Ideal mixing proportions of carrier materials used for lifting ores for deep sea mining by sphere falling tests

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Abstract. To transport ores from seafloor to sea surface is one of the crucial problems for deep sea mining. As one of novel and promising solutions for this, the authors proposed a carrier material circulation method. For this method, as the appropriate viscosity of the carrier materials are important for efficient transportation of the ores, the purpose of this research is to suggest the ideal mixing proportions of carrier materials. Thus, to evaluate viscosity of carrier materials and the terminal velocities, viscometer measurements and sphere falling tests were carried out. Then, by assuming the carrier materials as Bingham fluids, the ideal mixing proportions was suggested for ores of various diameters and densities.

1. Introduction
Transportation, especially lifting, of the marine mineral deposits, e.g., manganese nodules, is one of the crucial problems for deep-sea mining. Among various lifting methods suggested as far, as shown in Fig. 1. The carrier material circulation method was proposed as one of the novel and promising technologies (Tani et al., 2018). In this idea, the carrier materials, CMs, are the mixture of viscous fluids and fine particles, and are characterized as high transportability and pumpability. Orita et al. (2021) suggested that the mixture of bentonite suspension and sand as an appropriate CM with high lifting capacity. This research intends to propose the ideal mixing proportions for this CM.

![Figure 1. Proposed system of ore lifting by circulating carrier material.](image-url)

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2. Methods

Two kinds of methods were adopted to evaluate the viscous characteristics of the CMs. The one is the Sphere Falling Tests, SFTs, and the other is the viscometer measurements. The CMs were prepared as the mixtures of the bentonite suspensions using the bentonite clay, Kunigel GS of Kunimine Industries, Co. Ltd., and sand particles using Tohoku silicate sand No. 6. Regarding the mixing proportions of the CMs, two kinds of bentonite suspensions were used with the clay-water ratio, \( C/W = m_c/m_w = 7.34 \) and \( 9.16 \), where \( m_c \) and \( m_w \) are the masses of the bentonite clay and the water, respectively. Five kinds of sand concentrations were used, \( \theta = 0\% \) to \( 60\% \) with \( 15\% \) intervals, where \( \theta \) is the mass of the sand particles, for the viscometer measurements. While the CMs of \( \theta = 0, 15, 30\% \) were used for SFTs.

2.1. Sphere Falling Tests, SFTs

A series of SFTs were conducted to evaluate the viscous characteristics from the settling motions of the ore model, OM, in the vertical pipe. As shown in Fig. 2, the RFID, Radio Frequency IDentifier, system was applied to monitor the movements of the OMs. 8 antennas were set with 0.4m intervals along the vertical pipe, and an RFID tag was embedded in the center of each OMs. Using this RFID system, the relationships of the settling distance, \( l \), and the time, \( t \), were obtained, and the changes in the settling velocities, \( v_{OM} \), were calculated. The materials and the diameters of the OMs were varied. The densities of alumina balls were \( \rho_{OM} = 3.8\sim3.9 \ \text{Mg/m}^3 \) and those of zirconia balls were \( \rho_{OM} = 5.7\sim6.0 \ \text{Mg/m}^3 \), respectively. The diameters were \( d_{OM} = 12.7\sim50.8 \ \text{mm} \).

2.2. Viscometer measurements

The viscous characteristics of the CMs were also evaluated by the viscometer measurements. The measured results were compared with the results of the SFTs to confirm whether the viscous drags of CMs on the OMs in the pipe can be evaluated. The Brookfield (B-type) viscometer, Tokyo Keiki Inc., was used with No. 4 rotor. From rotation rates, \( N = 0.3, 0.6, 1.5, 3, 6, 12, 30, 60 \ \text{rpm} \), and the dial numbers, \( \theta_N \), the shear rates, \( \dot{\gamma}_{AB} = 0.215N \ 1/\text{s} \), and the shear strength, \( \tau_{AB} = 1.29 \theta_N \ \text{Pa} \), were calculated.

Figure 2. Sphere falling test
3. Results

3.1. Analyses of measured data of SFTs

Eq. 1 and Eq. 2 show the equation of the motion of the OM and the drag force model shown by Ansley & Smith, 1967, respectively.

\[ ma = W - F_B - F_D \]  \hspace{1cm}  (1)

\[
W = \frac{\pi}{6} d_{OM}^3 \rho_{OM} g, \quad F_B = \frac{\pi}{6} d_{CM}^3 \rho_{CM} g, \quad m = \frac{\pi}{6} d_{OM}^3 \rho_{OM}
\]

\[
F_D = 3\pi d_{OM} \eta_p v_{OM} + \frac{7}{8} \pi^2 d_{OM}^2 \tau_y \]  \hspace{1cm}  (2)

The three forces on the OMs are the self-weight, \( W \), the buoyancy, \( F_B \), and the drag force, \( F_D \). Among them, the values of \( W \) and \( F_B \) are derived from the diameters and densities of the OMs, whereas the value of \( F_D \) is derived by assuming the CMs as the Bingham fluids with the yield stress, \( \tau_y \), and the plastic viscosity, \( \eta_p \). The acceleration, \( a \), and the velocities, \( v_{OM} \), and settling distance, \( l \), of the OMs are derived as Eq.3, Eq. 4 and Eq. 5, respectively.

\[
a = \frac{W - F_B - F_D}{m} = \frac{\rho_{OM} - \rho_{CM}}{\rho_{OM}} g - \frac{21\pi \tau_y}{4 \rho_{OM} d_{OM}} - \frac{18\eta_p}{\rho_{OM} d_{OM}^2} v_{OM} = A - B v_{OM} \]  \hspace{1cm}  (3)

\[
av_{OM} = \frac{A}{B} (1 - e^{-Bt}) \]  \hspace{1cm}  (4)

\[
l = \frac{A}{B^2} (Bt + e^{-Bt} - 1) \]  \hspace{1cm}  (5)

where \( A = \frac{\rho_{OM} - \rho_{CM}}{\rho_{OM}} g - \frac{21\pi \tau_y}{4 \rho_{OM} d_{OM}}, \quad B = \frac{18\eta_p}{\rho_{OM} d_{OM}^2} \)

Fig. 3 shows an example of the measured results, the \( l-t \) and the \( v-t \) relationships with the relevant fitted curves by Eq. 5 and Eq. 4 using the least square method. As the CM were viscous, the values of \( v_{OM} \) reached the terminal velocity, \( v_{OM,t} \), immediately after the release where accelerations become zero.

3.2. Viscosity of CMs from SFTs

From the obtained values of \( A \) and \( B \), the rheological parameters for Bingham fluids, the yield stress, \( \tau_y \), and the plastic viscosity, \( \eta_p \), were derived. Fig. 4 show the relationships between the Bingham parameters, \( \tau_y \) and \( \eta_p \), and the sand concentration, \( C_p \). The values of both \( \tau_y \) and \( \eta_p \) appear to

\[\text{Figure 3. Example of result of Sphere Falling Tests.}\]
\[\text{CM: } C/W = 7.34, \quad C_p = 15\%, \quad \text{OM: alumina, } d_{OM} = 25.4 \text{ mm.}\]
be independent of the $C_p$. Moreover, the values of $\tau_y$ increase with the clay-water ratio, $C/W$, as $\tau_y = 10 \sim 80$ Pa for $C/W = 7.34$ and $\tau_y = 40 \sim 130$ Pa for $C/W = 9.16$. However, the values of $\eta_p$ do not depend on $C/W$, where $\eta_p = 0 \sim 3$ Pa.s

### 3.3. Viscosity of CMs from viscometer measurements

In Fig. 5, the results of the viscometer measurements, the shear strength, $\tau_{a,B}$, and the shear rate, $\dot{\gamma}$, were plotted. The shear strengths, $\tau_{a,B}$, increase more or less linearly with the shear rates, $\dot{\gamma}$, and their slop, $\Delta \tau_{a,b}/\Delta \dot{\gamma}$, are greater when $C/W$ is greater. Using the least square method, the linear regression lines are derived, $\tau_{a,B} = \tau_y + \eta_p \dot{\gamma}$. From these, the values of yield stress, $\tau_y$, and the plastic viscosity, $\eta_p$, were obtained by assuming the CMs as the Bingham fluids. Fig. 6 shows the relationships between the Bingham parameters, $\tau_y$ and $\eta_p$, and $C_p$ by viscometer measurements. For the cases of $C/W = 7.34$,

![Figure 4](image1.png)

**Figure 4.** Bingham Parameters, the yield stresses, $\tau_y$, and plastic viscosities, $\eta_p$, from SFTs. Top : $C/W = 7.34$, Bottom : $C/W = 9.16$, Left : $\tau_y-C_p$ relationship, Right : $\eta_p-C_p$ relationship.

![Figure 5](image2.png)

**Figure 5.** Relationship between shear strength and shear rate, Left. Viscous characteristics derived from fitted lines.
\( \tau_y \) and \( \eta_p \) are independent of \( C_p \), whereas, for the cases of \( C/W = 9.16 \), they increase with \( C_p \). Moreover, the values of \( \tau_y \) and \( \eta_p \) are greater for the higher \( C/W \).

4. Discussions

4.1. Viscosity of CMs

Fig. 7 compares the Bingham parameters, the yield stresses, \( \tau_y \), and the plastic viscosities, \( \eta_p \), measured by the viscometer and SFTs. The values of \( \tau_y \) by the SFTs are 10–80 Pa for \( C/W = 7.34 \) and 40–130 Pa for \( C/W = 9.16 \), and those by the viscometer measurements are close to their lower bounds. On the other hand, the values of \( \eta_p \) by the SFTs are 0–10 Pa·s for \( C/W = 7.34 \) and 9.16, while those by the viscometer measurements are greater, especially for \( C/W = 9.16 \). As the influence of the \( C_p \) for \( \tau_y \) and \( \eta_p \), the results of the SFTs do not show obvious effect of \( C_p \), whereas those of the viscometer measurements indicate the increase of \( \tau_y \) and \( \eta_p \) with increasing \( C_p \) except for \( C/W = 7.34 \). The discrepancies between the SFTs and the viscometer measurements are due to the non-linear nature of the rheological characteristics of CMs and the different ranges of the shear rates for the relevant two methods.

4.2. Terminal velocities

The terminal velocities, \( v_{OM,t} \), can be obtained from the SFTs and the viscometer measurements by Eq. 6 and Eq. 7, respectively;

\[
\text{SFTs:} \quad v_{OM,t} = \frac{A}{B} \\
\text{Viscometer measurements:} \quad v_{OM,t} = \frac{d_{OM}^2}{18 \eta_p} \left\{ \left( \rho_{OM} - \rho_{CM} \right) g - \frac{21\pi \tau_y}{4d_{OM}} \right\}
\]

Fig. 8 shows the relationships between the terminal velocity, \( v_{OM,t} \), and \( C_p \). In the SFTs, as the terminal velocities were reached without settling even a meter after releasing, \( v_{OM,t} \) by SFTs can be regarded as the actual terminal velocities. On the other hand, the values of \( v_{OM,t} \) by viscometer measurements are predicted by assuming the \( \tau-\dot{\gamma} \) relationships shown in Fig. 5 as those of the Bingham fluids. For \( C/W = 7.34 \), \( v_{OM,t} \) by viscometer measurements are similar with \( v_{OM,t} \) by SFTs. However, for \( C/W = 9.16 \), \( v_{OM,t} \) by viscometer measurements are greater than \( v_{OM,t} \) by SFTs, because the values of \( \eta_p \) by the viscometer measurements are much higher than those of SFTs as shown in Fig. 7.

![Figure 6](image)

**Figure 6.** Relationship between rheological parameters and sand concentration, \( C_p \).

Left: yield stresses, \( \tau_y \), Right: plastic viscosities, \( \eta_p \). Values of \( v_{OM,t} \) are extremely faster for the OMs with greater diameters and higher densities, and
decrease linearly with increasing $C_p$. Thus, the fitted lines by Eq. 8 using the least square methods are shown in Fig. 8.

$$v_{OM,t} = aC_p + b$$

where $a = \frac{\Delta v_{OM,t}}{\Delta C_p}$ and $b = v_{OM,t}$ at $C_p = 0$

Fig. 9, Left, shows the relationships between the rates of changes of $v_{OM,t}$ for $C_p$, $a = \Delta v_{OM,t}/\Delta C_p$, and the diameter of OMs, $d_{OM}$. The values of $a$ decrease with increasing $d_{OM}$ and are smaller for higher $C/W$ and larger $d_{OM}$. On the other hand, Fig. 9, Right, shows the relationships between the values of

![Figure 7. Comparison of the Bingham parameters by viscometer measurements and SFTs. Top: $C/W = 7.34$, Bottom: $C/W = 9.16$, Left: yield stresses, $\tau_y$, Right: plastic viscosities, $\eta_p$.](image)

![Figure 8. Relationships between terminal velocity and sand concentration of CM. Top: by SFTs, Bottom: by viscometer measurements, Left: $C/W = 7.34$, Right: $C/W = 9.16)](image)
\( b = v_{OM_1} \) in bentonite suspensions, \( C_p = 0 \% \), and the \( d_{OM} \). The values of \( b \) become greater with increasing \( d_{OM} \) and are greater for higher \( C/W \) and larger \( d_{OM} \).

### 4.3. Ideal mixing proportions of CMs for ore lifting

The ideal values of sand concentration, \( C_p^\star \), are proposed as \( C_p^\star = -b/a \) that makes \( v_{OM_1} \) zero estimated from Fig. 8, i.e., the ideal condition assuming the no settlement of OMs. Fig. 10 shows the relationships between \( C_p^\star \) and \( d_{OM} \). The values of \( C_p^\star \) tend to increase with increasing \( d_{OM} \) and are higher for lower \( C/W \) and for greater densities of the OMs, \( \rho_{OM} \). For the given conditions of the CMs and the OMs, the ranges of \( C_p \) need to be higher than \( C_p^\star (>20\%) \) to transport heavy and large OMs. It should be notice that there is an impossible range of \( C_p \). Fig. 11 shows the relationships between the void ratios of sand, \( e \) calculated by Eq. 9, and \( C_p \). In general, the value of \( e \) ranges 0.5–1.0, \( e_{\min} \) to \( e_{\min} \) of sandy ground which corresponds to \( C_p = 71\%–83\% \) when applied to the case of CMs. For this range of \( C_p \), CMs are similar to solid rather than fluid. Therefore, considering the fluid characteristics of CMs, \( C_p \) should be less than 71%.

### 5. Conclusions

As the promising method for lifting the marine mineral deposits, the carrier material circulating method was proposed, and the mixtures of bentonite suspension and sand were suggested as an appropriate CMs. The purpose of this research was to propose the ideal mixing proportion of these CMs. The Sphere Falling Tests, SFTs, and the viscometer measurements were conducted. The Bingham parameters of CMs and the terminal velocities were examined according to the mixing proportion of CMs. Furthermore, the values of sand concentration, \( C_p \), for become lower \( v_{OM_1} \) were proposed as the ideal sand concentration, \( C_p^\star \), for the ores with no settlement. \( C_p^\star \) were greater for larger \( d_{OM} \) and lower \( C/W \), and they should be larger than 20% at least. Besides, the upper bound of \( C_p \) was proposed as 71% to assume the fluid characteristics. In conclusion, from the Bingham parameters, \( \tau_y \) and \( \eta_p \), the ideal mixing proportions of CMs can be proposed in the range of \( C_p = 20\%–71\% \) although it

![Figure 9. Relationship between \( a \) & \( b \) and \( d_{OM} \).](image)

![Figure 10. Relationships between \( C_p^\star \) and \( d_{OM} \). (Left: Viscometer measurements, Right: SFTs.)](image)
will be different for the conditions of the OMs and CMs.

\[
e = \frac{\rho_s C_w + \rho_s C_c}{\rho w} C_p
\]

Where \(C_w\) and \(C_c\) is the concentrations of water and clay for the total mass.

Figure 11. Void ratio of CM changes according to sand concentrations.

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