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Research Article

Contrastive and experimental study on the characteristics of bauxite during shipping

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Abstract

Some bulk carriers have suffered accidents due to transporting cargo with potential liquefaction, which is classified as Group A material in the International Maritime Solid Bulk Code (IMSBC code). Bauxite has similar liquefaction behavior during shipping. However, Bauxite is not listed as Group A yet. In order to update the schedule of the IMSBC code, and provide more reliable guidance to the shipping industry, further studies are warranted to verify and expand on the liquefaction of bauxite. This study is of great significance to illustrate bauxite carrier accidents and to prevent the occurrence of new accidents. At first, general properties of bauxite were reviewed, then the distribution of moisture content was identified according to the statistical data; moreover, properties of other samples were compared with those of other bauxite, such as saturation, particle distribution, compactness and density. Third, an experimental analysis was performed based on bench of vibration and rolling device. The results show that the range of moisture content in the IMSBC rule is lower, the density range is smaller, and the classification of Group C is improper. Especially, the liquefiable characteristics of bauxite were verified, and the critical moisture content of liquefaction was found. As a conclusion, a proposal for amending the relevant items of the IMSBC code was produced based on this contrastive and experimental study of the characteristics of bauxite during shipping.

1. Introduction

Bulk cargo transportation has been quite common in international trade for a long time. A special kind is called solid bulk cargo with potential liquefaction, CPL for short, in the industry. CPL is defined as cargo containing some fine particles and a certain amount of water, and when moisture content exceeds the Transportable Moisture Limit (TML), it may form a free liquid level or solid-liquid 2-phase flow layer (Ministry of Transport of the People's Republic of China, 2011). CPL was classified as Group A in the IMSBC code adopted by the IMO (International Maritime Organization, 2008).

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At present, the liquefaction characteristics of CPL have been studied from the aspect of moisture content of concentrate, nickel ore, kaolin, copper concentrate, and wet coal. Some research institutes have regarded solid bulk cargo, including broken glass and ceramic tile, as Class A from the perspective of fluidity or shifting of cargo. Bulk carrier accidents carrying CPL have always attracted much attention all over the world. In recent years, there have been many incidents of accidental capsizing of ships carrying CPL; for instance, fined iron ore carried by MV Stellar Daisy capsized in 2017, bauxite carried by MV Bulk Jupiter capsized in 2015, and nickel ore carried by MV Marita Bauxite capsized in 2013. Nickel ore is the most dangerous and largest type of cargo in the case of capsizing accidents (DNV GL, 2015). In recent years, there have been frequent accidents due to carrying iron ore powder and concentrate, which are treated by the IMO as mandatory CPL during the entirety of a maritime operation.

The total amount of bauxite resources in the world is 30 billion tons, which are mainly distributed in Africa, Oceania, South America, and Southeast Asia. As the largest producer of alumina in the world, and with the increase of alumina production capacity, domestic bauxite resources are gradually dwindling. The import of bauxite has increased from about 2.3 million tons in 2007 to 82.62 million tons in 2018 (Ministry of Commerce of the People's Republic of China, 2019). Relevant reports show that the external dependence of bauxite in China may increase steadily to 55 - 60 % from 2019 to 2024 (China Aluminium Network, 2018). For instance, imports of bauxite from Guinea reached 38.19 million tons in 2018, a 38 % surge over the previous year. Bauxite imports from Australia increased to 29.77 million tons.

Such a huge import is mostly transported by and very large ore carriers (VLOCs) and Handy carriers which refer to Handysize and Handymax bulk carriers. VLOCs are usually designed for ore, including CPL. Even if liquefaction of cargo occurs during transportation, the impact on stability remains under control. However, Handy carriers have no special structure or function to respond to cargo liquefaction. Therefore, if such ships are used to carry bauxite, it is necessary to detect the behavior of bauxite in marine environments, especially to evaluate the risk of liquefaction and its impact on ship stability and safety.

As the provision stipulate specifically in Chapter VI of the SOLAS Convention 1974, as amended (International Maritime Organization, 2008), for concentrates or other liquefiable cargoes, cargo information provided by the shipper should also be provided on the moisture content of the cargoes and the certificate of Transportable Moisture Limit. Liquefaction is the typical characteristic of Group A cargoes; however, bauxite has not been treated as Group A in the IMSBC code. At present, the knowledge of bauxite characteristics is still in the description of characteristics in the schedule of the IMSBC code. After the accident of M.V. Bulk Jupiter, considering the liquefaction risk of bauxite, since 2015, the IMO has constantly reminded the shipping industry to be alert (International Maritime Organization, 2015).

In some views, special attention should also be paid to other physical properties beyond moisture content (Munro & Mohajerani, 2016). For example, Gebeng bauxite (Muzamir et al., 2017) was further researched in terms of several properties including particle size distribution and specific gravity. The loading process also requires special attention and, thus, Portella (Portella et al., 2011) proposed a synchronous drain-loading process for bauxite carriers to reduce the initial risk of stress superimposed on hull structures during single-hold loadings.

Ship motion acceleration (Wang, 2015), rolling, pitching, and hull vibration caused by onboard machinery is not only harmful to the safety of the ship structure (Ding, 2017), but can also change the characteristics of the cargo on board (Munro & Mohajerani, 2016) and facilitate the liquefaction of cargo (Drzewieniecka, 2014). Focusing on the Handy bauxite carrier, Wu et al. (2019), simulated the first stage of the bauxite maritime transportation process, and obtained spatial correlation between transportation risk and ship position.

According to the findings of Wu et al. (2020), seaborne bauxite presents potential danger when interacting with a carrier in a specific environment; therefore, it is necessary to develop an approach to study the transportation safety of bauxite on the basis of a safety system engineering method. Here, literature comparison and experimental verification are used to study the real characteristics of seaborne bauxite to address a critical examination of the related provision of the IMSBC code and provide an experimental basis for the revision of relevant provisions.

The general properties of bauxite, including saturation, particle distribution, compactness, and density, have been analyzed and discussed. The migration mechanism of bauxite particles and moisture has been found in the verification test. Accordingly, the authors have come to a conclusion of bauxite liquefaction.

2. Materials and methods

2.1 Review of transport management regulation related bauxite properties

Many countries and international organizations have also made some progress in the study of bauxite. China has always complied with the bauxite standards established by the International Organization for Standardization (such as the bauxite ore-sampling procedure (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China/China Standardization Administration, 2010a), preparation of samples (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China/China Standardization Administration, 2010b), and determination of the moisture content of bulk materials (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China/China Standardization Administration, 2010c), and internationalized them. In September 2015, the International Organization for Standardization appointed China as the Secretary of the ISO/TC79/SC12 (Bauxite Ore) International Standardization Subcommittee, and formulated relevant international standards for bauxite, which has generated a considerable voice for China's international trade in bauxite and for international shipping safety.

At the second session of the Subcommittee on Cargo and Container Transport (CCC) of the IMO Maritime Safety Committee from 14th to 18th September 2015, matters relating to bauxite transport were considered and a circular CCC.1/Circ.2 (International Maritime Organization, 2015) was approved to remind people of the potential risks of bauxite moisture in maritime transport through the accident of MV Bulk Jupiter. In October 2015, Australia, Brazil, China, Malaysia, the Marshall Islands, and the Baltic International Shipping Association (BIMCO) jointly submitted the CCC2/5/21 and CCC2/5/22 proposals to the Subcommittee on CCC calling for a careful assessment of the possible liquefaction properties of marine solid bulk bauxite in order to promote maritime safety. From 11th to 15th September 2015, at the 4th session of the Subcommittee on CCC, draft amendments to classify certain bauxite as a liquefiable cargo (Group A) were determined and submitted to the Maritime Safety Committee for consideration (International Maritime Organization, 2017). The proposal is expected to be adopted at the 101st session of the Maritime Safety Committee in 2019 and will go into force on 1st January 2021.

2.2 Statistical analysis

The Yantai Maritime Safety Administration of the People’s Republic of China has conducted a 3-month follow-up survey of bauxite transport ships. The average moisture content is about 13 %. For bauxite from Southeast Asia (such as Indonesia, Malaysia, etc.), the average moisture content is 14 - 15 %, and even more than 18 % for some bauxite. Guinea has a hot climate, and a high temperature in summer, which lasts for a long time. There is a long rainy season in Guinea, the same as other major origins such as Indonesia and Malaysia. Continuous rain makes it difficult to export bauxite normally. Bauxite crushing or ship delays will happen frequently, limited by inadequate port facilities. A survey has shown that the moisture content of bauxite from India is about 10 % (Chen, 2015). According to a study of moisture content in 4 samples of Gebeng bauxite (Muzamir et al., 2017), the moisture content is 15 - 24 %, which is the parameter of primary ores at original mining sties. However, the data of moisture content collected by the Yantai Maritime Bureau were those of bauxite after marine transportation.

2.3 Experimental analysis

Sample preparation

The most typical characteristic of CPL is moisture content. According to the definitions of mobile moisture point, moisture content, representative samples, and the TML of liquefiable cargoes in terms of clauses 1.7.10, 1.7.20, 1.7.23, and 1.7.27 of the Bulk Cargo Rules, the restrictive provisions on the loading of fluidized cargoes in terms of clauses 7.3.1.1 and other relevant provisions, the moisture content and the extreme moisture content of the cargoes concerned are very high. Limits refer to the shipment of cargoes, but not specifically to the moisture content of some constituents and TML. Therefore, in the selection of bauxite cargo samples, it is necessary to strictly follow the IMO-approved method of sampling and testing, to obtain the actual moisture content (MC), TML, and flow moisture point (FMP) representing the whole cargo.

Because of the large size of primary bauxite particles, it is necessary to screen debris particles of less than 100 mm, which meets the needs of terminal customers. Therefore, many mines in Indonesia, for example, clean ores by rotary sieves to produce fine and coarse bauxite. Separated fine materials are shipped separately for export or re-matched with coarse materials for export. High-pressure water is used to force ore into the rotary screen from the charging funnel, which greatly increases the moisture content of fine particles, and even forms mud. The ore will not lose water subsequently due to natural drainage or drying (UK P&I Club, 2015). Fine materials have high moisture content, which is usually more than 15 %. The moisture content of the whole bauxite will be reduced by mixing fine materials with coarse particles.

In order to obtain the data of physical properties, such as moisture content, of bauxite samples, the bauxite imported from Yantai Port from 1st August 2016 to 31st July 2017 was tracked and counted for one year. The bauxite imported from Yantai Port comes from 7 ports in 6 countries; the Port of Boke Guinea has the largest imports, which accounts for up to 16.72 million tons, or 57 %. The second is the Port of Gove and Weipa in Australia, which accounts for 28 % of the total imports.

Experimental procedure

Based on assuming that a solid-liquid 2-phase body was formed from the precipitation of bauxite moisture under a complex maritime environment, the liquefiability of bauxite was verified by the vibration test and rolling test, where bauxite samples were ordered as No.1 and No.2, respectively. After the vibration test for higher MC of 8 and 9 %, for sample No.1 with the same moisture content, the rolling test was carried out successively to further study the characteristics under the rolling attitude of bauxite carriers. In the following, sample No.2 with low MC of 6 and 7 % was developed by the rolling test; after that, the vibration test was carried out for samples with the same moisture content, in order to further discover the characteristics under the vibration condition of bauxite carriers.

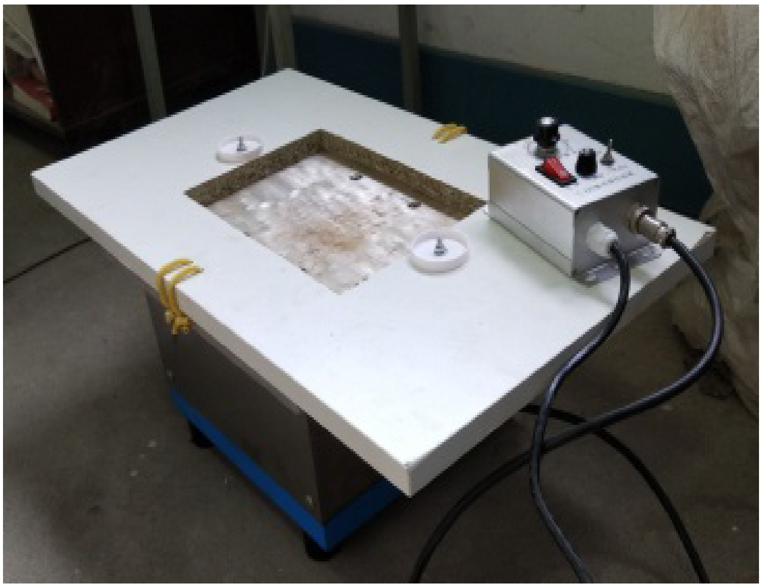


Figure 1 The experimental bench of vibration.

Vibration test

Based on the vibration data of the cargo hold of the real ship, a cargo hold model with scale 1:125 and an experimental bench of vibration were constructed, as in **Figure 1**. The vibration test bench included a vibrator, a controller, and a frame of cap. The effects of vibration conditions on vertical migration characteristics of bauxite particles and moisture were studied. Due to the weight of bauxite in the model box being only 5 kg, which is too small to reflect the scale effect as per a real ship, the equivalent treatment was adopted to redouble experimental acceleration, that is, the super gravity acceleration method. The vibration acceleration used in the model experiment is 125 times of that of a real bauxite carrier.

Figure 2 The experimental table of rolling.

Rolling test

Based on the statistical data on the heeling angle of Handy carriers at sea, an experimental table of rolling was designed and manufactured, as in **Figure 2**. This device includes a power part, a control unit, a transmission mechanism, a cap part, accessory parts, and an indication unit. It could be used as an experimental platform to test the characteristics of bauxite and other solid bulk CPL under the conditions of multi rolling angles and variable rolling speeds. With this device, the effects of rolling conditions on the transversal migration characteristics of bauxite particles and moisture were studied.

3. Results and discussion

3.1 General characteristics

Bauxite is an ore that is mined simply from under the ground, with simple processing or not, similar to fine iron ore powder and nickel ore. Bauxite is usually brown clay and soil. Bauxite is insoluble in water and has certain hygroscopicity and diffusivity.

The general characteristics of bauxite are as shown in **Table 1**, which is excerpted from the bauxite schedule of the IMSBC Code. However, bauxite was formally listed in Group C (cargoes which are neither liable to liquefy (Group A) nor possess chemical hazards (Group B)) by the IMO, regardless of particle size.

Table 1 Bauxite schedule in the IMSBC Code.

Moisture content	Bulk density (kg/m^3)	Stowage factor (m^3/t)	Particle size	Group
0 - 10 %	1,190 - 1,389	0.72 - 0.84	70 to 90 % lumps:2.5 - 500 mm; 10 to 30 % of fine particles less than 2.5 mm	C

Additionally, bauxite particles have compaction during storage and transportation. Under the action of ship vibration and rolling, the pores between particles gradually get narrower and the surface of the cargo sinks. Subsidence and compaction are related to particle size, shape, stowage factor, surface state, and moisture content.

3.2 Moisture content

According to statistics from the bauxite yard of Yantai Port from 1st August, 2016 to 31st July 2017, which was provided by the Technical Center of the Shandong Yantai Inspection and Quarantine Bureau, the moisture content of imported bauxite is generally 8.0 - 9.0 %, the minimum moisture content is 7.02 %, and the maximum moisture content is 9.86 %.

52.6 % of the sample had moisture of between 8.0 and 8.5 %, and samples with moisture of less than 8.0 % only accounted for 9.2 % of the total test sample, as shown in **Figure 3**. This is quite different from the experimental results of bauxite and the actual moisture content control standard, which is set at 8.0 %. According to the test results of bauxite moisture content in different yards, moisture content between 8.0 - 8.5 % is in the leading position in all yards. That is to say, bauxite moisture content in every yard generally exceeds 8.0 %.

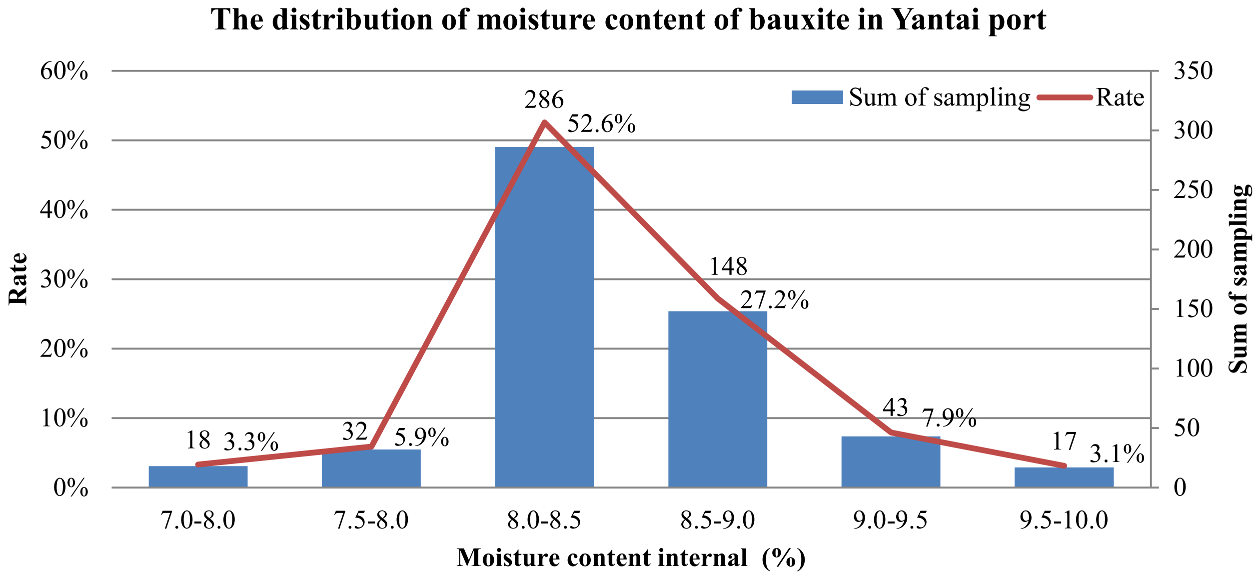


Figure 3 Distribution of moisture content of bauxite in Yantai Port.

The extreme moisture content of bauxite in different yards in **Figure 4** shows a span of 7.02 - 8.79 % in minimum, and 8.76 - 9.86 % in maximum. The water protection measures of bauxite are different during storage in each yard.

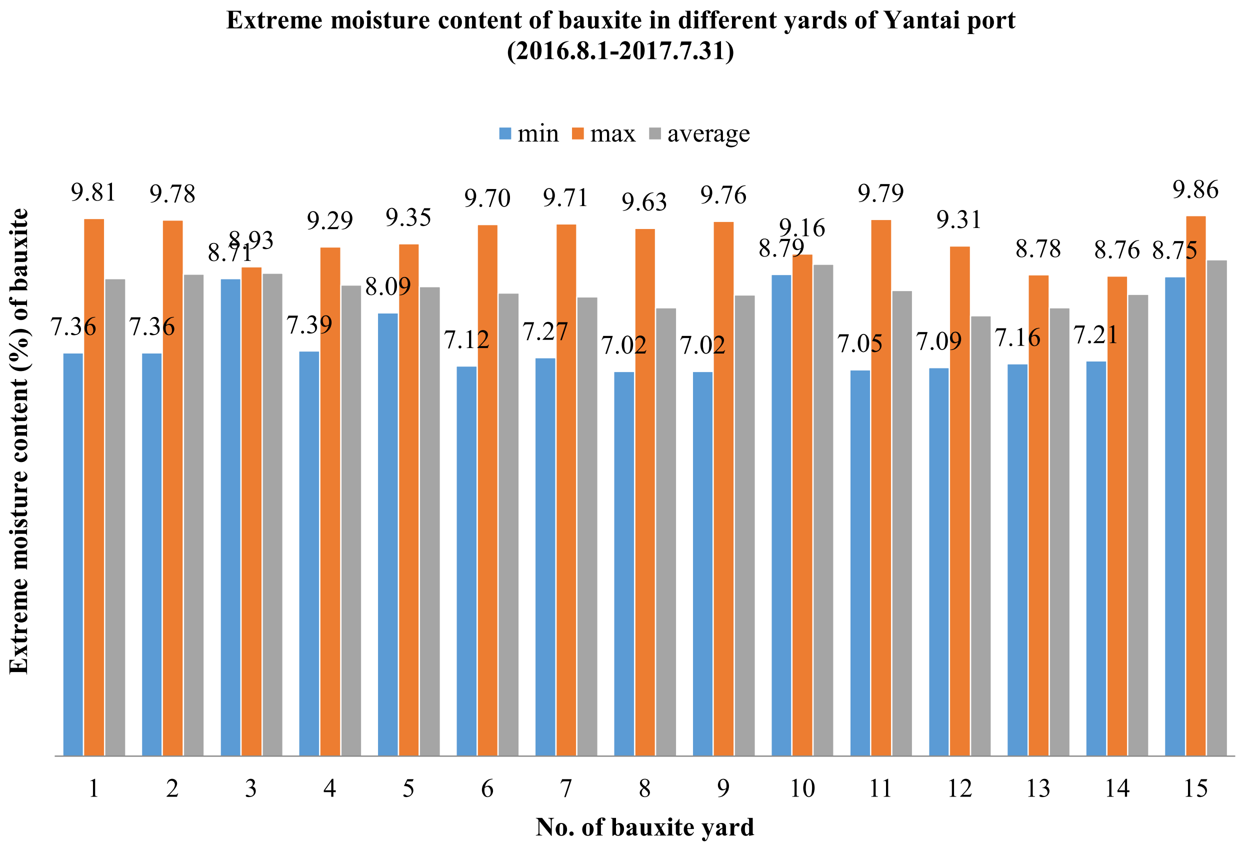


Figure 4 Extreme moisture content of bauxite in different yards.

The average moisture content measured in April and May was lower, at 7.8 and 8.02 % respectively; while July, August, and December' moisture content was higher, at 8.96, 8.80, and 8.93 %, respectively. It is suspected that the weather in July and August is more wet and rainy. As far as the date of extreme moisture content is concerned, the minimum moisture content occurs in February, April, June, and August, while the maximum occurs in February, July, August, October, and December, as **Figure 5** shows.

Under this weather, bauxite with moisture exceeding the control standard was still safely transported to port. Because bauxite is regulated according to Group A, TML is stipulated. Not every ship carrying cargo whose actual moisture content is higher than TML will finally capsize or sink, nor will all cargo whose actual moisture content is lower than the suitable water limit reach the destination port safely. Other physical properties of bauxite, such as particle distribution, saturation, compactness, and density, should also be fully considered.

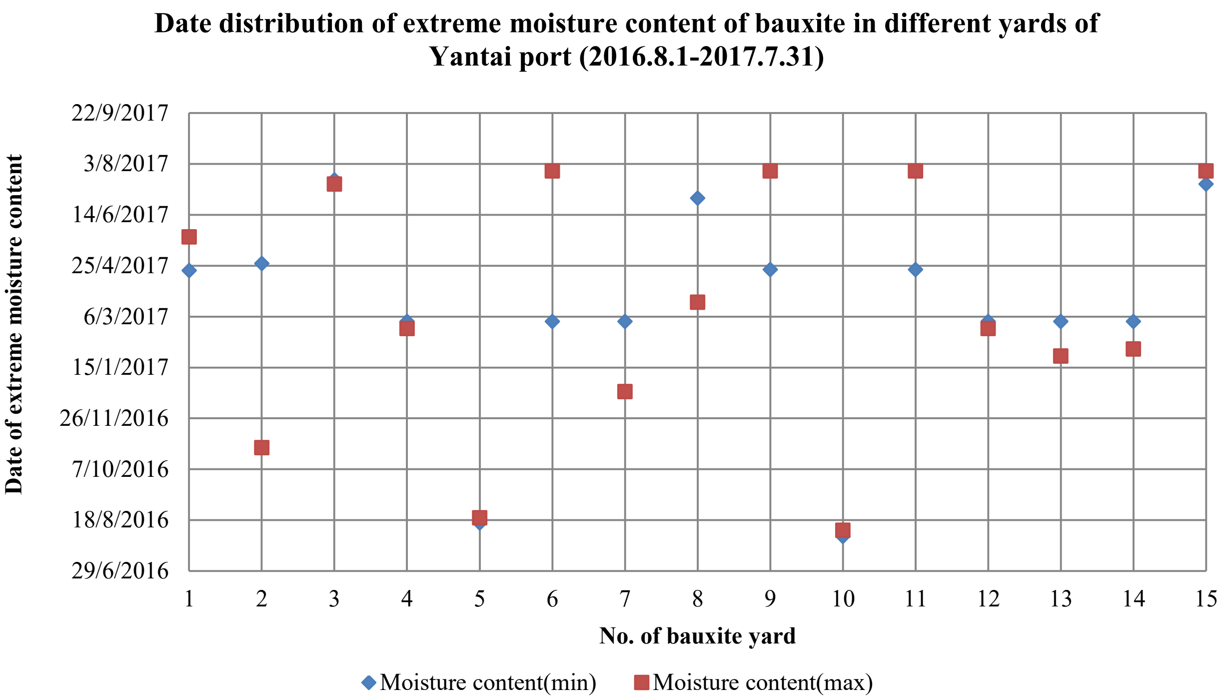


Figure 5 Date distribution of extreme moisture content of bauxite.

3.3 Saturation

For separated bauxite fines, the water between the fine particles is retained due to the high moisture content. If the ore is saturated, some natural drainage may occur. If the bauxite particles are nearly saturated, the water released from the cargo or immersed in the outside may lead to aggregation around the bauxite stack or in the lower area. However, the existence of fine particles in the bottom layer and small pores between the particles may prevent the water from being freely discharged into the sewage well and effectively discharged from the cargo hold through the drainage pump.

If the proportion of powdery particles is high, there will be an obvious free water layer or slurry in the upper layer of the cargo stack. The closer to the surface of the cargo stack, the higher the moisture content and saturation of the particles; the closer to the bottom of the cargo stack, the lower the moisture content and saturation of the particles. If the proportion of bulk particles in the cargoes is high, the phenomenon of wet bottom exists in the stack. In the lower part of the stack, the higher the moisture content and saturation, the lower in the upper part. That is to say, if there is a phenomenon of wet bottom or bottom slip in the stack, the grain size of the cargoes is bound to be larger.

The moisture content and saturation at different heights of the reactor have a corresponding functional relationship with its grain size (UK P&I Club, 2015). The greater the vertical height difference of the reactor, the more significant the moisture content difference, but the gradient difference of particle saturation is slightly flat.

3.4 Particle distribution

Bauxite has a wide range of particle sizes, ranging from very fine powders to very large rocks. Usually, bauxite is transported according to the export regulations of raw ore particles, but at present, the end-users of bauxite need to crush larger blocks of bauxite ore when extracting alumina to produce bauxite products; thus, bauxite is pretreated in the source area, making the size of marine bauxite usually less than 100 mm.

The IMO Bauxite Maritime Transport Working Group has studied the partitioning of bauxite particles to meet industrial needs. More than 30 % of the particle size is less than 1 mm, and more than 40 % of the particle size is less than 2.5 mm, which can be treated as fine bauxite (group A); the proportion of particles less than 1 mm in size is less than 30 %, or the proportion of particles less than 2.5 mm in size is less than 40 %, which can be treated as massive bauxite (group C) (Global Bauxite Working Group, 2017). Particle size distribution is not uniform, especially if the middle particle size is small or missing, the cargo pore volume is large, and liquid flows; therefore, it is easy to take small particles away. In a static state, the seepage stability of water is poor. Once instability occurs, pipe emergence occurs easily.

3.5 Compactness

Depending on the actual voyages of ships operating the bauxite-China routes, the height changes of cargo before and after loading and unloading (traces of bulkhead cargo or the height of cargo to the hatch cover) are observed and recorded, and then the compaction degree is estimated. The surface morphology of cargo can also be observed by laser scanning (Wang, 2015), or image recognition, and then the compaction of cargo can be estimated. In addition, the volume change of cargo can also be reflected by the water volume record of the sewage well at the bottom of the cabin.

The real ship data of Australian bauxite transport ships show that the average compactness of crude ore is 2.53 %, and that of more homogeneous bauxite is 3.28 %. It can be inferred that the influence of ship motion on the change of cargo stack shape during navigation is very small. The reason for compaction is that the angle of the stack tip exceeds the static angle of the cargo at some points. The measured data of the bauxite transport ship from Brazil further reflect that the degree of compaction of the cargo is not obviously related to the motion of the ship, and the average degree of compaction is about 1.1 %.

From November 2015 to April 2016, 31 bauxite carriers from Kuantan Port, Malaysia, were counted. The data show that effective compaction was produced in the early stage of the voyage, with an average of 0.5 %, and a maximum compaction of 6 %. Continuous late observations show that compaction is not related to voyage duration. The measured data of the bauxite carrier from Guinea also show that the compactness is not related to the voyage time, and the average compactness is 0.2 - 2.3 %.

3.6 Density

According to the characteristics of bauxite in the IMSBC code formulated by the IMO, the bulk density of bauxite is 1,190 - 1,389 kg/m^3. There are disputes about the density range in the industry. Through the detection of bauxite in actual ships and the laboratory test of samples collected, different density characteristics were obtained.

Considering the compactness of the cargoes, the Global Bauxite Working Group (GBWG) obtained the following density characteristics of the cargoes (Global Bauxite Working Group, 2017), as shown in **Table 2**.

Table 2 Density of bauxite sample (kg/m^3).

Source of sample	Mean density (departure)	Mean density (arrival)
Australia	1,470	1,510
	1,410	1,440
Brazil	1,930	1,950
Malaysia	1,810	1,830
	1,820	1,830
Guinea	1,460	1,480

The above density range between 1,410 and 1,950 kg/m^3 is wider than IMO's recommended value. Therefore, the GBWG Working Group recommended that the characteristics of bauxite in the IMSBC code be revised, and the density range be revised to 1,100 - 2,000 kg/m^3.

Relevant scholars have carried out laboratory tests on the collected bauxite, such as Gandhi's RL measurement of the density of bauxite between 2,500 - 3,000 kg/m^3 (Gandhi et al., 2013). Muzamir et al. (2017), tested 4 bauxite samples from Gebeng ore field with densities ranging from 2,750 to 2,880 kg/m^3. These 2 types of laboratory data are far beyond the current reference range of bauxite density in the IMSBC code and the scope is to be revised.

The density characteristics of bauxite samples from Yantai Port yard were tested experimentally. For bauxite samples with 7 % actual moisture content, the density in solid state is 2,193 kg/m^3, while for bauxite samples with 9 % actual moisture content, the density in solid state is 2,283 kg/m^3. It can be seen that the measured density of bauxite samples is 2,000 - 2,500 kg/m^3.

In summary, the density characteristics of bauxite are as follows: different producing areas, different moisture content, different particle distribution, and different compaction degree will produce different density characteristics. The obtained density values are distributed in each continuous interval. Generally, the density range of bauxite is 1,100 - 3,000 kg/m^3. It is necessary to revise bauxite density in the schedule in the current IMSBC.

3.7 Liquefaction characteristics

Results of experiments

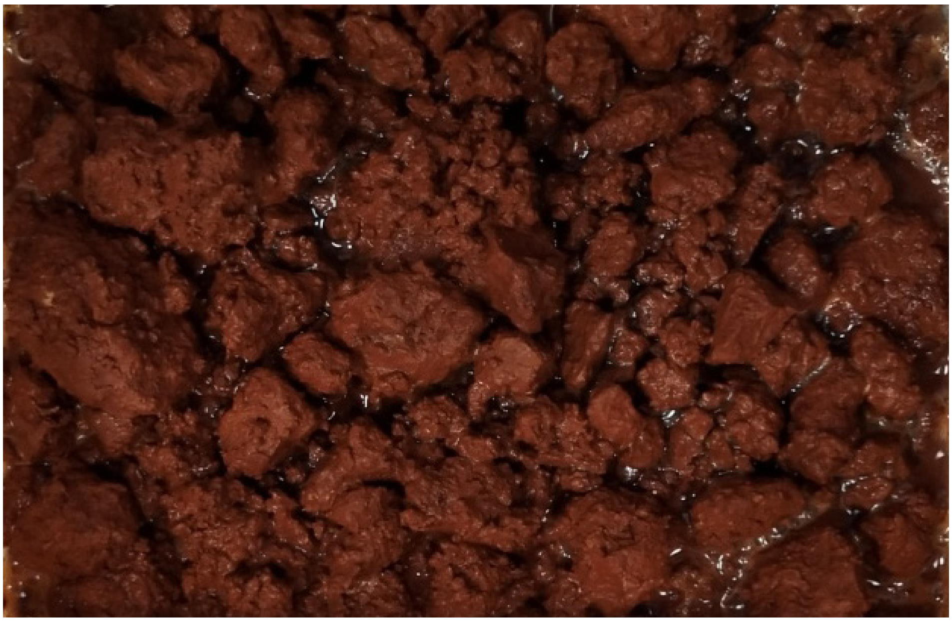
The liquefaction characteristics of bauxite with different MC were experimentally verified, as per **Figure 6**.

During the vibration test of bauxite with MC of 6 % or less, no obvious water evolution was found; even under the conditions of extreme vibration frequency and acceleration, no liquefaction would occur. Under the conditions of higher vibration frequency and acceleration, bauxite with MC of 7 % will liquefy in 5 minutes, and the water level will remain stable after 30 minutes, when water separation is basically completed. Under the conditions of lower vibration frequency and acceleration, bauxite with MC of 8 % will liquefy in 20 minutes; liquefaction of bauxite with 8 % and 9 % moisture will continue to slow down after 30 minutes, and the water will basically reach a stable level after 45 minutes, when water separation is basically completed.

In the rolling experiment, the sample with MC of 7 % showed no cargo shifting; no obvious cargo shifting was found in the sample with MC of 8 %; Some large particles shifted on the surface of the cargo when the MC was 9 %. The water born from the sample with MC of 8 % was relatively little, and there was water deposition on a single side when rolling at higher angle and speed. When the MC was 9 %, water deposition did not occur at a single side, and there was water level difference on both sides, as shown in **Figure 7**.

The experimental phenomenon is consistent with the liquefaction of bauxite in No. 4 cargo hold of MV Orchid Island arrived at the destination safely (Michael & Abbas, 2016). This Handy carrier with bauxite followed the same route of the accidental carrier MV Bulk Jupiter, from Kuantan port, Malaysia to Shandong, China.

(a) Pre-liquefaction behavior of bauxite with 8 % moisture



(b) Liquefaction behavior of bauxite with 8 % moisture

Figure 6 Water shifting behavior of bauxite under vibration conditions.


(a) Liquefaction behavior of bauxite with moisture 9 %


(b) Fluidization behavior of bauxite with moisture 9 %

Figure 7 Fluidization behavior of bauxite under rolling conditions.

Characteristics based on vibration test

Fine particle were deposited in the lower middle space of the bauxite pile by long-time vibrations, and larger particles were transferred to the upper space of the pile. The fine particles were arranged densely at the bottom, and the porosity was small. The moisture carried by the particles got rid of the adsorption force after being shaken by the vibration and was in a free state. Since the water density was much smaller than that of the bauxite particles, and was squeezed by the fine particles, the water particles floated up from the bottom, gradually expanding from the "wet bottom" to the entire cargo space, resulting in a rise in the bulkhead.

The slurry formed by liquid with finer particles spread over the upper space of the pile. Due to the precipitation, the fine particles remained in the boundary area between the slurry and the solid particles, which further prevented the liquid from flowing back into the cargo pile. The moisture and slurry eventually remained in the space above the cargo pile and the junction space from the bulkhead and cargo.

Characteristics based on rolling test

The destructive rolling experiment with the maximum angle and frequency had no obvious effect on the bauxite, which indicates that the cargo particles have good water absorption and larger viscosity. The rolling angle did not exceed the repose angle of the cargo, indirectly proving that the repose angle is greater than 22.5 degrees. The inertial force generated by the maximum rolling speed was insufficient to overcome the frictional resistance of the particle movement.

The trend is that, under the same rolling conditions, the higher the MC of bauxite, the more water is deposited, and the greater the fluidity of the upper layer slurry. In the case of a smaller rolling angle, the water level on both sides under the equal rolling angle is inversely related to the rolling speed. The greater the rolling speed, the lower the water level. The speed at which the slurry flows to both sides in a rolling posture is affected by the rolling speed. If the rolling speed is very slow, it is slow for the low side to return to the equilibrium point, and the slurry flows to the low side without resistance or even backflow; that is, there is no phase difference. If the rolling speed is very large, in the case of a large rocking angle, during the process of the slurry flowing to one side of the ship, and at the same time the low side returning to the equilibrium point, the slurry flowing speed is slowed down, and is gradually subject to resistance, and may not reflow; that is, there is a large phase difference. It is highly probable that a severe rolling on one side will happen even on bauxite carrier which capsizes.

3.8 Liquefaction characteristics based on experiments

The above phenomena showed that the bauxite samples with MC of 7 - 9 % were liquefied under the excitations of specific vibration and rolling. Based on the above analysis, the critical MC of seaborne bauxite liquefaction is between 7 and 8 %. Therefore, bauxite meeting some conditions should be classified as Group A - solid bulk cargo liable to liquefy. It is necessary to revise the group of bauxite (Group C) in the current IMSBC code as soon as possible.

4. Conclusions

Based on the hazards of liquefaction of solid bulk cargoes on ship safety, the paper examined and reflected the characteristic table of bauxite listed in the IMSBC Code. The saturation, density, particle distribution, and water content of bauxite ore were studied by 4 methods, including literature comparison, the statistics of bauxite properties, experimental analysis, and objective behavior onboard.

The results show that the description of properties of bauxite in IMSBC code needs to be further revised: the density range needs to be revised, and it has liquefiable properties. It should be revised from C-group to A-group.

Moreover, it was determined that liquefaction of bauxite can occur during marine transportation. Meanwhile, the influencing factors and mechanism of fluidization were revealed. The purpose of this study is to correct the positioning of bauxite characteristics by the IMSBC code and remind the industry to be alert to the liquefaction risk of bauxite shipping and to avoid further losses due to improper regulations related to bauxite.

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