ABOUT GEOTECHNICAL PROPERTIES OF THE DEEP SEABED POLYMETALLIC NODULES

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Exploring polymetallic nodules deposits on the deep seabed, also their geotechnical properties are studied. Basic physical properties are determined right onboard immediately after the nodule sample is retrieved from the seabed. The values of volume density and water content of nodules depend on their genetic type and vary from 1.75-2.08 g/cm^3 and from 39-66 %, respectively. Other physical properties like dry nodule density, porosity, void ratio and specific nodule density are calculated taking into account a special correction for water salinity M=0.035. Specific nodule density are determined also in stationary labs using pycnometric method. Mechanical property of nodules represents uniaxial compressive strength. Mean values for the respective parameter vary from 0.64 MPa (the fraction > 10 cm) to 3.29 MPa (the fraction 0-2 cm). The bigger the nodule, the lower its strength and *vice versa*. This parameter is useful for such mining technique, which supposes to crush nodules before lifting them up to the surface of the sea. Technological properties include rip off force resistance, nodule apparent density and angle of repose. Rip off force resistance depends also on nodule grain size and for the medium fractions (4-8 cm) ranges from 0.17-1.48 kPa. Nodule apparent density measurements provide the information that about 1200 kg of non-crushed nodules can be placed to 1 m^3 container. The angle of repose measurements revealed that a slope stability of the heap of nodules ends at 33°.

KEY WORDS: polymetallic nodules, physical, mechanical, technological properties.

1. INTRODUCTION

Polymetallic nodules, rich in metals such as manganese, nickel, copper, cobalt etc., belong to the deep seabed minerals. The most nodule abundant province is Clarion-Clipperton Zone in the Pacific Ocean, where nodules occur at depths 3700-5500 meters. As the period of exploration is finally reaching its conclusion, the nodule rich fields are being delineated and technical equipment for the mining is being developed. One of main features of the nodule mineral deposits is that they are 2-dimensional, highly beneficial for miners, as the nodules can be collected from the surface of the seabed, then washed, crushed and transported to the mining vessel. The transport from the seabed (lifting) itself will be the most complicated phase of the future mining operation. The whole process of taking the nodules from the deposit on the seabed to the furnace at onshore processing facility will be complicated by a variety of circumstances. Clear knowledge of geotechnical properties of the nodules will enable the assessment of process characteristics under such circumstances. Deep seabed polymetallic (manganese, ferromanganese) nodules (fig.1) form natural, polymineral aggregations of ferromanganese hydroxides and clay minerals, which contain in more than 50 elements in their chemical composition, Kotlinski (1999). Ferromanganese hydroxides precipitate on the nuclei formed by, e.g., fragments of old nodules and/or volcanic rocks, zeolites, fish teeth etc. The nodules have been described as potatoe-like, cannon balls, marbles, tablets, and a number of other less recognizable forms, Mero (1965).

Fig. 1 Deep seabed polymetallic nodule (from left: top, bottom, cross-section)

For decades they were considered only a scientific curiosity, but are now, because of their economic value, the focus of much attention. The polymetallic nodule deposits contain billions of tons of metals and besides manganese, are rich in nickel, copper, cobalt, iron and traces of two dozen other metals, Kennett (1982). Nodules have significant potential to supply rare earth elements (REEs) to the marketplace as a byproduct of the extraction of Mn, Ni, Cu and Co, Hein (2012). A description of physical, mechanical and technological properties of polymetallic nodules has been an essential part of geotechnical studies included in the Interoceanmetal Joint Organization (IOM) “plan of work for exploration for polymetallic nodules”, approved by the International Seabed Authority in 1997. The Clarion-Clipperton zone deposits are on the surficial sediments of the deep seabed in the northeastern tropical Pacific, Morgan (2000). In terms of their mode of formation, the nodules are classified into hydrogenetic H, diagenetic D and, a transition form, hydrogenetic-diagenetic HD. From the standpoint of geotechnical research, nodules are coarse-grained, non-cohesive formations, Dreiseitl (2009).

2. METHODOLOGY OF MEASUREMENTS

The relevant properties are determined in both shipboard and land-based laboratories. The shipboard analyses include nodule volumetric density and water content, determined immediately after the samples were retrieved. Other physical properties, such as dry nodule density, porosity, void ratio and specific nodule density, are subsequently calculated. Specific nodule density is also determined at land-based laboratories using the pycnometric technique, Dreiseitl and Bednarek (2011). During the exploration period nodules can be retrieved from the seabed in two ways: at stations with coordinates by the sampler – box corer with dimensions of 0.5x0.5x0.5 m or by the dredge with the open mouth 1.4x0.4 m towed on the surface of the seabed. According to morphological type and size, 3-4 typical nodules of the box core sample are usually selected for shipboard measurements. Six size fractions are distinguished, in cm: 0-2, 2-4 (small), 4-6, 6-8 (medium), 8-10 and 10+ (big). Frequent morphological nodule types (morphotypes) occur as follows: D – discoidal, E – ellipsoidal, S – spheroidal, T – tabular, P – polynuclear, accreted, I – irregular, fD – fragments of discoidal, f – non identified fragment.

2.1. PHYSICAL PROPERTIES

Volumetric density (moist unit weight), ρ [g/cm^3], is a ratio between the weight of a nodule, including air and water present, and its volume, Johnson, Degraff (1988). A method of hydrostatic weighing is applied taking into account density of pore seawater, equaling 1.025 g/cm^3, Neizvestnov (2004). Dry nodule density (dry unit weight), ρ_d [g/cm^3], is based on nodule weight without water to the total volume of nodule ratio:

$$\rho_d = \frac{\rho}{1 + w \times 0{,}01}$$

where ρ = volumetric density, w = water content corrected for pore seawater mineralization M = 0.035.

Water content, w [%], is the amount of water contained in a nodule; it is expressed in terms of the mass of water evaporated at 105˚C per mass of dried nodule. During evaporation, the pore water-contained salts precipitate in the nodule pores and a result has to be corrected for pore seawater mineralization M=0.035:

$$w = \frac{w_0 \times (1 + M)}{1 - M \times w_0 \times 0{,}01}$$

where w_0 = water content with no regard of M, M = 0.035 pore seawater mineralization.

Natural water content, w_n [%], is expressed as the mass of water evaporated at 105˚C relative to the mass of a wet nodule sample.

In deep seabed sediments, including the nodules, pore seawater fills the spaces between solid particles. The amount of the spaces can be expressed by porosity and void ratio. Porosity, n [%], represents the proportion of total volume of nodule mass occupied by spaces (voids) while void ratio, e [no unit], expresses the relationship between the volume of spaces and the volume of solids, Zaruba, Mencl (1976):

$$n = w\, \rho_d / \rho_w$$

where ρ_w = density of pore seawater with M = 0.035 at t = 20˚C (ρ_w = 1.025 g/cm^3), and $e = n / (100 - n)$.

Dry nodule density and void ratio are used to calculate the specific (solid particles) nodule density, $\rho_s = \rho_d (1+e)$ [g/cm^3]. Land-based laboratories allow for the determination of only one engineering parameter, the specific nodule density by a pycnometric technique. The determinations are conducted on dried and crumbled nodules. The density of solid particles is calculated by dividing their mass by volume.

2.2. MECHANICAL (STRENGTH) PROPERTIES

Uniaxial compressive strength σ [MPa] is a single mechanical (strength) property that can be determined in a shipboard laboratory. The property expresses the force that needs to be applied to break a nodule. This is not a standardized testing because in nodules it is impossible to cut a standard shape – the cylinder. Besides the force, expressed in newtons [N], the rupture area is measured. The need for the measurements of this property will appear in phase between nodule collection on the seabed and their transportation to the surface in the crushed form in the pipeline.

2.3. TECHNOLOGICAL PROPERTIES

The determination of the technological properties of the nodules is important for future mining operations and the transportation of the nodules from the mining site to an on-shore processing plant. Rip off force is the force needed to detach a nodule from sediment, and is expressed in newtons [N], fig.2.

Fig. 2 A special device for rip off force measurements

However, in practice it is nodule resistance to the rip off force that is determined, this is why the area of nodule-sediment contact is additionally measured. Therefore, rip off force resistance $P = 10\, N/S$ [kPa], where N = rip off force [N], N = n_s - n_w, where n = force of separation the nodule from the sediment read from device, n_w = weight of nodule, S = area of the contact nodule-sediment [cm^2].

This property can be of importance for certain techniques (e.g. sucking) in seabed nodule mining.

Nodule apparent density, ρ_{app} [kg/m^3], provides information on the amount (by weight) of nodules that can be placed in a $1m^3$ container. Maximum nodule apparent density, ρ_{appmax} [kg/m^3], is obtained when a container of nodules is shaken and refilled. The angle of repose is determined as the tangent of angle α between the height of the nodule heap and the half-diameter of the heap.

The two latter properties are best determined when a large amount of nodules (hundreds of kilograms) is collected by seafloor dredge and it is delivered onboard.

3. RESULTS OBTAINED

A large amount of data relating to the geotechnical properties of polymetallic nodules was obtained in four at-sea expeditions from 2001 – 2016, informational reports on cruises IOM-2001, IOM-2004, IOM-2009, IOM-2014. The IOM exploration area is a 75,000 km^2 large and was explored in 2001 and 2004. At those times, the most promising areas were marked: exploration blocks H11 and H22, researched in expeditions "2009" and "2014", respectively.

3.1. PHYSICAL PROPERTIES

The physical properties of nodules found at 50 sample stations within exploration block H11 are presented in table 1.

Table 1

The physical properties of all nodule genotypes from the exploration block H11 (173 samples)

	w, %	ρ, g/cm^3	ρ_d, g/cm^3	n, %	e	ρ_s, g/cm^3	w_n, %
Mean	46	1.97	1.35	61	1.57	3.46	32
Median	46	1.98	1.36	61	1.58	3.52	32
Maximum	57	2.06	1.51	66	1.96	3.68	37
Minimum	36	1.83	1.18	53	1.14	2.98	27
Av deviation	3.48	0.04	0.06	2.21	0.14	0.13	1.65

Within exploration block H22 all of known genetic types and most of morphotypes nodule were found. Two hundred and five representative nodules were examined in detail, selected from 48 stations (table 2), Dreiseitl (2012).

Table 2

The physical properties of all nodule genotypes from exploration block H22 (205 samples)

	w, %	ρ, g/cm^3	ρ_d, g/cm^3	n, %	e	ρ_s, g/cm^3	w_n, %
Mean	47	1.97	1.34	62	1.62	3.49	32
Median	47	1.97	1.34	62	1.61	3.51	33
Maximum	71	2.27	1.75	72	2.56	3.68	42
Minimum	29	1,77	1.03	46	0.86	3.05	22
Av deviation	2.94	0.04	0.05	1.56	0.11	0.06	1.39

Fragments of ellipsoidal nodules fE were found to be the prevalent morphotype (70 samples), while unbroken nodules are represented with E ellipsoidal (51) and D discoidal (13) morphotypes (table 3). Morphotypes occurring in less than 10 examples, e.g. spheroidal or tabular, were omitted in table 3, Dreiseitl (2012).

Table 3

The physical properties of nodules according to morphotype (186 samples)

Morphotype	w, %	ρ, g/cm^3	n, %	ρ_s, g/cm^3	No of trials
fE	47	1.99	62	3.53	70
f	46	1.99	61	3.49	52
E	49	1.94	62	3.46	51
D	50	1.93	63	3.45	13

Regarding nodule grain size, a small fraction is presented in 65 samples, a medium fraction - 114 samples and a large fraction - 23 samples (table 4).

Table 4

The physical properties of nodules according to grain size (202 samples)

Fraction, cm		*w*, %	*ρ*, g/cm^3	*n*, %	ρ_s, g/cm^3	No of trials
Small	0-2	53	1.87	63	3.32	6
	2-4	48	1.95	62	3.46	59
Medium	4-6	47	1.98	62	3.51	60
	6-8	47	1.98	61	3.50	54
Large	8-10	46	1.99	61	3.51	18
	10+	48	1.96	62	3.50	5

The “natural water content” determination is extremely important for an estimation of nodule reserves in dry condition. The results presented in tables 1 and 2 clearly affirm that 1/3rd of nodule weight in their natural state is pore seawater, Dreiseitl (2012).

A clear relationship between volume density and water content was found to exist (fig.3). The majority of the coupled data (points) are located around the trend line. According to chemical analysis, about 95 % of nodule samples have diagenetic origin. It is observed that volume density mostly varies between 1.90 and 2.05 g/cm^3 while water content ranges from 40-55 %.

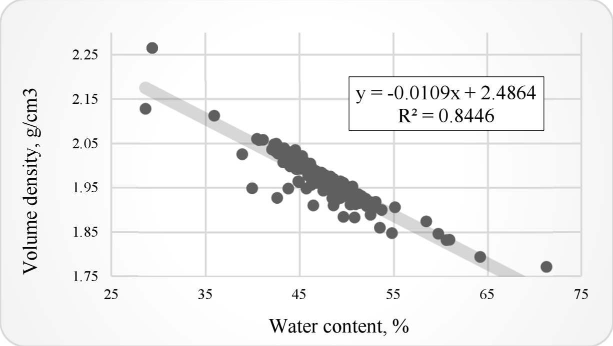

Fig. 3 The relationship between volume density and water content of nodules
(205 nodule samples from H22)

A pycnometric technique for the determination of nodule specific density was applied at a land-based laboratory for 30 nodules and nodule fragments retrieved in the dredge. The results correlated well ($\sigma = 0.0732$) with mean value of 3.31 g/cm^3. This property was also calculated to take into account the same nodule sample: $\rho_s = 3.33$ g/cm^3, Dreiseitl, Bednarek (2011). The results were found to match.

3.2. MECHANICAL (STRENGTH) PROPERTIES

A logarithmic relationship was noted between the nodule fraction (grain size) and strength (fig.4) expressed by uniaxial compressive strength property at 256 nodule samples. The strength of medium fraction of nodules, as the most frequent (127 measurements), ranges (in mediana) from 1.02 to 1.34 MPa. Large fractions are usually very fragile with a strength of < 1 MPa because of the usual presence of ruptures and their tendency to crush very easily, this assisted by benthic organisms. The rule is: the bigger the nodule, the lower its strength, Dreiseitl (2009).

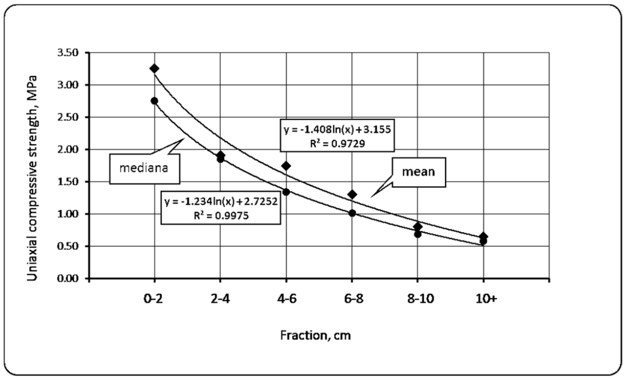

Fig. 4 Nodule strength and the fractions

3.3. TECHNOLOGICAL PROPERTIES

One possible technique that could be utilized to collect deployed nodules on the surface is to "suck" them from the seabed in a vacuum motion. Nodules appear to be affixed to the underlying sediment and a certain level of force is required to rip them off. Data presents the rip off force resistance in fraction dependence (table 5), Dreiseitl (2009).

Table 5

The rip off force resistance for all nodule morphotypes, kPa

Fractions	Min	Max	Mean	No of trials
Small	0.23	1.27	0.71	5
Medium	0.17	1.48	0.67	116
Large	0.19	1.24	0.53	71

Four dredge-samplings were carried out within the "2014" expedition with 2309 kg of nodules being retrieved onboard. It is likely the three parameters presented in table 6 will be not of any practical use as if the nodules are recovered via hydraulic method of mining (method preferred by IOM), they are supposed to be crushed into a single small fraction right at the seabed before being taken into vertical pipeline to the surface.

Table 6

The technological properties of nodules

Dredge No.	Nodule apparent density, ρ_{app} [kg/m^3]	Maximal nodule apparent density ρ_{appmax} [kg/m^3]	Angle of repose [deg]
2229 Tp-1	1136	1250	33
2229 Tp-2	1121	1220	33
3521-1 Tp-1	1106	1242	30
3521-1 Tp-2	1068	1205	30

4. CONCLUSIONS

- The physical properties of nodules as a deep seabed mineral are influenced by mineralization and pore seawater density,
- There is no practically difference in the physical properties of particular nodule morphotypes, however, differences between particular fractions (grain size) exist,
- 1/3rd of nodule's weight is made up pore seawater,
- The pycnometric technique for the determination of nodule specific density corroborates the accuracy of the formula adopted for its calculation,
- The larger the nodule, the more fragile it is,
- The larger the nodule, the smaller the force required to separate it from sediment,
- More than 1200 kg of non-crushed nodules can be fitted into a 1 m^3 container.

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