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해양에서 유출된 기름의 해변 토양 침투거동에 미치는 영향인자 규명 실험

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Laboratory Study for the Identification of Parameters affecting the Penetration Behavior of Spilled crude oil in a Coastal Sandy Beach

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요 약 문

기름의 침투거동에 관한 정보는 처리대책의 수립 및 생물학적 영향을 최소화 하기 위한 중요한 단서가 된다. 본 연구에서는 사질지형의 조간대 모형을 이용하여 유출된 기름의 토양침투 거동을 파악하고 침투에 미치는 주된 영향인자를 규명하는 것을 목적으로 하여 연구를 수행하였다. 해수와 유출된 원유의 연안 해변 토양 침투거동은 전혀 달랐다. 해수는 파도와 조석의 물리적 작용에 의해서 토양 중으로 침투를 하였으나, 유출된 원유는 파도에 의해서는 침투되지 않고 조석작용에 의해서만 토양 중으로 침투하는 것을 알 수 있었다. 그리고 평방미터당 1 L의 유출유가 표착하였을 경우 약 70%이상의 유분이 토양 표층 2 cm의 부분에 집중되는 침투경향을 나타내었다. 그리고, 유출된 기름의 토양침투에는 온도의 변화에 의존하는 기름의 점도가 강한 영향을 미치는 것을 알 수 있었다.

주제어 : 연안오염, 모형해변, 유출원유, 파도와 조석의 작용, 기름의 점도

ABSTRACT

Understanding the penetration behavior of the spilled oil is very important to remove itself and to minimize its impact on intertidal biological communities by earlier treatment of the oil. The purpose of this study is to clarify the effects of wave and tidal actions on the penetration of spilled oil and to evaluate main factors of oil penetration using a sandy-beach model. Infiltration processes into the sediments showed significant difference between seawater and crude oil. Seawater was infiltrated by both wave action and tidal fluctuation into the sediments in sandy beach. However, spilled crude oil penetrated into the sediments only by falling tides and not by wave action, and the first tide is most important for the penetration of stranded oil. Over 70% of bulk fraction in penetrated crude oil was concentrated to the top 2 cm sediment-layer when spilled oil volume was 1 L/m^2. Moreover, the penetration of stranded oil into the sandy beach sediments was strongly correlated with the oil viscosity affected by temperature.

Key words : Coastal pollution, Sandy beach model, Spilled crude oil, Wave and tidal action, Oil viscosity

1. Introduction

Various anthropogenic pollutants ultimately threaten the coastal zone. One of significant anthropogenic pollutions is the oil pollution. Oil enters marine environment in many ways like natural seeps, refinery emission, ship cleaning operations and accidental spills. It is estimated that 1.7~8.8 million tons of petroleum hydrocarbon are released into marine environment annually[1].

Tanker accidents induce large scale of oil pollution and

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one of the largest oil spills was that of the *Exxon Valdez*, which discharged approximately 36,400 tons of Alaskan North Slope crude oil into Prince William Sound in March 1989. About 50% of the spilled oil stranded on shores and contaminated about 2,000 km of shorelines along Gulf of Alaska[2,3].

When spilled oil penetrates into the shoreline sediments, the oil affected the ecosystem of sediments directly and indirectly through changing shore sediment into anaerobic[4], reducing grazing pressure of grazer[5], and decreasing nutrients supply from seawater to benthic organism[6]. In order to minimize biological injury in the ecosystem, it is necessary to remove the oil as quickly as possible. Cleaning techniques of penetrated oil include manual pick-up with absorbent pads, mechanical treatment using equipments such as grader and scraper, chemical treatment by use of dispersant, digging trenches and bioremediation[7]. To approach the cleaning techniques, knowledge on the penetration behavior of spilled oil into the sediments is very important to upgrade the efficiency of treatments attempted. And, penetration depth of stranded oil into the sediments is one of the most significant factors in biodegradation cleansing processes[8].

In previous studies[9-11], oil penetration was investigated lately after from the penetration of spilled oil on intertidal sediments. However, understanding the initial penetration behavior is very important to remove the spilled oil before the oil penetrates into the sediments, and to minimize impact by penetrated oil on intertidal biological communities. Unfortunately, the penetration behavior of spilled oil into the sediments has not fully understood.

The purpose of this study is to clarify the effects of wave and/or tidal action on penetration of oil into the sediments and main factors in oil penetration using sandy-beach model.

2. Experimental methods

2.1. Sandy-beach model

The model is composed of sandy beach (L 5.0 m×W 0.8 m×H 1.0 m), a wave maker (breaking wave height: ~50 mm high), a tide control device (tidal period: 1~7hr), a reservoir (4 m^3), and temperature control system (3~30°C). This facility is automatically controlled by the computer system shown in Fig. 1. The body of simulator is made of FRP and has two observation windows with 0.9 m wide and 0.6 m long. The simulator was filled with transparent glass beads (diameter=1 mm, density=2.5 g/cm^3) as model sediments to visualize the penetration of spilled oils into sandy beach sediments.

The sediment was profiled with a slope approximately 1/10. Synthetic seawater was made to have a salinity of 32±2‰ psu using tap water and commercial salt for aquarium (MARINE-TEC. Co. Sealife). In this study, breaking wave height (Hb) and wave periods were set at 50 mm and 0.8 s, respectively, because low energy waves which had Hb of 50~100 mm and wave periods of 0.8~2.0 s were often observed in enclosed Hiroshima Bay, Japan. There is no wave reflection in the simulator, because wave absorber was set up in the opposite side and absorbs generated wave. Tide was controlled with semi-diurnal tidal cycle, and vertical fluctuation velocity of seawater by tide was determined as 0.009 cm/s based on the mean tidal range of 2 m in the Hiroshima Bay. The water level was fluctuated with the range of 45 cm, up 15 cm and down 30 cm from the sediment surface of observation window of right side (Fig. 2). Out of tidal range was set as lag time

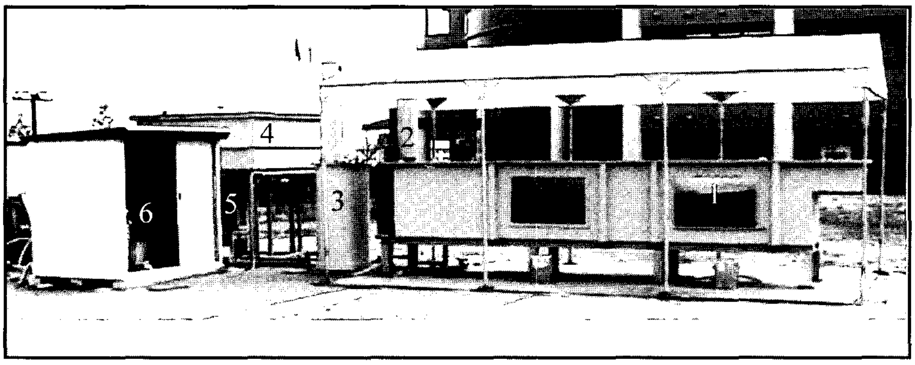

Fig. 1. Image of model sandy beach (1: sandy beach, 2: wave maker, 3: tide control device, 4: reservoir, 5: temperature control system, 6: computer control system).

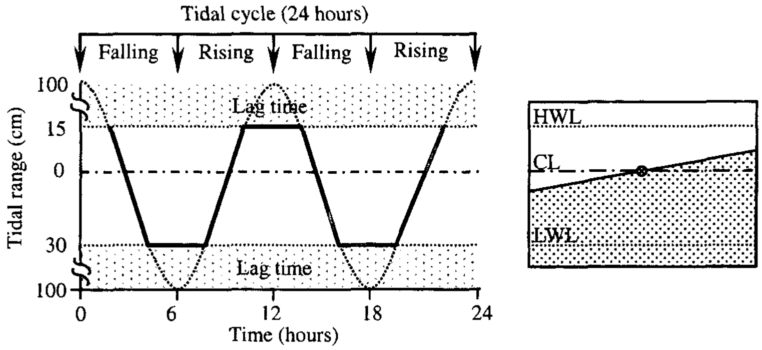

Fig. 2. Tidal fluctuation. Dashed line shows tidal range from the sediment surface of observation window on right side (HWL; high water level, CL; center line, LWL; low water level)

for next rising or falling tide to simulate the tidal fluctuation of field, because the oil penetration is correlated with tidal period.

2.2. Seawater tracer and test oil

Potassium permanganate was used as seawater tracer to compare the infiltration behaviors with and without oil on the sediment surface. Specific gravity of the potassium permanganate was 1.01. The potassium permanganate of 25 ml was applied.

Upper Zakum crude oil was used in the study and its physico-chemical properties is shown in Table 1. Different kinds of silicon oil in viscosity as 12, 125, 1,650 and 21,000 mm^2/s were prepared to clarify effects of viscosity on oil penetration. These silicon oils were colored in blue (Orient Chemical Industries, LTD., Oil Blue 2N) for visual observation of penetration depth.

2.3. Penetration of spilled oil with wave and/or tidal actions

To clarify the effects of wave and/or tidal actions on infiltration of oil and seawater into sandy beach sediments, 1 L/m^2 of the crude oil was spilled over the water surface and 25 mL of the potassium permanganate solution (0.02 mol/L) was dropped by pipette on the saturated sediment surface[6]. The volume of oil applied was determined by the previous studies on oil spills[12-16].

Table 1. Physico-chemical properties of crude oil used in this study

Items	values
Viscosity at 15°C (mm^2/s)	28
Density at 15°C (g/cm^3)	0.87
Pour point (°C)	-15
Sulfur content (% wt.)	2.00
Water content (vol.)	0.1

Three experimental approaches were conducted; wave only (for 5 minutes), tide only (for 6 hours) and the combination of wave and tide (for 6 hours). In the case of the "wave only", waves were applied for 5 minutes without any tidal movement. In the case of "tide only", the water level was lowered from HWL to LWL (Fig. 2) by tidal fluctuation at tidal velocity of 0.009 cm/s without any wave. Both wave and tidal fluctuation were applied for a tidal cycle in case of "wave and tide combination".

The infiltration of the oil and seawater was measured by visual observation and image analysis taken by video camera (SONY Co., Digital Handy Camera DCR-VX1000).

2.4. Long-term penetration behavior of stranded oil

To estimate penetration of stranded oil into the sediments, the crude oil was spread over the water surface at HWL, and evenly stranded on the sediment surface by falling of water level. The vertical movement of stranded oil in the sediments was monitored under "wave and tide combination" for 15 tidal cycles.

At the end of experiment, oil contaminated sediments was sampled with a cylindrical acryl (diameter = 5 cm, length = 30 cm) to determine the vertical distribution of the oil contents. The sediments was sliced with 2 cm interval and mixed completely prior to extraction by dichloromethane. The oil concentration was determined by Thin layer Chromatography (TLC) in combination with a flame-ionization detector (FID) employing Chromarod III (Iatron Laboratories Inc., Tokyo).

2.5. Effect of viscosity on the oil penetration

The viscosity of oil as a function of temperature was determined by U-tube Reverse Flow Viscometer equipped with kinematic viscosity bath TV-5S (Thomas Kggaku Co., LTD).

To clarify the relationship between viscosity and penetration, the dyed silicon oils and the crude oil were applied to glass beads column with 5.5 cm in diameter and 50 cm in length at 15°C. Oils were applied by using syringe on the water surface at HWL which risen 5 cm from the surface of the filled glass beads, and then the water level was also fallen with 0.009 cm/s. After a falling tide, the penetration depths of the oils were recorded.

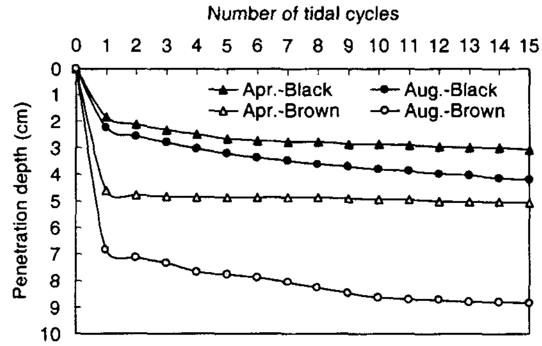

Fig. 4. Long-term penetration of the stranded crude oil into the sediments in April 20-27 and August 20-27.

3. Results and discussion

3.1. Penetration of spilled oil with wave and/or tidal actions

Fig. 3 shows the penetration depths of the crude oil and seawater into the sediments by wave and/or tidal actions. Seawater infiltrated into the sediments to 21 cm from the sediment surface by just wave action for 5 min, whereas the crude oil did not penetrate into the sediments.

Seawater also infiltrated into the sediments by the tidal fluctuation. The crude oil, however, penetrated into the sediments with much slower velocity than seawater. The infiltration depth of seawater after a tide was approximately 4.8 cm.

Under the combination of wave and tidal actions, the oil showed almost the same penetration behavior as the tidal fluctuation without wave. That means that the tidal fluctuation acts main role for penetration of the oil into the sandy beach sediments.

3.2. Long-term penetration behavior of stranded oil

The vertical penetration of the crude oil over 15 tidal cycles is shown in Fig. 4. The experiments were conducted in April 20-27 and August 20-27. Oil layer after tidal cycles could be separated into black and brown layers. The strong penetration of the oil occurred at first tidal cycle both in April and August. The penetration depth of black and brown layers slightly declined after first tidal cycle to 15th tidal cycle in April. In August, on the other hand, black layer gradually declined with tidal cycles from 2.2 cm after first tidal cycle to 4.2 cm after 15th tidal cycle, and brown layer also declined from 6.8 cm and 8.8 cm. The oil in August penetrated almost two times deeper than that in April. That means that the penetration depth is probably correlated with viscosity affected by temperature, because the mean temperatures of air and water in April 20-27 were 15°C and 14°C, and those of August 20-27were 23°C and 17°C, respectively.

Fig. 5 shows the vertical distribution of hydrocarbon concentration in the sediments after 15th tidal cycle from

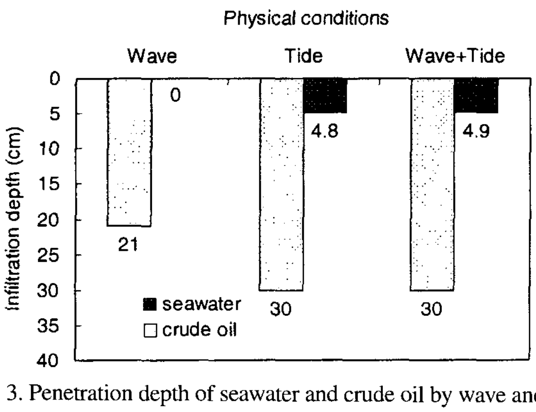

Fig. 3. Penetration depth of seawater and crude oil by wave and/or tidal actions.

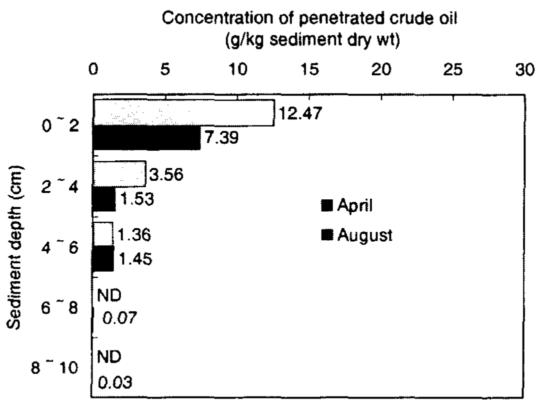

Fig. 5. Vertical distribution of oil concentration after 15 tidal cycles in April and August ND; not detected.

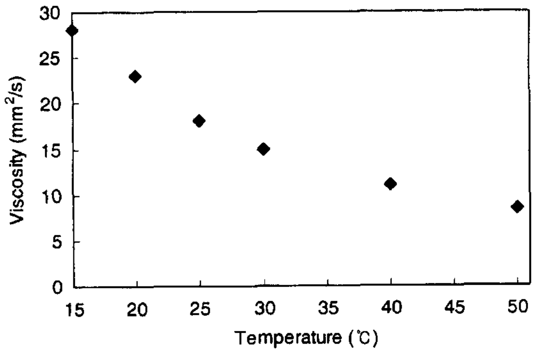

Fig. 6. Relationship between viscosity and temperature in the crude oil.

stranding of the crude oil. The hydrocarbon was detected to 6 cm below from the sediment surface in April, whereas in August it was detected to 10 cm below. However, the results indicate that over 70% of the penetrated crude oil was confined to the top 2 cm sediment- layer and the highest concentration was shown at the top 2 cm sediment-layer. The detected depth of hydrocarbon was coincided with the penetration depth of black and gray layers after 15th tidal cycles (see Fig. 4).

From these results, it is evident that the vertical distribution of hydrocarbon showed significant difference between April and August.

3.3. Effect of viscosity on oil penetration

The relationship between viscosity and temperature was obtained and shown in Fig. 6. The viscosity of the crude oil was quite different and significantly affected by temperature.

To clarify effects of viscosity on oil penetration, column experiment was conducted using silicon oils with different kinds of viscosity. Fig. 7 shows the relationship between viscosity and penetration depth of silicon oil. The penetration depth of the crude oil was fitted in Fig. 7. At the lowest viscosity of silicon oil (12 mm^2/s at 15°C), the penetration depth was 15.3 cm, whereas the depth was 1.1 cm at the highest one (21,000 mm^2/s at 15°C). However, that of crude oil was not exactly fitted in the range of that of silicon oil. Reed *et al.*[17] and Bear *et al.*[18] reported that the penetration depth of spilled oil into the sandy beach sediments depended on the viscosity and specific gravity of the oil. It is judged that the difference of penetration depths between crude oil and silicon oil in the same viscosity range is probably caused by difference of specific gravity as crude oil of 0.87 g/cm^3 and silicon oil of 0.96 g/cm^3 at 15°C.

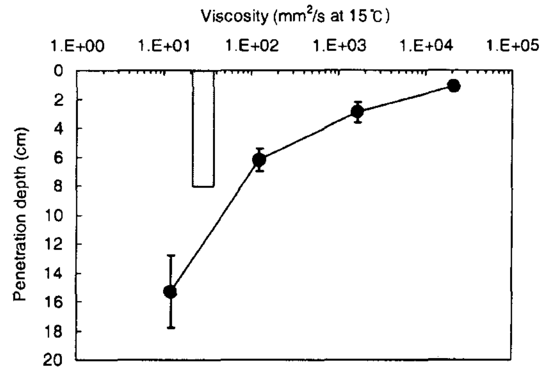

Fig. 7. Relationship between viscosity and penetration depth in the silicon oil and crude oil. Symbols show the penetration depth of the silicon oil (black circle and standard deviation) and the crude oil (gray panel) with standard deviation (error bar).

From these results, therefore, it is clear that the penetration of oil into the sandy beach sediments is significantly affected by viscosity.

4. Conclusions

The purpose of this study is to clarify the effects of wave and/or tidal action on penetration of spilled oil into the sediments and to clarify main factor in oil penetration using a sandy-beach model.

Infiltration processes into the sediments showed significant difference between seawater and crude oil. Seawater was infiltrated by both wave action and tidal fluctuation into the sediments in sandy beach. However, spilled crude oil penetrated into the sediments only by falling tides and not by wave action, and the first tide is most important for the penetration of stranded oil. Over 70% of bulk fraction in penetrated crude oil was concentrated to the top 2 cm sediment- layer. Moreover, the penetration of stranded oil into the sandy beach sediments was strongly correlated with the oil viscosity affected by temperature.

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