Construction of Seabed Structures by New Development Covering Material Using Fly Ash

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Abstract

In recent years, many seabed structure materials are needed for extraction of methane hydrate and submarine hydrothermal polymetallic ore in Japan. Although covering material is required to make the protection disturbance for environmental issues at seabed, it has high mobility, and does not bleed, etc. after construction. Therefore, a construction material which uses a material mixture of the surface-active agent with fly ash was developed. Usage of fly ash instead of cement leads to improved mobility, reduced construction cost and so on.

In considering these points, in order to clarify to what degree the contents of surfactant affects the properties of the injected fly ash mixture into the construction of seabed structures, different combinations of fly ash, surfactant and water were considered by means of multiple experiments.

Keywords: fly ash, surfactant, injection material, seabed structure

Introduction

Exploration and extraction of methane hydrate and submarine hydrothermal polymetallic ore are developing in Japan because a lot of energy and mineral resources are found in deep waters. On the other hand, the importance of biodiversity conservation is indicated because mining activity gives serious impacts to surrounding environment and there are a lot of ecosystems in the sea. Namely, rehabilitation in the deep seabed mining has to be considered in order to minimize environmental disturbance and conserve the ecosystem. As one of efficient techniques, it can be expected the application of covering material based on ground improvement techniques in Japan for construction of seabed structure.

Ground improvement technique is often used in order to improve the stability of construction by improving the weak floor by cement injection. Furthermore, it is also used for immobilization of toxic material of polluted soil by solidification (Wuana and Okieimen, 2011). This technique was applied for seabed structure to cover the seafloor in order to prevent the diffusion of radioactive substance in Fukushima disaster in 2011. Considering from above, it can be expected that the application of ground improvement technique for the construction of seabed structure is one of solutions to prevent environmental disturbance by the deep seabed mining. From these considerations, assessment of application of cements materials to the construction of seabed structure is conducted by means of multiple laboratory experiments and pilot test in Kagoshima Bay area in this study.

Tasks of Cement Construction in Deep Sea Area

Methane hydrate is often called fiery ice. Methane hydrate looks like an ice, and starts burning when an open flame is brought close to it; hence the name. Only water is left after combustion. It is a strange substance. Note that the natural methane hydrate – existing in areas surrounding Japan – that MH21 Research Consortium aims to develop is not purely a white agglomeration like artificial methane hydrate. Since methane hydrate exists in between the sand particles of sandy sediments as shown in the photo below, the methane hydrate-bearing layers do not appear white but rather look similar to soil (MH21 Research Consortium, 2010). Figure 1 shows the massive methane hydrate.

The methane hydrate layers targeted for development are methane hydrate concentrated zones consisting of pore-filling type methane hydrate layers in sandy sediments. The production method that has been used is called the depressurization method-based approach. It has become clear that the existing systems are applicable, as they are or with small modifications, to the production facilities and equipment (development systems). The fact that the existing systems are capable of supporting methane hydrate development systems means that the production of methane hydrate is able to be carried out almost in the same way as oil and natural gas development once methane hy-

Fig. 1. Massive methane hydrate (MH21 Research Consortium, 2010)

Rys. 1. Uwodniony metan (MH21 Research Consortium, 2010)

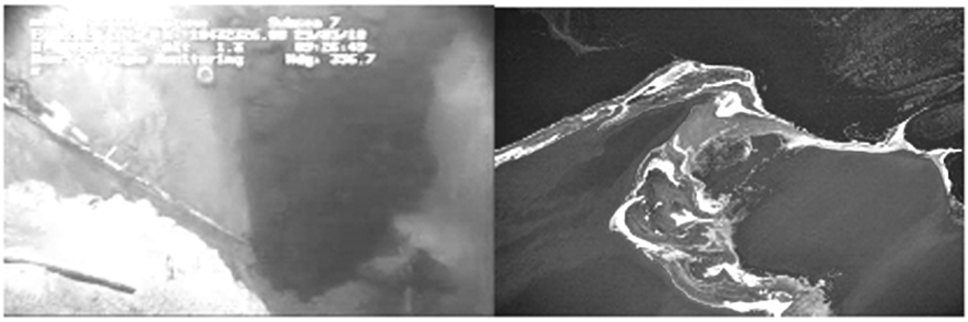


Fig. 2. Deep water horizon oil spill in the Gulf of Mexico (AP Communications, 2010)

Rys. 2. Wyciek ropy naftowej na dużej głębokości w Zatoce Meksykańskiej (AP Communication, 2010)

drate is dissociated in the layers. If the methane hydrate layers are developed, it is necessary to consider how the methane hydrate extracts effectively. In this case, the cement construction has to be investigated in deep sea area.

The other side, the deepwater horizon oil spill is an oil spill in the Gulf of Mexico which flowed for three months in 2010 (See Figure 2). The impact of the spill still continues even after the well was capped. It is the largest accidental marine oil spill in the history of the petroleum industry. The spill continues to cause extensive damage to marine and wildlife habitats as well as the Gulf's fishing and tourism industries. In late November 2010, 11,000 km^2 of the Gulf were re-closed to shrimping after tar balls were found in shrimpers' nets. The accident once made at deep sea area is difficult to hold the damage to a minimum. Figure 2 shows the situations of the deepwater horizon oil spill in the Gulf of Mexico.

From these points of view, the injection material for the offshore structure is started developing.

General Problem into the Offshore Structures

Deepwater wells pose special challenges: severe pressures and temperatures, as well as the need for specialized equipment and lots of cement. The wellhead of the Deepwater Horizon operation sat on the ocean floor, nearly a mile from the surface. The drill hole itself went another 4,000 m into rock. All cement begins as slurry with cement flakes and water. Contractors then add ingredients to make the cement set at the right time and to keep out gas and oil. Once the consistency of the mixture is decided on, it is pumped deep into the well, where it first sinks to the bottom and then oozes upward to fill the narrow spaces between the steel casing pipe and rock walls. When the cement sets, the casing and cement are supposed to form an impenetrable wall to keep gas or oil from pushing into the hole anywhere but the bottom, where its flow up the pipe can be controlled.

However, if gas bubbles invade the setting cement, they can form a channel for pressurized gas and oil to surge uncontrollably up the well, usually around the casing. The cement must be strong enough to withstand up to 35 MPa, to keep the well walls from collapsing (AP Communications, 2010).

In a connection operation, the volume of space between the steel casing pipe and rock walls is vast because the cement slurry is not filled com-

Tab. 1. Compositions of cements materials

Tab. 1. Skład materiałów cementowych

	Biding agent	**Superplasticizer**	**Underwater non – disjunction agent**	**Retarder**
OPC type	Portland cement	Polycarboxylic acid Ether system	Hydroxyethyl cellulose system	
TB type	Portland cement Alumina cement Calcium sulfate anhydrite			Sodium tartrate
Slag type	Slag			
FA type	Fly ash Portland cement Calcium sulfate anhyrite	MIGHTY 21 HP (Kao Chemicals)	Anion, cation system Viscotop	

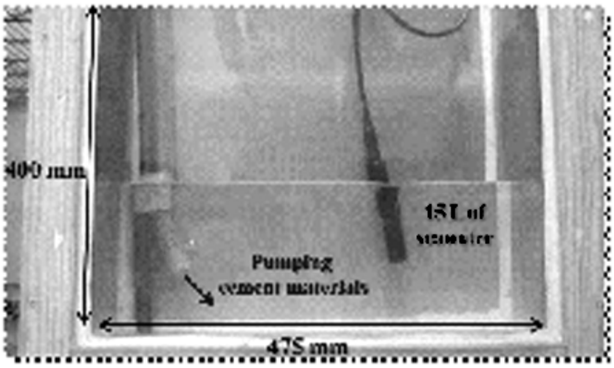


Fig. 3. Pumping test

Rys. 3. Testy pompowania

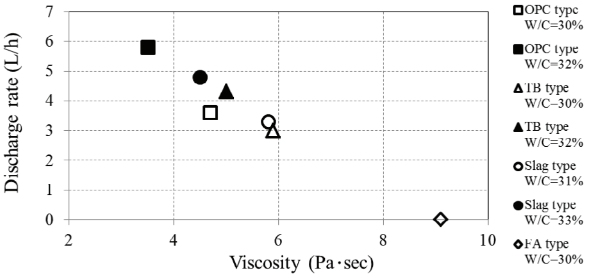


Fig. 4. Relationship between viscosity and discharge rate

Rys. 4. Zależność pomiędzy lepkością a stopniem wycieku

pletely at the injection space due to its bleeding property. Moreover, if the ratio of cement and water is increased, it is very difficult to inject into the injection point due to high viscosity. As a result, contamination of the surrounding ocean space occurs from the injection point. In addition, as the stiffness is weak, failure of the construction or the outflow of the injection point is exhibited. In order to mitigate this problem, application of the material comprised of flyash cement mixed with the surfactant Viscotop, which has excellent fluidity and settlement property, was attempted.

Assessment by Laboratory Experiment

Table 1 shows the 4 types of cement materials used in this study to assess the characteristics as the construction of seabed structure. Viscosity, pumping, diffusion, leveling, mechanical strength parameter, and characteristics of landform following are assessed from point of view of the construction of seabed structure by multiple experiments as described following sections.

Viscosity and Pumping

It is considered to use a pumping to construct seabed structure by cement materials. Therefore, the measurement of viscosity by Leo meter and pumping test were conducted. Figure 3 shows the appearance of pumping test. In this test, 400 mL of cement materials were discharged to the box filled 15 L of seawater by using 7 m length of peristaltic pump and 9.5 mm diameter with 30 rpm of rotary speed. Viscosity is calculated with assuming Bingham fluid (Mohammed et al., 2014). Figure 4 shows the relationship between viscosity and discharge rate. From these results, it is indicated that the pumping can be assessed by viscosity of cement materials because there are clear correlation between both parameters. Furthermore, FA type which viscosity was 9.1 Pa·sec could not be pumping due to high viscosity.

Diffusion

The pollution of water is suspected when the seabed structure is constructed by cement injection to the underwater. In order to assess the diffusion, suspended substance (SS) was measured by turbidity meter 10 minutes after 100 g of the cement materials injected to 400 mL of the underwater. Figure 5 shows the relationship between viscosity and SS. From these results, SS increases with a decrease of viscosity for every cement type

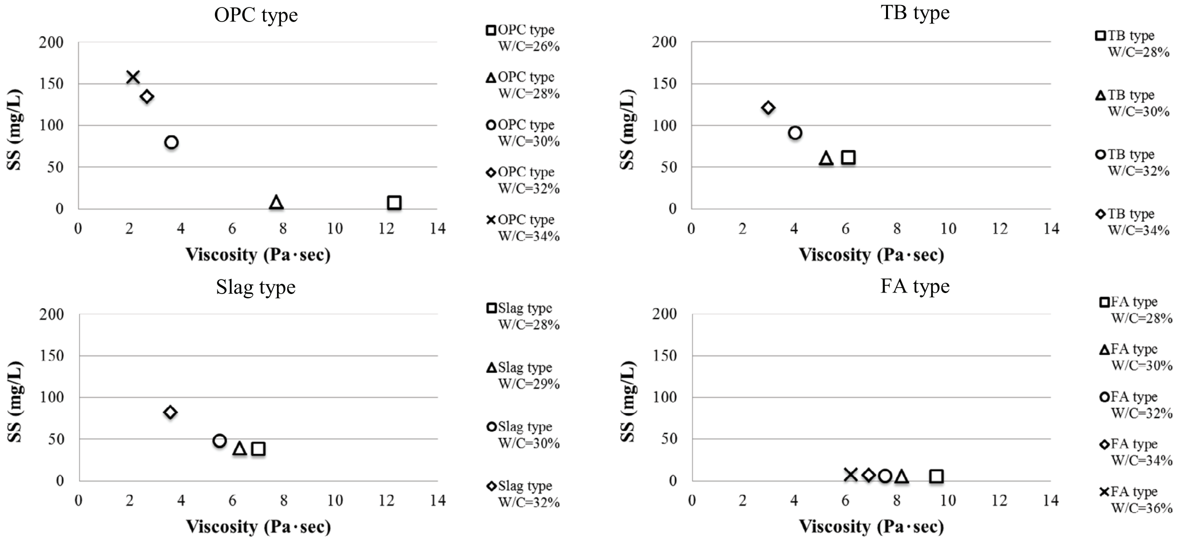


Fig. 5. Relationship between viscosity and SS

Rys. 5. Zależność pomiędzy lepkością a zawartością zawiesin stałych

though there is difference about reduction tendency between each cement type. According to Japanese standard that SS is regulated 50 mg/L (Iwasaki, 1991), it can be considered that Slag type and FA type have small impact to the water pollution and OPC type and TB type have relatively big impact.

Leveling

In the construction of seabed structure, it is required that cement materials covers wider area in the seafloor. Therefore, slump test was conducted in order to assess leveling. The slump test is defined as the Japanese industrial standard. The dimension of the flow cone device is 50 mm x 51 mm as shown Figure 6. After the mixture was set into the cone on the glass board, the cone was pulled up from the original position. The mixture spread out after pulling the cone up from the original position, the length of the mixture was measured as the flow value. Figure 7 shows the results of the slump test. There are not clear correlations between viscosity and flow value under the low viscosity. However, the flow value of FA type which has high viscosity is relatively smaller than that of others. According to Japanese standard that the flow value is regulated 180 + 10 mm (Iwasaki, 1991), it can be considered that FA type has poor leveling.

Mechanical Strength Parameter

The water pressure is increased with an increase of depth of the sea. Furthermore, there are the external forces in the seafloor such as flow of the ocean, sea tide, and seismic sea wave. Therefore, a certain number of mechanical strength is required for the seabed structure against the high water pressure and the external forces. A cylindrical mold 50 mm in diameter and 100 mm deep was used to produce the specimens. The considered curing times for the specimens were 1 and 28 days in 15 degree of water curing, and an unconfined compressive strength test was performed on the specimens after the aforementioned curing period. Each type of strength test was run on 5 to 10 specimens and the results were averaged to obtain the mean value of their properties.

Table 2 shows the results of unconfined compressive strength test. As the table show, OPC type and TB type are hardened after curing 1 day. Moreover, TB type has the characteristics of rapid hardening because the unconfined compressive strength is higher than others. On the other hands, Slag type and FA type are not hardened though FA type is slightly hardened after curing 28 days. Therefore, it can be assessed that the mechanical strength parameter of OPC type and TB type is better than that of Slag type and FA type.

Characteristic of Landform Following

It is required that the seabed structure is constructed uniformly even in the seafloor with its many ups and downs. Besides, it is also required to cover the seafloor with corresponding the changing the landform such as subsidence and cracking caused by the extraction of mineral resources as shown Figure 8. Therefore, storage modulus and loss modulus obtained dynamic viscoelastic mea-

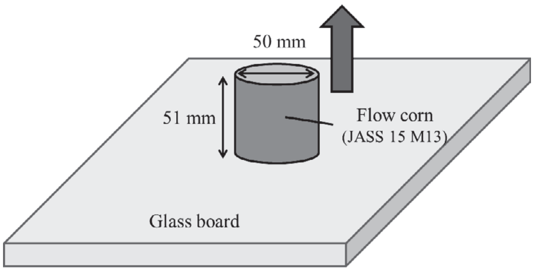


Fig. 6. Slump test

Rys. 6. Test spadku

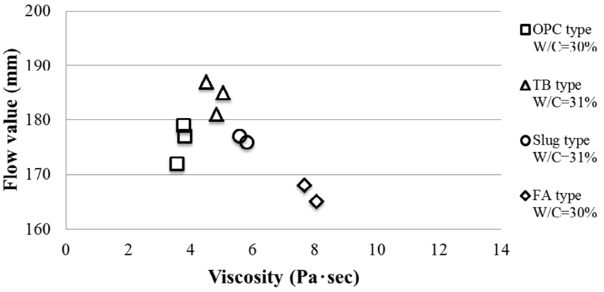


Fig. 7. Results of slump test

Rys. 7. Wyniki testu opadowego

Tab. 2. Results of unconfined compressive strength test

Tab. 2. Wyniki testu nieograniczonej siły nacisku

	OPC type	**TB type**	**Slag type**	**FA type**
1 day (MPa)	8.0	18.2	0	0
28 days (MPa)	38.6	30.3	0	6.1

surement (Papadogiannis et al., 2003) were calculated in order to assess the characteristics of landform following.

Characteristic of Landform Following

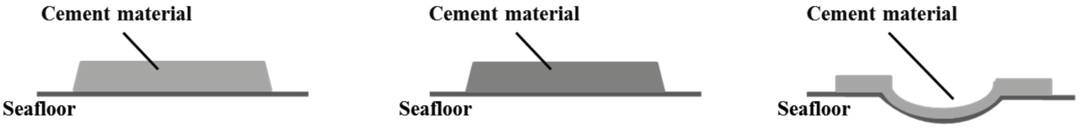
It is required that the seabed structure is constructed uniformly even in the seafloor with its many ups and downs. Besides, it is also required to cover the seafloor with corresponding the changing the landform such as subsidence and cracking caused by the extraction of mineral resources as shown Figure 8. Therefore, storage modulus and loss modulus obtained dynamic viscoelastic measurement (Papadogiannis et al., 2003) were calculated in order to assess the characteristics of landform following.

Usually, cement materials have viscoelasticity properties which exhibit both viscosity and elasticity characteristics. Viscosity indicates the stiffness for viscous materials and elasticity indicates the stiffness for elastic body. The cement materials show the behavior as viscous materials when the value of storage modulus is smaller than that of loss modulus. On the other hands, the cement materials show the behavior as elastic body when the value of storage modulus is bigger than that of loss modulus (Franck, 2013).

According to the results of dynamic viscoelastic measurement (Figure 9), FA type shows the behavior as elastic body because the value of storage modulus is smaller than that of loss modulus while OPC type, TB type, and Slag type show the behavior as viscous materials. It is considered that the cement materials which show the behavior as elastic body have higher applicability to construct seabed structure than that of viscous materials in the seafloor which changes the landform such as subsidence and cracking caused by the extraction of mineral resources as shown Figure 8. Moreover, FA type is not hardened immediately after cement injection according to the results of unconfined compressive strength test shown in the previous section. For these reasons, the characteristic of landform following of FA type is better than that of others.

Assessment as the Construction of Seabed Structure

Table 3 summarizes the multiple experiments. OPC type, TB type, and Slag type have favor property for pumping because the cement materials can be discharged by pumping. According to Japanese standard, Slag type and FA type have small impact to the water pollution, and OPC type and TB type have good leveling. Furthermore, the mechanical strength parameter of OPC type and TB type is better than that of others because both types of cement materials are hardened and have a certain number of mechanical strength. The characteristic of landform following of FA type is better than that of others because FA type is not hardened immediately and shows the behavior as elastic body. From these results, it can be considered that proper selection of cement materials is



Construction of seabed structure by the cement materials.

Extraction of mineral resources below the seafloor.

Deformation of cement materials with corresponding the changing the landform.

Fig. 8. Image for landform following

Rys. 8. Obraz ukształtowania terenu

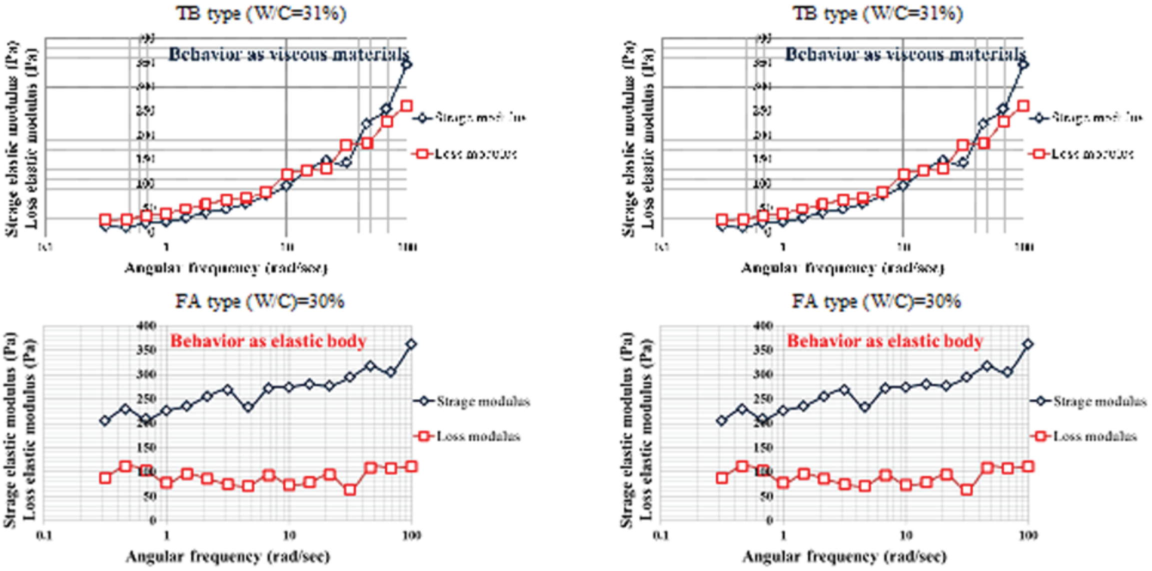


Fig. 9. Storage modulus and loss modulus of cement materials

Rys. 9. Moduł zachowawczy oraz moduł stratności materiałów cementowych

needed according to the field which constructs seabed structure by considering the characteristics of each cement material because there is no cement material which is satisfied with all of parameter required as seabed structure.

Pilot Test in Kagoshima Bay Area

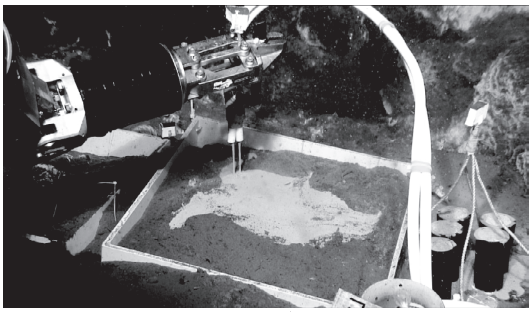
In order to understand the behavior of cement materials in the seafloor, pilot test was conducted in Kagoshima Bay area. In this pilot test, the diffusion was assessed by using video camera when the cement materials injected to the seafloor in depth of 200 m. The water temperature was 16 degree.

Figure 10 shows appearance of cement injection to the seafloor. As a result of pilot test, OPC type and Slag type could be injected to the seafloor without diffusion in the underwater though TB type and FA type could not. This result is different with the result of laboratory experiment. Therefore, the viscosity of cement materials under the water pressure of 0.5 MPa was measured because the difference between laboratory and pilot test was depth of water. Figure 11 shows the results of viscosity under the water pressure of 0.5 MPa. From these results, the viscosity of TB type and FA type is decreased with increasing water pressure. For TB type, this is the reason why the dispersion of cement particles is occurred before coagulation by breaking of chemically formed linkages between the particles which is sodium tartrate added as retarder (Wallevik, 2009). Besides, for FA type, the hydrophobic interaction is inhibited in micelle formation by underwater non-disjunction agent due to high water pressure (Shibayama, 2011). Therefore, a decrease of viscosity of TB type and FA type are attributed to the diffusion of cement materials because SS increases with a decrease of viscosity according to the

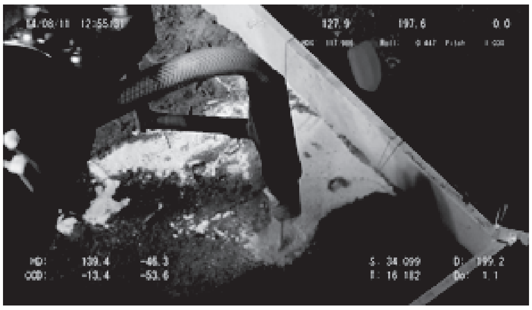
Tab. 3. Summarizes the multiple experiments

Tab. 3. Podsumowanie eksperymentów

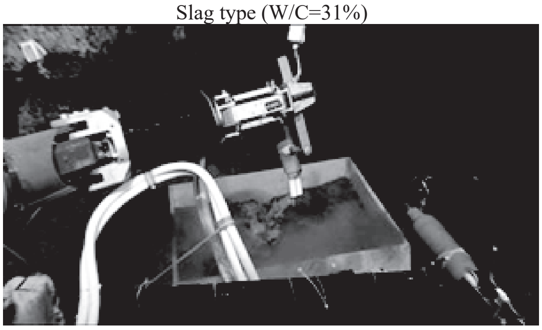
	Pumping	Diffusion (mg/L)	Leveling (mm)	Mechanical strength parameter (MPa)	Characteristic of landform following
OPC type; W/C=30%	○	×(80.2)	○(176.0)	○(38.6)	×(Viscous materials)
TB type; W/C=31%	○	×(60.3)	○(184.3)	○(30.3)	×(Viscous materials)
Slag type; W/C=31%	○	○(48.0)	○(176.3)	×(0)	×(Viscous materials)
FA type; W/C=30%	×	○(5.5)	×(166.5)	×(6.1)	○(Elastic body)



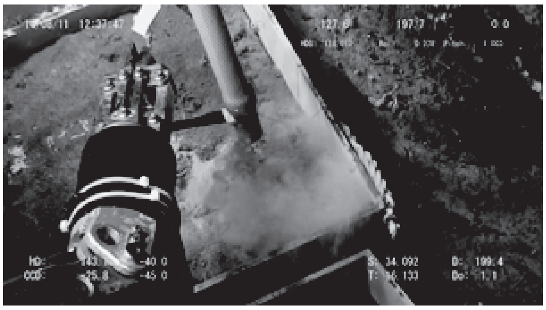
OPC type (W/C=30%)



Slag type (W/C=31%)



TB type (W/C=31%)



FA type (W/C=30%)

Fig. 10. Appearance of cement injection to the seafloor

Rys. 10. Wprowadzanie cementu do podłoża morskiego

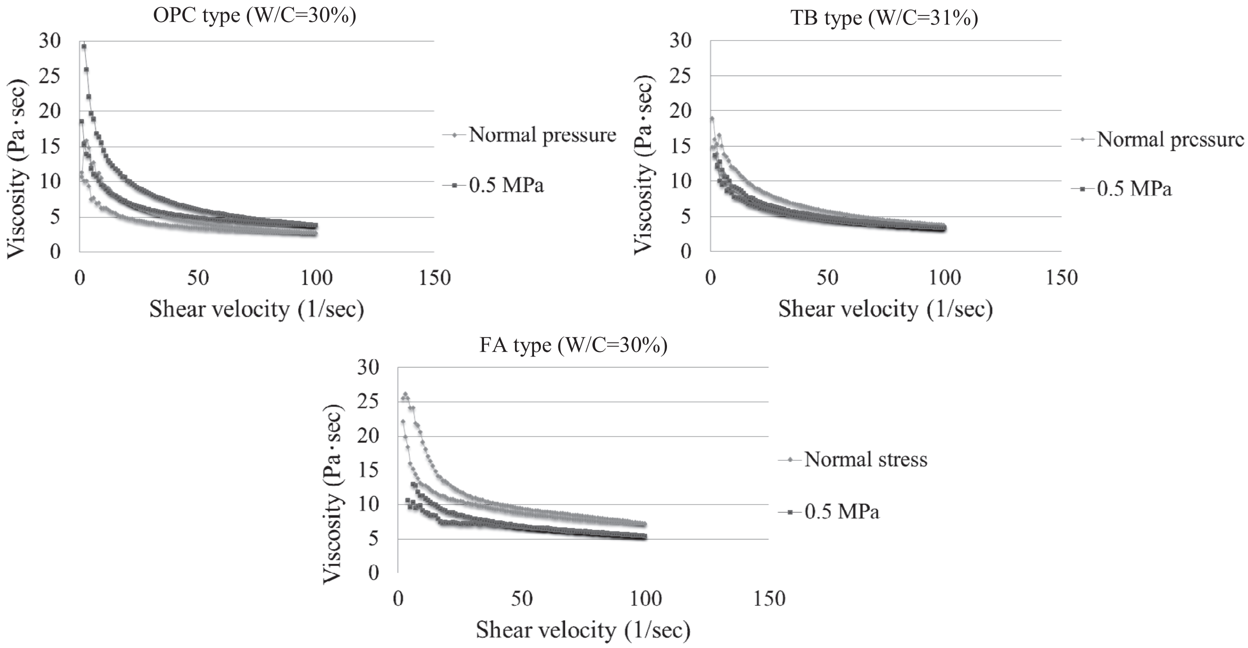


Fig. 11. Viscosity of cement materials under the different water pressure

Rys. 11. Lepkość materiałów cementowych pod wpływem różnego ciśnienia wody

relationship between viscosity and SS shown in the previous chapter.

Considering the results of pilot test, it can be expected that OPC type and Slag type which are insulated from the influence of water pressure can be applied in the deep sea. In contrast, TB type and FA type are expected to apply in the shallow sea area. Additionally, it can be expected that TB type can be applied in the seafloor which there are the effects of external forces such as flow of the ocean and seismic sea wave and FA type can be applied in the seafloor with its many ups and downs or which changes the landform such as subsidence and cracking caused by the extraction of mineral resources.

Conclusions

In this study, the application of cement materials as seabed structure is discussed by multiple experiments to assess viscosity, pumping, diffusion, leveling, mechanical strength parameter, and characteristics of terrain following and pilot test in Kagoshima Bay area to understand the behavior of cement materials in the seafloor. As a result, the application guidelines are suggested for 4 types of cement materials which have different characteristics. As the next step, the application of cement materials as seabed structure in the deep sea and under high temperature near seafloor hydrothermal system, and the effect on the sessile organism in the seafloor are the subject of further study.

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Konstrukcja struktur dna morza za pomocą nowych materiałów pokrywających z użyciem popiołów lotnych

W ostatnich latach istnieje potrzeba obecności wielu materiałów w strukturze dna morza aby możliwe było wydobycie uwodnionego metanu oraz hydrotermalnych podwodnych złóż polimetalicznych w Japonii. Materiał okładziny jest potrzebny aby ochraniać środowisko naturalne dna morza, posiada on dużą mobilność oraz nie odpowietrza się po zainstalowaniu. Wynaleziono materiał konstrukcyjny, który składa się z mieszaniny odczynnika powierzchniowo-czynnego z popiołem lotnym. Zastosowanie popiołu lotnego zamiast cementu prowadzi do lepszej mobilności, redukcji kosztów instalacji itp.

Mając na względzie te cechy, aby stwierdzić w jakim stopniu zawartość surfaktanta wpływa na właściwości wprowadzonej mieszaniny popiołu lotnego do konstrukcji struktury dna morskiego zastosowano różne kombinacje popiołu lotnego, surfaktanta i wody. W tym celu przeprowadzono wiele eksperymentów.

Słowa klucze: popiół lotny, materiał wprowadzany, struktura dna morskiego