Experimental study of ore lifting efficiency with mixture of bentonite suspension and sand as a carrier material for deep sea mining

K Orita1, K Tani2, A Suzuki3 and T Kosho4

1Metals Environment, Seafloor Mineral Resources and Coal Unit, Japan Oil, Gas and Metal National Corporation, 2-10-1 Tranomon Minato-ku Tokyo, Japan
2Department of Marine Resources and Energy, Tokyo University of Marine Science and Technology, 4-5-7 Konan Minato-ku Tokyo, Japan
3Soil Improvement Business Unit, Fudo Tetra Corporation, 7-2 Nihonbashi-koami-cho Chuo-ku Tokyo, Japan
4Hokuriku Branch, Fudo Tetra Corporation, 5-1 Bandaijima Chuo-ward Niigata city Niigata, Japan

orita-kiyotaka@jogmec.go.jp

Abstract. Carrier material (mixture of viscous fluid and fine particles, CM) circulation system was proposed to lift up deep sea mineral resources. This study focuses on appropriate mixing proportions of CM for lifting up heavier and coarser ores. The results of model tests of ore lifting demonstrated that CMs of mixture of water, bentonite and sand particles could lift up heavier and coarser ores than those lifted in the conventional system by far lower vertical flow velocities. Moreover, ore lifting efficiencies were found to be improved by restricting movements of CMs around ores via the wall of the vertical pipe.

1. Introduction

Deep sea mineral resources like “Polymetallic Massive Sulphides (PMS)” exist on the sea floors around Japan. For commercial development of them, lifting up ores to sea surface is one of the critical technologies. The Figure 1 (a) shows the conventional ore lifting system. Mixture of crushed ores (density $\rho=3.2$ Mg/m$^3$, diameter: $d=30$ mm) and seawater were pumped up via vertical flow velocity $v_{CM}=4.8$ m/s from depth of 1600 m to the sea surface at the field test conducted by JOGMEC [1]. However, density of PMS is 3.2~4.1 Mg/m$^3$ [2]. Moreover, crushing ores on deep seafloor is burdensome since changing cutter head of an excavating machine to a jaw crusher was needed [1]. Therefore, technology as to lift up heavier and coarser ores than the conventional system is necessary.

For this purpose, the authors proposed carrier material (mixture of viscous fluid and fine particles, CM) circulation system as shown in the Figure 1 (b) [3]. Since CMs have much higher viscosity than water, they are expected to lift up heavier and larger ores than water. A series of model tests of ore lifting were conducted using CMs of mixture of water, thickener of CMC (Carboxymethyl Cellulose, CMC HP-80, Daicel Miraizu., Ltd) and particles of sand (silica sand No.6, coefficient of uniformity $U_c=2.19$, 50% grain size $D_{50}=0.32$ mm) [4], [5]. CMs could lift up ore model (Spherical ball, OM) of density $\rho_{OM}=2.68$ Mg/m$^3$ and diameter $d_{OM}=25.0$ mm via $v_{CM}=3.66\times10^{-2}$ m/s. CMs showed larger
ore lifting efficiency than water since water in the same \( \rho_{CM} \) couldn’t lift up the ore. However, ores of the same density as PMS was not lifted. Thus, it is necessary to investigate more appropriate mixing proportions of suitable materials for CMs with higher transport capacity.

Bentonite suspension is one of the candidate viscous fluids since it is widely used as drilling liquids for lifting cuttings. Therefore, this research intended to evaluate ore lifting efficiency by using CMs of mixture of water, bentonite and sand particles.

2. Evaluation of rheological properties of CMs

Rheological properties of CMs were evaluated since they affect the ore lifting efficiency [4]. Table 1 shows the mixing proportions of CMs. \( C_w, C_t, C_c \) and \( C_p \) are mass concentration of water, CMC, bentonite (Kunigel-GS, Kunimine Industries Co., Ltd) and sand particles. \( T/W \) and \( C/W \) are calculated as \( C_i/C_w \) and \( C_c/C_w \).

Rheological properties of CMs of mixture of water, bentonite and sand particles were measured by using a viscometer type B (B8M, Tokyo Keiki Inc) [6]. On the other hand, rheological properties of CMs of mixture of water, CMC and sand particles were measured by using the Sphere Falling Test [7]. Rheological characteristics of both CMs were assumed as Bingham fluid following the modeling of high-fluidity concrete whose mixing proportions are similar to those of CMs [8]. The shear stresses of

![Figure 1. Ore lifting (a): conventional system [1], (b): proposed system [2].](image)

| Method of evaluating rheology | Scale of model tests of ore lifting | \( C_w \) (%) | \( C_t \) (%) | \( C_c \) (%) | \( C_p \) (%) | \( T/W \) (%) | \( C/W \) (%) | \( \eta_p \) (Pa⋅s) | \( \tau_y \) (Pa) | \( \rho_{CM} \) (Mg/m³) |
|-----------------------------|-----------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|----------------|---------------|-------------------|
| Viscometer type B [6]       | Small                             | 93.2         | 0.00         | 6.84         | 0.00         | 7.34         | 3.56         | 12.6           | 1.12          |
|                             | Small [4]                         | 79.2         | 0.00         | 5.81         | 15.0         | 0.00         | 7.34         | 3.74           | 11.8          | 1.35              |
|                             | Small & Large                     | 65.2         | 0.00         | 4.79         | 30.0         | 0.00         | 7.34         | 4.24           | 9.04          | 1.59              |
|                             | Not used                          | 51.2         | 0.00         | 3.76         | 45.0         | 0.00         | 7.34         | 5.18           | 11.9          | 1.83              |
| Sphere falling test [7]     | Small                             | 37.3         | 0.00         | 2.73         | 60.0         | 0.00         | 7.34         | 6.71           | 12.3          | 2.07              |
|                             | Small [4]                         | 91.6         | 0.00         | 8.39         | 0.00         | 9.16         | 10.2         | 22.1           | 1.14          |
|                             | Not used                          | 77.9         | 0.00         | 7.13         | 15.0         | 0.00         | 9.16         | 56.0           | 35.7          | 1.38              |
|                             | Not used                          | 64.1         | 0.00         | 5.87         | 30.0         | 0.00         | 9.16         | 37.9           | 43.3          | 1.61              |

Table 1. Mixing proportions of carrier materials (CM).
Bingham fluid increase linearly with the share rate, the slope of which is the plastic viscosity \( \eta_p \), and the intercept is the yield stress \( \tau_y \).

Figure 2 shows the relationship between \( \eta_p \) and \( C_p \), and the relationships between \( \tau_y \) and \( C_p \). Increasing \( T/W \) and \( C/W \) enhanced both values of \( \eta_p \) and \( \tau_y \). On the other hand, the value of \( \eta_p \) become large with increasing \( C_p \). However, the value of \( \tau_y \) were independent of \( C_p \) except CMs of \( C/W \)=9.16%.

A method to predict ore lifting velocities was proposed using model shown in Figure 3 [4]. The vertical flow velocity of CM, \( \nu_{CM} \) of density \( \rho_{CM} (\leq \rho_{OM}) \) is assumed to be uniform within an infinite space. The OM is assumed to move at a constant vertical velocity \( \nu_{OM} \) without horizontal and rotational movements. The drag force \( F_D \), the buoyant force \( F_B \) and the gravitational force \( W \) act on the OM. Equation (1) shows the static equilibrium, \( F_B \) and \( W \) are independent of relative velocity between CM and OM, \( \nu_{CM} \cdot \nu_{OM} \). As shown in equation (2), \( F_D \) on OM in a uniform flow of Bingham fluid is derived in two terms according to the Ansley and Smith’s model [9]. The first term \( \Delta F_D = 3\pi d_{OM} \eta_p (\nu_{CM} - \nu_{OM}) \) is attributed to \( \nu_{CM} \cdot \nu_{OM} \) and \( \eta_p \). The latter term \( F_{D,v=0} = 7\pi^2 d_{OM}^2 \tau_y/8 \) is attributed to \( \nu_{OM} \) shown in equation (3) and ore lifting efficiency \( \nu_{OM}/\nu_{CM} \) shown in equation (3)’ were derived from the equations (1) and (2) where \( \Delta F_{D,0} \) denotes the \( \Delta F_D \) when \( \nu_{OM}=0 \). These equations were divided into three cases. The case \( F_{D,v=0} \geq W-F_B \) indicates that \( \nu_{OM} \) and \( \nu_{CM} \) would be the same \((\nu_{OM}=\nu_{CM}) \). Whereas, the case \( F_{D,v=0} < W-F_B < \Delta F_{D,0} \) indicates that the OM would not be lifted \((\nu_{OM} < 0 \leq \nu_{CM}) \). The case \( W-F_B < \Delta F_{D,0} < W-F_B \) implies that the OM would be lifted but its velocity is smaller than that of CM \((0 < \nu_{OM} < \nu_{CM}) \). These equations demonstrate that the value of \( \tau_y \) would determine the ore lifting efficiency of CMs. CMs of mixture of water, bentonite and sand particles showed larger \( \tau_y \) than CMs of mixture of water, CMC and sand particles. Therefore, CMs which use bentonite as a substitute of CMC would lift up heavier and coarser ores more efficiently than the former CMs.

\[
\begin{align*}
F_D + F_B - W &= 0 \quad (1) \\
F_D &= \Delta F_D + F_{D,v=0} = 3\pi d_{OM} \eta_p (\nu_{CM} - \nu_{OM}) + \frac{7}{8} \pi^2 d_{OM}^2 \tau_y \quad (2)
\end{align*}
\]

**Figure 2.** Relationship between \( \eta_p \) and \( C_p \) (Left), and relationship between \( \tau_y \) and \( C_p \) (Right) (Mixture of water, Bentonite and sand particles [6], mixture of water, CMC and sand particles [7]).

**Figure 3.** Model of ore lifting.
3. Model tests of ore lifting

3.1. Experimental method

Figure 4 shows the experimental apparatus. Two set-ups with different sizes were used. These apparatuses were composed of a tank, a progressive cavity pump (small-scale model tests: NHL15FN, large-scale model tests: NYT50, HEISHIN, Ltd), an inlet, a vertical pipe, a return pipe and a separating device for OMs. The vertical pipes have the height $h_{pipe}=1.20$ m and the inner diameter $d_{pipe}=0.05$ m for the small-scale apparatus, and $h_{pipe}=4.00$ m and $d_{pipe}=0.15$ m for the large-scale apparatus. CMs of mixture of water, bentonite and sand particles shown in Table 1 were used. The non-pulsating flows of CMs were controlled at the average vertical velocity within the vertical pipe $v_{CM}=0.57-0.62, 2.15-2.32$ and $3.68-3.88 \times 10^{-2}$ m/s for the small-scale tests. Much higher velocities $v_{CM}=20.7 \times 10^{-2}$ m/s for the large-scale tests. OMs shown in Table 2 were used. $d_{OM}=12.7, 15.9, 19.1$ and $25.4$ mm for the small-scale tests and $d_{OM}=19.1, 25.4$ and $50.8$ mm for the large-scale tests. $\rho_{OM}=2.15-2.21, 3.75-3.89$ and $5.61-6.00 \text{ Mg/m}^3$ were used as OMs considering the range of density of PMS $3.2-4.1 \text{ Mg/m}^3$. RFID (Radio Frequency Identification) equipment was used to measure the relationship between lifting height $l$ and elapsed time $t$ of OMs to pass the antennas from the moment of activating pump. Wireless communication can be made between the antenna (small-scale model tests: TR3-HA201A, large-scale model tests: TR3-SA102, Takaya Corporation., Inc) and the RF tags (MBT-1003N, Toda Kogyo Corporation., Inc) via the wall of the vertical pipe and CMs. RF tags were set at the center of each OM.

OMs were placed into the pipe from the inlet. Along the vertical pipe, 3 antennas at 0.40 m interval ($l=0.65, 1.05$ and $1.45$ m) for the small-scale tests and 4 antennas at 1.00 m interval

![Diagram of model tests of ore lifting](image)

Figure 4. Set up of model tests of ore lifting (left: configuration, middle: picture of small-scale apparatus, right: picture of large-scale apparatus).


Table 2. Ore model (OM) for model tests of ore lifting.

| $d_{OM}$ (mm) | $\rho_{OM}$ (Mg/m$^3$) | Scale of the model tests |
|--------------|------------------------|--------------------------|
|              | PTFE | Alumina | Zirconia |              |
| 12.7         | 2.21 | 3.75 | 5.61 | Small |
| 15.9         | 2.19 | 3.76 | 5.65 |              |
| 19.1         | 2.15 | 3.77 | 5.78 | Small & Large |
| 25.4         | 2.18 | 3.86 | 5.93 |              |
| 50.8         | 2.17 | 3.89 | 6.00 | Large |

($l=1.15, 2.15, 3.15$ and $4.15$ m) for the large-scale tests were installed. The average ore lifting velocities between each antenna, $v_{OM}$ were calculated as $(l_{n+1}-l_n)/(t_{n+1}-t_n)$, where $n$ denote the locations of antennas $n=1$–$2$ for the small-scale tests, $n=1$–$3$ for the large-scale tests.

3.2. Test results

Figure 5 shows the relationships between $l$ and $t$. $l$ increased linearly with increasing $t$ in both of the small-scale and the large-scale model tests.

Figure 6 and Figure 7 show the relationships between $v_{OM}$ and $v_{CM}$ in the small-scale and the large-scale model tests. $v_{OM}$ increased with increasing $v_{CM}$. $C/W$ and $C_p$ enhanced $v_{OM}$. OM of $d_{OM}=25.4$ mm and $\rho_{OM}=5.93$ Mg/m$^3$ were lifted by using CM of $C/W=7.34$ % and $C_p=60.0$ %, and CM of $C/W=9.16$ % and $C_p=30.0$ % in the small-scale model tests via $v_{CM}=0.57-0.58\times10^2$ m/s. This OM was also lifted in the large-scale model test $v_{CM}=20.7\times10^2$ m/s. This OM was 0.8 times coarser than the ores successfully lifted by JOGMEC and 1.4–1.9 times heavier than PMS [1, 2]. Moreover, the OM of $d_{OM}=50.8$ mm and $\rho_{OM}=3.89$ Mg/m$^3$ was lifted in the large-scale model test via $v_{CM}=20.7\times10^2$ m/s. This OM was 1.7 times coarser than the ores successfully lifted by JOGMEC and 0.9–1.2 times heavier than PMS [1, 2]. However, the OM of $d_{OM}=50.8$ mm and $\rho_{OM}=6.00$ Mg/m$^3$ couldn’t be lifted.

3.3. Discussions

3.3.1. Relationship among $v_{OM}/v_{CM}$, $\rho_{OM}/\rho_{CM}$ and $d_{OM}$

Figure 8 shows the relationships between $v_{OM}/v_{CM}$ and $\rho_{OM}/\rho_{CM}$, and the relationships between $v_{OM}/v_{CM}$ and $d_{OM}$. Each plot shows the ratio of measured ore lifting velocities $v_{OM,me}$ and the average flow velocities of CMs $v_{CM}$. Lines in Figure 8 top and curves in Figure 8 bottom show the ratio of

![Figure 5. Relationship between $l$ and $t$. (left: small-scale model test, right large-scale model test).]
predicted ore lifting velocities $v_{OM,pre}$ and $v_{CM}$ which were calculated by equation (3) using the rheological properties measured by viscometers.

When $F_{D,v=0} \geq W - F_B$, $v_{OM,pre} / v_{CM} \cong 1$. In this range, $v_{OM,me}/v_{CM} \approx 1$ in the small-scale model tests. Then, the Figure 8 showed that $v_{OM,me}/v_{CM}$ were independent of $\rho_{OM}/\rho_{CM}$ and $d_{OM}$. These results demonstrated that CMs with sufficient $\tau_y$ assured high lifting efficiency of OMs. On the other hand, $v_{OM,me} > v_{CM}$ and independent of $\rho_{OM}/\rho_{CM}$ in the large-scale model tests. When $W - F_B - \Delta F_{D,v=0} > W - F_B$, $0 < v_{OM,pre}/v_{CM} < 1$. $v_{OM,pre}/v_{CM}$ would decrease with increasing $\rho_{OM}/\rho_{CM}$ and $d_{OM}$. Then, slopes of $v_{OM,pre}/v_{CM} - \rho_{OM}/\rho_{CM}$ graph and $v_{OM,pre}/v_{CM} - d_{OM}$ graph would be milder with increasing $\eta_p$. Figure 8 demonstrated that $v_{OM,me}/v_{CM}$ and $v_{OM,pre}/v_{CM}$ showed similar qualitative behavior. Thus, $\eta_p$ enhanced ore lifting efficiency. However, most of $v_{OM,me}/v_{CM} > v_{OM,pre}/v_{CM}$ in the small-scale model tests. The difference between $v_{OM,pre}/v_{CM}$ and

![Figure 6](image_url)

**Figure 6.** Relationship between $v_{OM}$ and $v_{CM}$ in the small-scale model tests.

![Figure 7](image_url)

**Figure 7.** Relationship between $v_{OM}$ and $v_{CM}$ in the large-scale model tests.
$v_{\text{OM,pre}}/v_{\text{CM}}$ became larger with increasing $d_{\text{OM}}$. On the other hand, $v_{\text{OM,me}}/v_{\text{CM}} < v_{\text{OM,pre}}/v_{\text{CM}}$ in the large-scale model tests.

When $F_{D_{v}}=W-F_{B}-\Delta F_{D_{v}}$, OMs would not to be lifted ($v_{\text{OM,pre}}/v_{\text{CM}}<0$). However, Some OMs with large $\rho_{\text{OM}}/\rho_{\text{CM}}$ and $d_{\text{OM}}$ were lifted against prediction in the small-scale model tests.

### 3.3.2. Reason of discrepancy between predicted and measured ore lifting velocities

Ignoring the vertical pipe for the assumption of a uniform flow of CMs in an infinite flow would be a reason for the discrepancies between $v_{\text{OM,pre}}$ and $v_{\text{OM,me}}$. The vertical pipe causes two phenomena to affect movements of OMs.

The first phenomenon is that the flow of CMs in a vertical pipe is non-uniform. The distribution of $v_{\text{CM}}$ would be larger at the center of the vertical pipe and smaller at the wall than average $v_{\text{CM}}$ because of the friction between CMs and the wall [10]. Thus, if OMs move along the wall, $v_{\text{OM,pre}}>v_{\text{OM,me}}$. On the other hand, If OMs move at the center of the vertical pipe, $v_{\text{OM,pre}}<v_{\text{OM,me}}$.

The second phenomenon is that the movements of CMs adjacent to the OMs would be restricted. Figure 9 left shows the movements of CM around OM. When OMs tend to move in CMs, CMs adjacent to the OMs would move outward and opposite-ward of relative movement. However, if the wall of the pipe is too close to the OMs as shown in the Figure 9 right, the movement of CMs would be restricted. The restriction of movements of CMs would reduce relative velocity between OMs and CMs. Thus, ore lifting efficiency would be enhanced.

![Figure 8](image-url)

**Figure 8.** Comparison of measured and predicted ore lifting velocity (Top: relationship between $v_{\text{OM}}/v_{\text{CM}}$ and $\rho_{\text{OM}}/\rho_{\text{CM}}$. Bottom: relationship between $v_{\text{OM}}/v_{\text{CM}}$ and $d_{\text{OM}}$).
4. Conclusions
To lift up heavy and coarse ores, mixture of water, bentonite and sand particles was suggested as one of the candidate carrier materials (mixture of viscous fluid and fine particles, CM). Viscous characteristic of this type of CMs can be modelled as a Bingham fluid. Because of their large yield stresses, i.e. shear stress when shear rate are zero, they were predicted to enhance ore lifting efficiency.

The results of model tests of ore lifting demonstrated that heavier and coarser ores than the ores lifted by JOGMEC were successfully lifted via far smaller vertical flow velocities. Moreover, ore lifting efficiencies were found to be enhanced by limiting movements of CMs around ores by the wall of the vertical pipe.

Acknowledgments
This work was supported by JSPS KAKENHI Grant Number 17H01355. Experiments were helped by Mr. Hongseok Choi and Mr. Zhang Jinhua in Tokyo University of Marine Science and Technology.

References
[1] Okamoto N, Shiokawa S, Kawano S, Yamaji N, Sakurai H, and Kurihara, M 2019 Proc. of the 29th International Offshore and Polar Engineering Conference, (Honolulu) (California: The International Society of Offshore and Polar Engineers) pp.1–7.
[2] ANRE and JOGMEC 2018 Summary Report of Comprehensive Assessment concerning Development of Seafloor Polymetallic Sulphides (Tokyo: Ministry of Economy, Trade and Industry). (in Japanese)
[3] Tani K, Obayashi J, Suzuki A and Tanaka K 2018 Japan Patent No. 6570000 (in Japanese)
[4] Orita K, Tani K, Suzuki A and Kosho T 2021 Proc. of ISOPE-2021 (Rhodes) (California: The International Society of Offshore and Polar Engineers) 7p. (in printing)
[5] Orita K, Tani K, Suzuki A and Suga S 2019 Proc. of the 5th ISRM Young Scholars’ Symp. on Rock Mechanics and Int. Symp. on Rock Engineering for Innovative Future (Okinawa) (Lisbon: International Society for Rock Mechanics and Rock Engineering) 75–80.
[6] Orita K, Tani K, Kosho, T and Suzuki A 2021 Proc. of 56th JGS Dom. Sym (Yamagata) (Tokyo: Japanese Geotechnical Society) 2p (in printing, in Japanese)
[7] Orita K, Tani K, Kosho, T, Suzuki A and Tanaka K 2020 J. of JSCE, Ser, B3 (Ocean Engineering) 76(2) L_881-L_886. (in Japanese)
[8] Yoshino A 1994 Doctoral thesis (Aichi: Nagoya University) (in Japanese)
[9] Ansley R W and Smith T N 1967 AIChE Journal 13(6) 1193–96.
[10] Buckingham E 1921 ASTM Proc. 21 1154-61.