higher temperature to about 1.5 in the range up to 50° C. For the sand in winter, so long as its temperature is raised, Q_{10} is about 2.5 in the range up to 30° C, which shows the activity rises more than for the sand in summer.

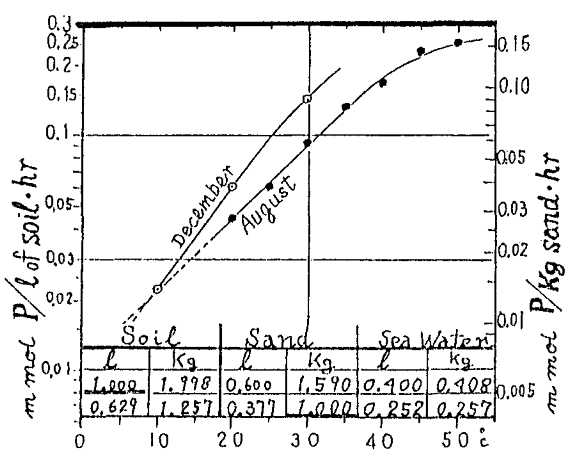

Fig. 6. Phosphatase activity related to temperature

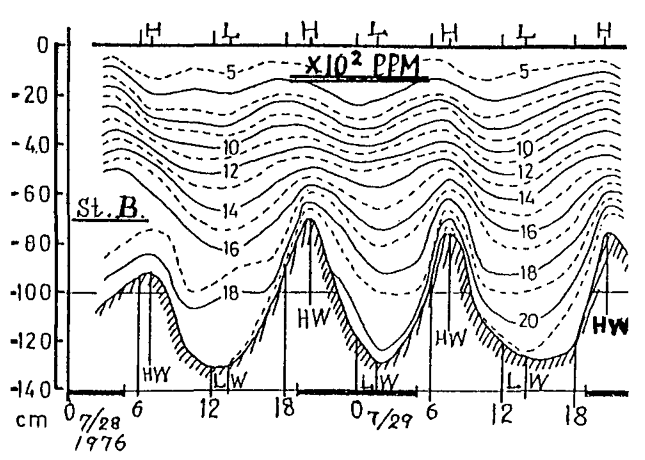

Fig. 8. Daily isopleth of CO_2 $10^2 ppm$ in air porosity

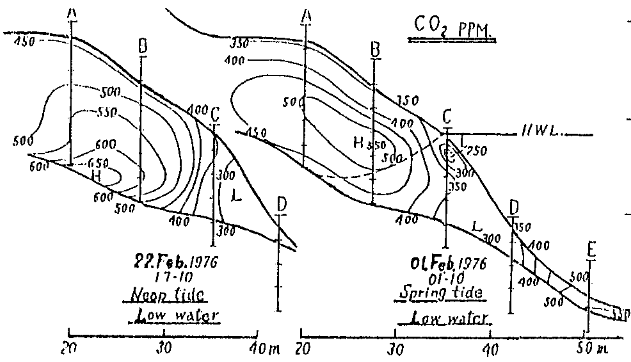

Fig. 7. Sectional distribution of CO_2 in winter season

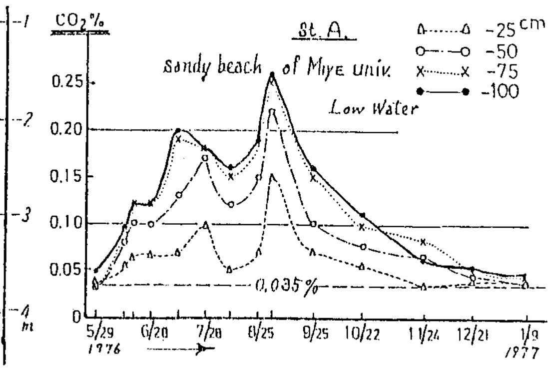

Fig. 9. Seasonal change of CO_2 level in air porosity

The result of the measurement by Dr.M.Umebayashi is which he determined by gas chromatography, the concentration of CO_2 in specimens sampled at low tide from the air pore at a spring tide and a neap tide in winter when microbial activities are markedly inhibited due to low temperature, is shown in Fig. 7 in sectional distribution. Just over the tidal sphere, the center of a sphere with a high concentration about 2 times as high as the concentration in the standard atmosphere remains. Among the isopleths for a hot summer season, shown in Fig. 8, a concentration higher than 2,500ppm, that is, 7 times as high as the concentration in the atmosphere, is found. Violent progress of aerobic decomposition of organic materials may be imagined from the above. An example of yearly seasonal changes of the CO_2 concentration in each layer is shown in Fig. 9. It is clear that the biochemical respiration continues through a year though it is controlled by soil temperature. This means that not only the dissolved oxygen in the sea water on the beach-line which intrudes on the flood tide, but also the oxygen in the atmosphere which intrudes from the ground surface to diffuse into the pore space on the ebb, contributes to the decomposition of organic materials in the captured water.

The cyclic exchange of air for water with the substance of biochemical aerobic decomposition incorporated has been defined as "**Respiration of the Sandy Beach**".

4. Exchange Rate of Captured Water

The sea water on the beach-line which has intruded into the shift pore space in the sandy beach on the flood tide, mixes with the captured water while it flows through the pore space between sand particles, and the mixed water oozes out form the sandy beach on the ebb. The result of an estimation tried through a model experiment, for the exchange rate of captured water per cycle of tide, is shown in Fig. 10. At a speed corresponding to a round trip time within one hour per meter of sand column, a turbulent mixing occurs, and the higher the speed is (the shorter the round trip time is), the larger exchange ratio is reached. Besides, the more smaller the salinity of intruding water (S in) is than that of captured water (S cap), the larger the exchange ratio comes.

Where round trip time is 12 hours in the range from −10 to +30pss of ΔS = S cap − S in, the exchange ratio (R%) is given by the following empirical formula:

$$R\% = 35 + 0.917 \cdot \Delta S \qquad \text{eq.2}$$

With no difference in Salinity, R is 35%. If the capture water is lower in salinity than the intruding water, it is pushed up by the dense water and reseats at the ebb, and such process is repeated. Nevertheless more than 15% is exchanged for every saturation with water.

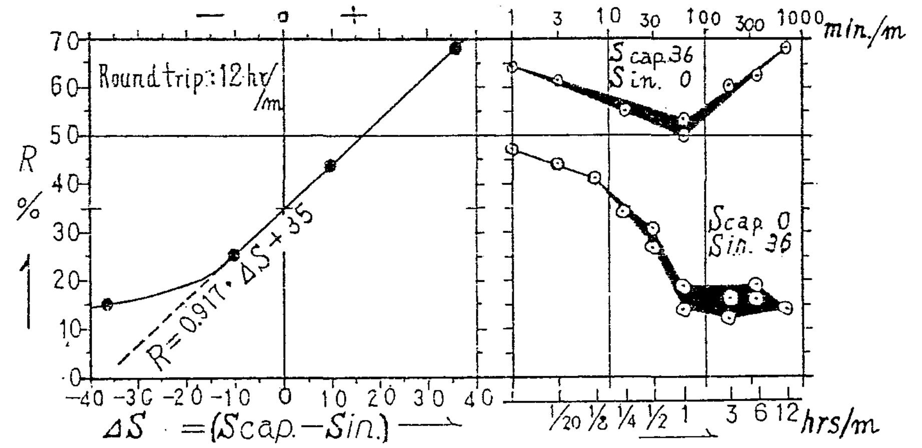

Fig. 10. Exchange rate of the captured water related to the salinity of intruding water and speed of the flooded round trip

5. Removal of COD by Respiration in Sandy Beach

In order to grasp the seasonal change of the respiratory function in the sandy beach of Miye University, intertidal observations were performed 21 times extending over two years till the end of 1978.

Table 2. Removal Rate of Organic (COD) Load, and its analysis

Beach of Miye Univ.		Environment		Observed		Expected		Difference			Removal Rate		Obs./Exp.	
		Temp.	Org.Load	Removed	Oozed Out	Remove	Out flow	Re.−Exp.						
	Date	θ	L	Re	Out	exRe	exOut	=ΔRe	ΔRe/exRe	−ΔRe/exOut	Re/L	exRe/L	Re/exRe	Out/exOut
No	Y. M. D	℃	$\mu g \cdot at.COD/l$						%					
1	1976 1 22	6.0	218	68	150	84.2	133.8	−16.2	−19.2	12.1	31.2	38.6	80.8	112.1
2	12 09	12.0	120	96	24	66.4	53.6	29.6	44.6	−55.2	80.0	55.3	144.6	44.8
3		13.2	120	60	60	69.4	50.6	−9.4	13.6	18.6	50.0	57.8	86.5	118.5
4	1977 05 03	18.5	258	206	52	163.0	95.0	43.0	26.4	−45.3	79.8	63.2	126.4	54.7
5		24.6	258	197	61	185.3	72.7	11.7	6.3	−16.1	76.4	71.8	106.3	83.9
6	6 11	22.7	153	84	69	110.6	42.9	−26.6	−24.1	62.7	54.9	72.3	75.9	162.7
7	7 2	23.7	246	199	47	174.5	71.5	24.5	14.0	−34.3	80.9	70.9	114.0	65.7
8	20	27.2	259	209	50	194.6	64.4	14.4	7.4	−22.4	80.7	75.1	107.4	77.6
9		28.5	252	204	48	193.8	58.2	10.2	5.3	−17.5	81.0	76.9	105.3	82.5
10	8 15	25.5	291	221	70	210.4	80.6	10.6	5.0	−13.2	75.9	72.3	105.0	86.8
11	16	28.0	414	312	102	303.2	110.8	8.8	2.9	−7.9	75.4	73.2	102.9	92.1
12	23	25.1	255	186	69	185.0	70.0	1.0	0.5	−1.4	72.9	72.5	100.5	98.6
13	10 12	21.4	169	85	84	118.0	51.0	−33.0	−28.0	64.7	50.3	69.8	72.0	164.7
14		20.5	169	110	59	115.8	53.2	−5.8	−5.0	10.9	65.1	68.5	95.0	110.9
15	1978 2 6	6.3	39	21	18	17.7	21.3	3.3	18.6	−15.5	53.8	45.4	118.6	84.5
16	5 11	17.7	82	73	9	55.8	26.2	17.2	30.8	−65.6	89.0	68.0	130.8	34.4
17	6 20	27.6	365	183	182	268.4	96.6	−85.4	−31.8	88.4	50.1	73.5	68.2	188.4
18	7 20	28.0	837	773	64	578.6	258.4	194.4	33.6	−75.2	92.4	69.1	133.6	24.8
19	9 18	26.3	89	72	17	71.9	17.1	0.1	0.1	−0.6	80.9	80.8	100.1	99.4
20	11 1	18.3	125	78	47	83.4	41.6	−5.4	−6.5	13.0	62.4	66.7	93.5	113.0
21	12 1	12.7	119	54	65	68.1	50.9	−14.1	−20.7	27.7	45.4	57.2	79.3	127.7
Range		6.0~28.5	39~ 837	21~ 773	9~ 182	18~ 579	17~ 258	−33~ 194	−32~ 45	−75~ 88	31~ 92	39~ 81	68~ 145	25~ 188
Mean		20.7	230.4	166.2	64.1	158.0	72.4	8.2	2.2	-3.4	68.0	66.6	102.2	97.5
Median			218	110	61	118	58	3	3	-8	75	70	103	92

The difference in COD between the beach-line water and the water oozing out of the sandy beach on the ebb, indicates the capability of mineralizing, or removal, of organic materials in the sea water on the beach-line, as the overall result of the removal of 1) suspended minute particulates by trapping through filtration in the surface layer on the beach-line, 2) the aerobic decomposition of dissolved organic materials in the course of passing through the pore space in sand, 3) the exchange of water body with the captured pore water, 4) the continuation of aerobic decomposition by intruding atmosphere of organic materials in the captured water, 5) the strong cleaning and oxidization of organic materials in particulate form trapped on the beach-line, etc. This is located in the category of "**Purification**" from the view point of lightening of a burden to the dissolved oxygen in the intruding water, because the intruding atmosphere takes part in keeping the aerobic condition.

According to the results of observations, as shown in Table 2, the COD load (L) from the intruding water was 39 to 837 $\mu g \cdot at.COD/l$ (0.6 to $13.4 mgCOD/l$), and the residual COD in the oozedout water was 19 to $182 \mu g \cdot at.COD/l$ (0.14 to $2.91 mgCOD/l$), therefore 21 to 773 $\mu g \cdot at.COD/l$ (0.34 to $12.4 mgCOD/l$) was removed.

It was concluded that the expected removal of COD ($exRe_{COD}$) may be given by the following multiple regression formula with soil temperature ($\theta° C$) and the load (L_{COD}) from the intruding beach-line water taken as monad:

$$exRe_{COD} = 0.263 \cdot L_{COD}^{0.918} \cdot \theta^{0.450} \quad \left[\begin{array}{c} 5 < \theta^{\circ} C < 30. \\ 30 < L_{COD}\, \mu g \cdot at/l < 1000. \end{array}\right] \qquad \text{eq.3}$$

$$(n = 21 \, , r^2 = 0.928)$$

A diagram for the expected removal rate with the observed removal rate appended is shown in Fig. 11.

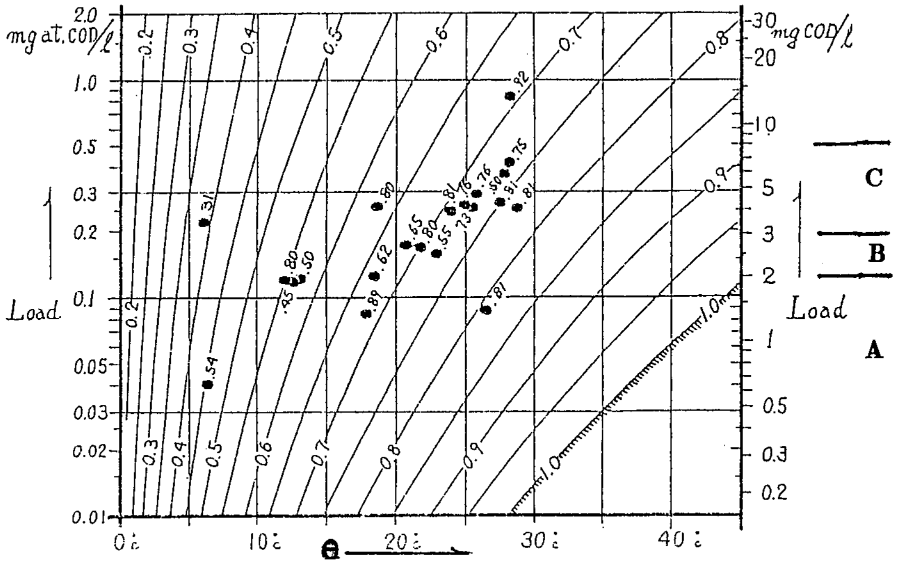

Fig. 11. Diagram for the Removal Rate ($exRe_{COD}/L_{COD}$) of organic load related to temperature and load magnitude at the beach of Miye University.

While the typical standard values A, B and C based on COD (respectively 2, 3 and $8 mgCOD/l$. and less) are established for the coastal waters of Japan, the standard for discharge into the waters is $20 mgCOD/l$. and less, and an extraordinary biogenetic rise of the COD value in the waters is the rule in the innermost part of inland bays. It is to be desired that the respiration in sandy beach should be rated high in view of its qualitative effect on preservation of water quality along the shoreline, since its extremely **stable function corrects and purifies continuously even nonconforming water of C type to conforming water of B or A type.**

6. Adsorption of Heavy Oil by Sands and Decomposition in the Tidal Sphere of Sandy Beach

In every accidental oil spill, large scale mobilization has come in operation and longterm great confusion has been raised, for withdrawal work with oilabsorbing polypropylene mats and for atomization and dispersion work by surface active agent. Besides, the incineration of withdrawal mats has caused local air pollution. Getting a hint from observation of the process where the driftedashore oil which was sandwiched in the sandy beach disappears without traveling, we studied utilization of sand as oil-absorbtive material and an oil disposal process by natural decomposition in the sandy beach.

Combinations of the beach-line sand 1 to $1/4 mm$ in grain diameter (Mdϕ : $1.15\phi = 0.45 mm$) from which all pebbles had been removed, and the fuel heavy oil B the character of which is shown in Table 3, were tested. Oil was extracted with CCl_4 and its content was determined quantitatively from the calibration curve on an average of the infrared absorbance at three wave lengths near $\lambda = 3.4 \mu m$.

Table 3. Character of IB oil

ρ	ν	FluidPt.	FlushPt.	ResidualC	$Kcal/l$	C	H	S	N	
0.911	29.8cst	−10° C	99° C	54.7g/l	9612	778.0	113.9	17.7	1.46	g/l
						64.8	113.0	0.55	0.104	$atoms/l$

Table 4. Catch Oil Rate of the beach Sand (Mdϕ = 1.15ϕ)

	Initial Pore	Sand	IB-Oil	Pore	Oozed Out	ρ	Weight
Dry Sand	Air 400	600	2 8 0	218 Air	182 Air	1.68	1.845 ton/1.098m³
Wet Sand	Sea Water		2 7 4	224 S.W.	176 S.W	1.88	2.069 ton/1.098m³
Water saturated Sand	1000 Initial Sand		1098 Oil Sand		(liter)	Formed Oil Sand	

The results of the test on dry sand and on wet sand saturated with sea water are shown in Table 4. Little difference was found between dry and wet sand in the amount of absorbed oil per unit volume of sand. About $1m^3$ in virtual volume of beach sand with porosity of 0.4 turned into the oil sand which expanded in virtual volume by about $100l$, after it absorbed about $250l$ of 1B oil. This means pore gas or captured pore water were discharged by about $180l$ in all.

A required quantity of oil saturated sand was diluted to a volume 3 times as much as its initial volume by adding sand 2 times as much as it, to give water permeability. This was put in a net tube $30cm$ in length and $3cm$ in diameter, and then wrapped in another sand doubly using two sand bags $10cm$ and $30cm$ respectively in diameter to get overall length of $50cm$.

These set of sand bags weighing $15kg$ per set were buried monitoring the pore water head on the line $2m$ inner to the land side from the beach-line at high water on a spring tide, in three groups divided by layers corresponding to the free pore water levels for low, mean and high water(TP: $-0.45m$, $+0.25m$, $+0.65m = 1.0m$ underground).

With the lapse of days these sand bags were dug up in turn and traced to measure the total amount of the oil oozed out of the inner tube and that of the residual oil.

The amount of the oozedout oil captured in the outer sand bag isolated more than $3cm$ from the inner tube reached its maximum on the 10th day for the lower layer, and after one month for the middle and upper layers, but it was only 1/100 to 1/300 of the amount of the residual oil in the inner tube throughout the 84 days in summer.

While the measurement was made in the season of high water level in summer, from June 13 to September 5, 1980, and ground surface temperature which had a range of 20° C or more in the change by day and night, reached 50° C at its maximum early in August, the lower layer group was in the process of temperature rise from 20° C to 22° C and even the upper layer group located $1.1m$ upper was in the similar process from 22° C to 27° C, because all the three layer groups were placed under and isolated from the day-and-night reversal layer which was upper than $50cm$ underground.

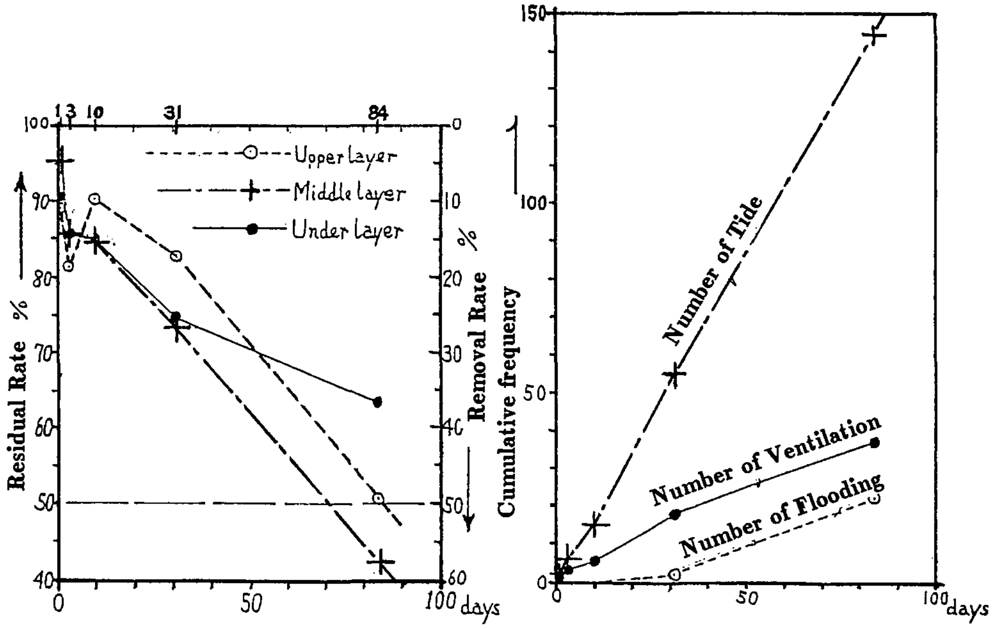

Fig. 12. Removal rate of IB heavy oil in the sandy beach

The upper layer was in wet state and under ventilative condition, and its was only 22 times from 30 days after that the pore water head reached the sand bags. The lower layer group was always flooded with the pore water and the chance that it was ventilated even if partially was given 37 times. The sand bags in the middle layer met the rise and fall of pore water head 145 times during the 84 days.

The lapse time result of this measurement is shown in Fig. 12. The amount of the residual oil in the upper and middle layers for which sufficient ventilation was insured, reduces linearly on and after the 10th day and comes to 1/2 of the initial amount of oil on the 85th day and 70th day respectively. For the lower layer, the halflife period for oil was estimated to come to 150 days or more because a delay to be considered due to a short supply of oxygen could be occur.

Since oxidation cracking of $1l$ of 1B oil requires a little over $3kg$ of oxygen, it owes much not only to use of the dissolved oxygen in the intruding water on the flood tide but also to the respiration of atmosphere on the ebb. It is expected that cracking of petroleum in the sandy beach can be markedly accelerated in a hot season by intermittent irrigation of the excrement sewage to provide high organic N (urea) load, because beach sand holds inorganic phosphorous trapped at a level of $3g.at/m^3$.

For an accidental oil spill, a quick grappling at the first stage of its occurrence is vitally important.

Utilization of sand and sandy beaches as excellent materials to enable procuring nearby the site has a favorable peculiarity in that it makes it **easy to construct diversified technical skills in agreement with the scale of the accident and situations at the site** and also **it produces no waste.**

7. Conservation of the Function of Water Purification by Beach Respiration

The sewage treatment by the activated sludge process is so efficient that it shows a removal rate larger than 80% for a high-density organic load of about $10mg{\cdot}atCOD/l$ ($160mgCOD/l$), but the treated water is discharged with a density of about $1mg{\cdot}atCOD/l$ ($16mgCOD/l$).
It is difficult and a heavy burden to treat further so as to get 1/10 of the above in Load density.
In water purification by beach respiration, the tidal rise-and-fall of sea level acts as pure natural power on the naturally formed ecosystem which composed of various bacterium being in the water-permeable multilayer structure, resulting from materials composing the beach, and the aerobic condition inside the sphere is insured by exposure to the atmosphere. It is particularly admirable that the level of intruded load of $1mg{\cdot}atCOD/l$ can be purified further to a level of 1/10 of such density.

To conserve the function of purification, as to the pebble beach, it must be formed into a flowthrough type by providing a sufficiently spacious open surface of water on the back side of the pebble bank, or its inner por space must be protected from filling with minute particulates by filtercoating through addition of sand onto the beach plane. The pebble beach joining with the shore is **a long refuse trap** as it is, and needs a treatment because the pore space will be rapidly lost.

The sandy beach is saved from blinding, since the minute particulates trapped in filtration are cleansed off by the process where the beach-line surface is always moved owing to disturbance from waves. Structures such as the offshore submerged moles which do not block the move of supplied sand along the shoreline, may be willingly accepted unless they do not intercept the yearly moving passage of offshore sand.
Beach conservation works **must be those answering the necessity of accretion of sand.** Besides, if heat release from thermal effluent or distributed discharge of treated-sewage-water into the sandy beach is introduced, the contribution of its function to the culture of algae will increase remarkably.

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