

Research into the Behavior of Bauxite During Shipping: An Overview of the Global Bauxite Working Group (GBWG) Findings

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Abstract

In ocean transportation, solid bulk cargoes containing considerable amounts of fine particles and moisture may shift when the ship is exposed to adverse sea conditions. In 2015, the loss of 18 seamen and a vessel has been attributed to bauxite cargo shift. Following the incident, the bauxite industry formed a research group (the Global Bauxite Working Group – GBWG) to develop research on the bauxite behavior during maritime transportation. The research aimed to provide technical background for bauxite safe shipping, allowing the International Maritime Organization (IMO) to amend regulation related to bauxite maritime transportation in bulk. Between 2015 and 2017, the GBWG collected and analyzed samples representing over 90 % of all seaborne traded bauxite. The various experimental techniques applied include cyclic triaxial testing and physical modelling to investigate all possible bauxite instability modes due to moisture. Based on the GBWG findings, the IMO has established: i) a particle size criterion to distinguish between finer bauxites that may exhibit instabilities due to moisture and coarser bauxites that may not; ii) a suitable laboratory test to determine the maximum moisture content (Transportable Moisture Limit – TML) of finer bauxites to avoid any potential instability due to moisture during maritime transportation.

Keywords: Bauxite, shipping, solid bulk cargo, maritime transportation, TML, Global Bauxite Working Group

1. Introduction

Bauxite has been shipped safely for many decades. However, recent events have changed this record and required industry to investigate the behavior of bauxites during shipping. In 2015, the vessel Bulk Jupiter sunk off the coast of Vietnam, registering 18 casualties. The vessel was carrying 19 men and 46,400 tons of bauxite from Malaysia to China. Investigation led by the vessel flag state attributed the incident to liquefaction of the cargo [1], [2].

After ship motions, solid bulk cargoes containing considerable amounts of fine particles and moisture may shift during an ocean voyage due to liquefaction phenomena. In soil mechanics, liquefaction describes the behavior of a material that flows in a viscous liquid fashion when monotonic, cyclic, or shock loading is applied. Such behavior is caused by pore pressure increase within the material, resulting in the loss of effective stress and shear strength [3], [4]. After liquefaction, the unstable cargo may move freely on vessel hold following ship motions. Later, the pile cargo may become stable again and accumulate at one side of the vessel hold. Due to this instability factor, the ship may develop a list or even capsize [5].

As recently concluded by Rahman [6], [7], [8] and others and reviewed by Munro and Mohajerani [4], “*Some incidents attributed to liquefaction may also be more accurately described as cyclic instability, which is a form of unstable behavior (strain softening) caused by a succession of dynamic load cycles*”.

After the Bulk Jupiter incident, concern was raised about safety of bauxite shipping and the bauxite industry formed the Global Bauxite Working Group (GBWG) with the aim of conducting a detailed investigation into the characteristics and behavior of bauxite during ocean transportation. The GBWG membership comprises a variety of stakeholders, with expertise in diverse disciplines, such as mine owners/operators, transporters (ship owner/operators), users (alumina refinery operators) and consultants with backgrounds in geotechnical and hydraulic engineering, maritime science, plant, port and ship operations [1].

The GBWG research output offers a contribution to the International Maritime Organization (IMO), which is the United Nations agency in charge of setting regulation and guidance for the safety of maritime transportation and prevention of pollution by ships. IMO’s International Maritime Solid Bulk Cargoes (IMSBC) Code is a rulebook issued by the IMO on how to deal with solid bulk cargoes. The document is periodically reviewed and updated by IMO’s Sub-Committee on Carriage of Cargoes and Containers (CCC) and by IMO’s Maritime Safety Committee MSC). In the IMSBC Code, general description and characteristics of solid bulk cargoes are presented in individual schedules of cargoes. Also, the Code classifies cargoes in 3 Groups: Group A – cargoes which may liquefy; Group B – cargoes which possess chemical hazards; Group C – those which are neither liable to liquefy nor to possess chemical hazards [9].

The Group A cargoes can only be shipped when moisture of the cargo is below its Transportable Moisture Limit (TML), which is assessed by one of the test methods prescribed by the IMSBC Code. The TML is the maximum moisture content for safe shipping of the cargo and due to particular cargo’s characteristics, improvements to existing test procedures may lead to more suitable test apparatus and more accurate test results. Following this line, TML test procedures specific for certain cargoes have been developed in the past years, such as the Iron Ore Fines Modified Proctor/Fagerberg test procedure [10] and the Coal Modified/Proctor Fagerberg test procedure [11].

As derived from IMSBC Code’s bauxite schedule, until 2015 bauxite cargoes were listed as Group C only. Hence, no moisture related hazard was considered. The GBWG research assessed characteristics of bauxites shipped worldwide, providing a science-based background for IMO’s review of IMSBC Code’s provisions on bauxite shipping.

This work brings an overview of the research conducted by bauxite industry and provides a brief summary of the current bauxite shipping regulatory frame.

2. Materials and Methods

Between 2015 and 2017 the GBWG collected and analyzed samples representing over 90 % of all seaborne traded bauxite. Bauxites characterized and investigated by the GBWG include those from Australia, Brazil, India, Indonesia, Guinea, Guyana, Jamaica and Malaysia.

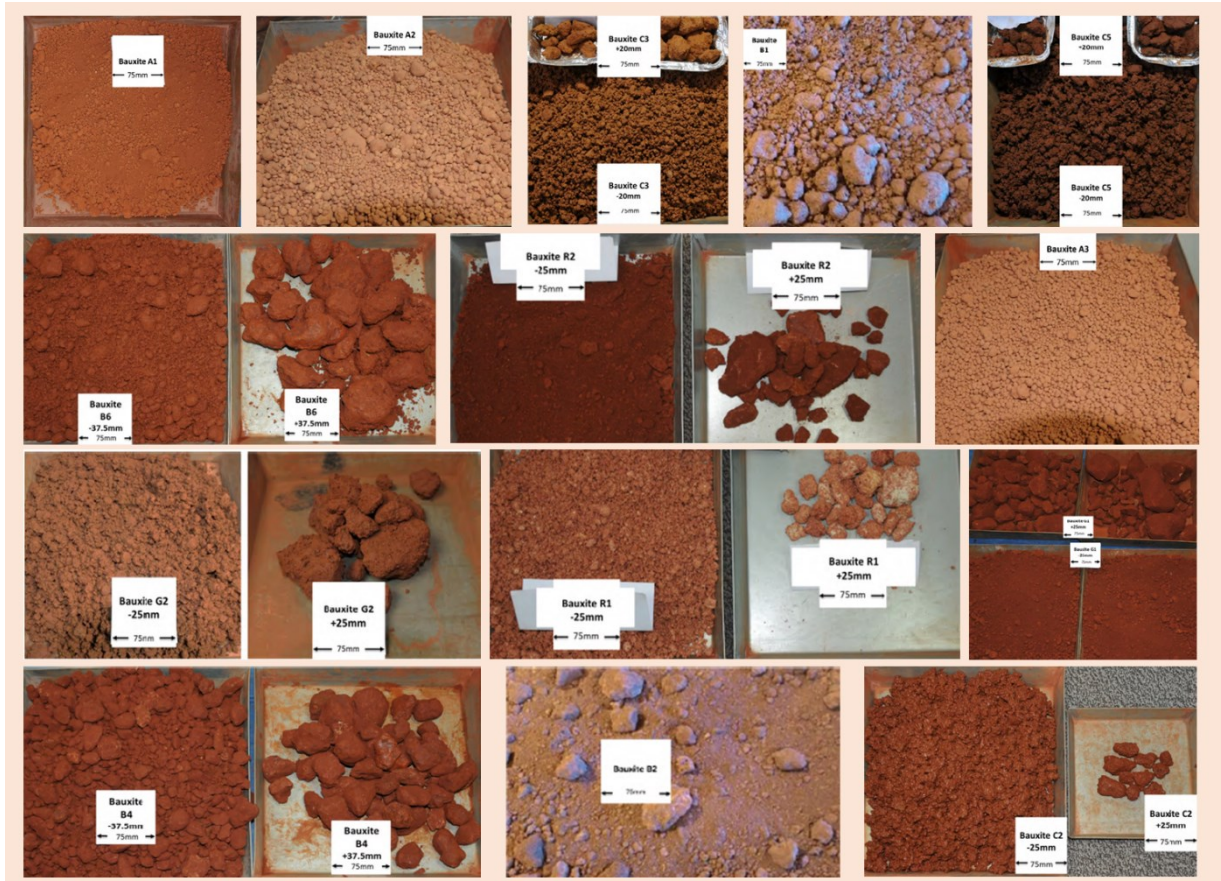


Figure 1. Some of the bauxite samples tested by the GBWG.

The particle size distributions (PSDs) of the bauxites were determined by wet screened sizing at Tyler mesh sizes ranging from 75 mm to 0.037 mm and finer fractions were read by hydrometer measurements. The bauxites have been labelled according to the respective supplier and the subsequent numbering represents different nominal products. The PSDs initials are labelled according to the following references:

- A – Australia (Exporter of Bauxite);
- B – Brazil (Exporter of Bauxite);
- C – China (Importer of Bauxite including from Indonesia, India and Malaysia);
- R – Ireland (Importer of Bauxite including from Guinea, Guyana and Jamaica);
- G – Guinea (Exporter of Bauxite);
- M – Malaysia (Exporter of Bauxite).

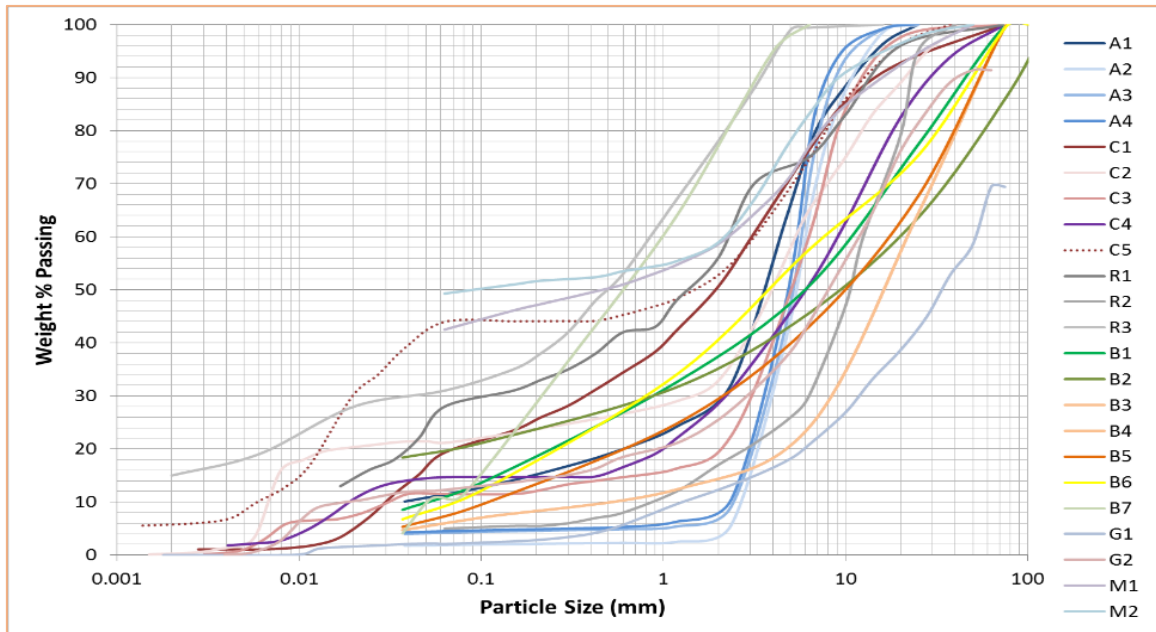


Figure 2. Particle size distributions of bauxites studied by the GBWG.

The research utilized various techniques to investigate all possible modes of instabilities of bauxite due to moisture, including:

- Laboratory analysis and testing for geotechnical, chemical and mineralogical characterization;
- Vessel monitoring and cargo observations where the vessel motion, forces and stability were determined and the behavior of cargo documented, including in-hold bulk density measurements;
- Small scale physical modelling, including Hexapod and Dynamic Centrifuge testing;
- Numerical modelling;
- Cyclic triaxial tests (CTT) were conducted under extreme case vessel motions at fully saturated and undrained cargo conditions, representing the worst-case condition that a cargo could experience. CTT tests determine the bauxite's resistance to liquefaction and its potential to withstand strain;
- Hexapod tests, where a small cargo pile is oscillated at sea state (6 degrees of freedom) or worst-case roll motions were conducted on bauxite cargoes at high moisture contents. This allowed for the identification of any instability due to moisture at conditions closer to the cargo hold although confining pressures are not scaled in these tests;
- Dynamic centrifuge tests, which are essentially the hexapod tests but with correctly scaled confining pressures, were undertaken at high cargo moistures to identify and quantify any instability due to moisture occurring in bauxite.

The main research testing utilized in the assessment of a cargo's potential to undergo any instability due to moisture were the cyclic triaxial, small scale physical models of the hexapod and dynamic centrifuge.

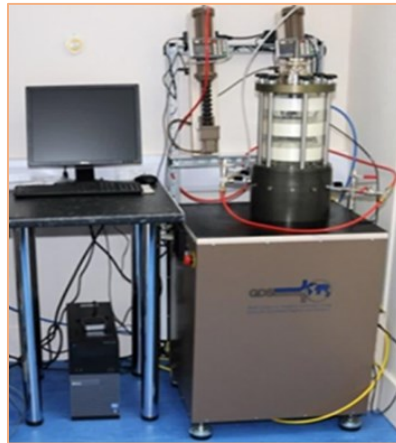


Figure 3. Cyclic triaxial test apparatus.

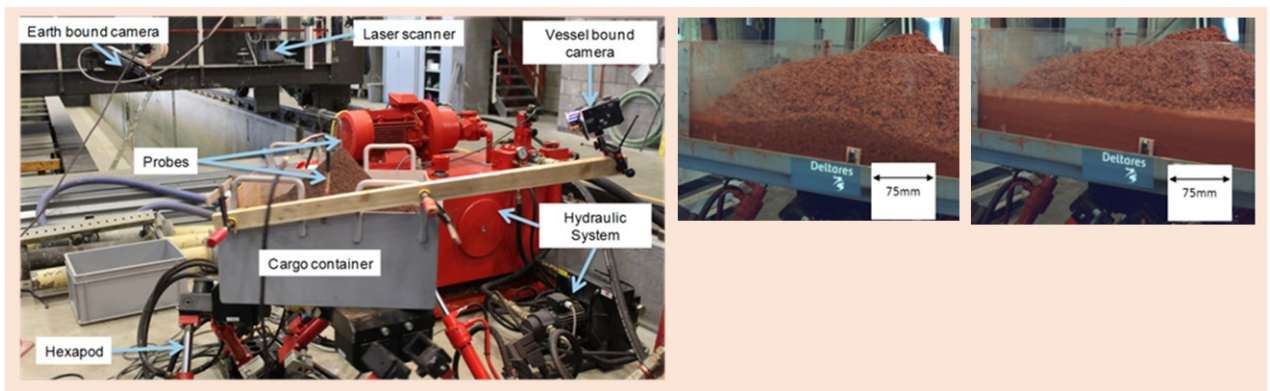


Figure 4. Hexapod test apparatus.



Figure 5. Dynamic centrifuge test apparatus.



Figure 6. Cargo observations before and after ocean voyages.

In-hold bulk density of bauxite before and after voyages is a key parameter for the development of the TML test. In order to get bulk density measurements, the cargo's weight was assessed by draft survey, while the cargo's volume in the hold was determined using laser scanning and photogrammetry techniques.

Laser scanning surveying consisted of recording the space of each empty ship's hold, and again after loading the ship with bauxite. The difference between the first and the second survey is used to calculate the volume of bauxite on board the ship.

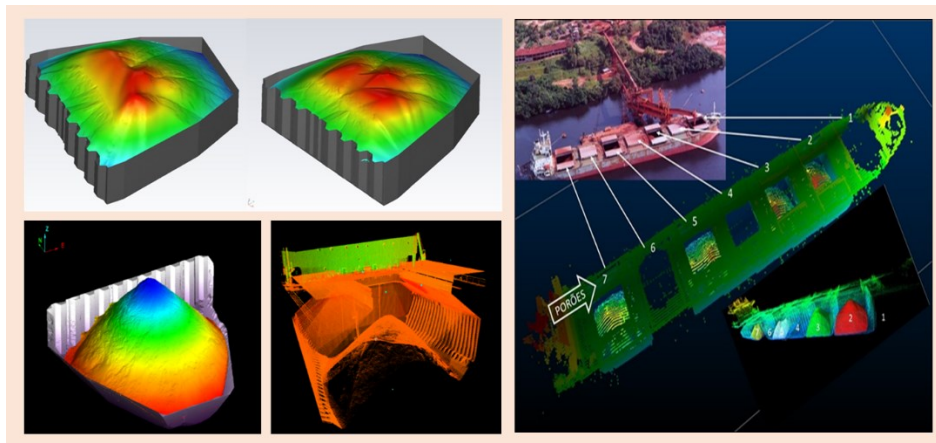


Figure 7. Laser scanning of cargo in vessel holds.

Photogrammetry utilizes multiple overlapping digital photo images taken from different locations in and around the cargo hold. Up to 300 images are taken for each hold and these were processed using softwares (Reality Capture, Scanmaster) to form a 3D mesh of the empty hold, before voyage loaded hold and after voyage loaded hold. From these 3D meshes, cargo volumes could be determined.

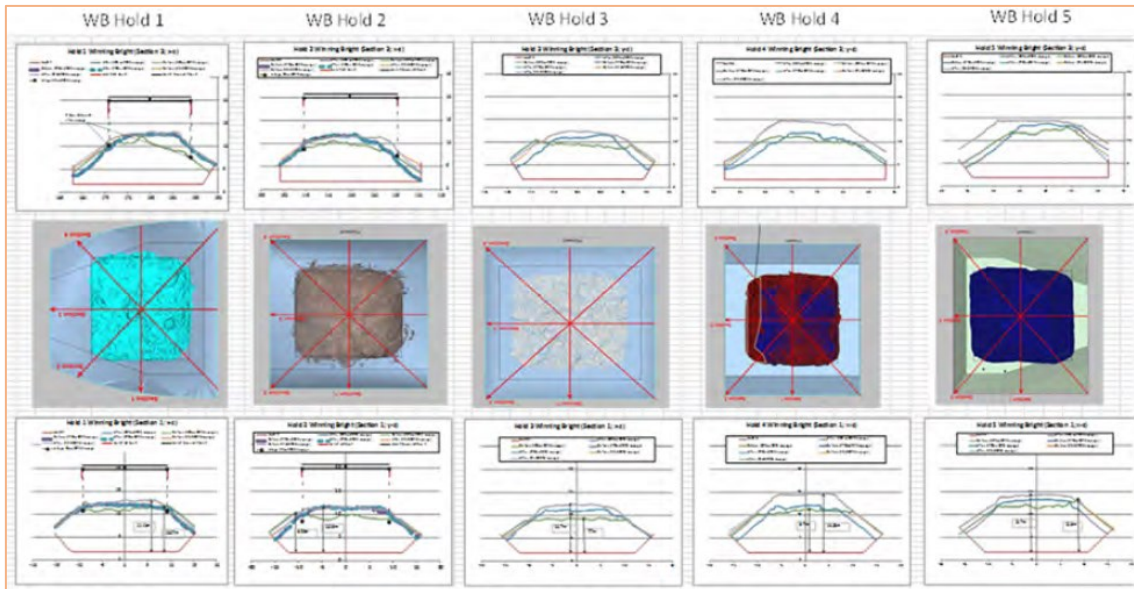


Figure 8. Photogrammetry of cargo in vessel holds.

As bauxites shipped worldwide exhibit a wide range of wide range of PSDs, some with very large top sizes, the TML test methods in the IMSBC Code present apparatus limitations regarding the largest particle size that can be tested. As such, the material tested for TML is not representative of the as shipped material. To address this, the development of a TML test appropriate for the wide range of seaborne traded bauxites was undertaken with guidance from the iron ore fines and coal research findings. Hence, the Proctor/Fagerberg test (PFT) was picked for developments to make it suitable for bauxite testing.

The development of the bauxite PFT involved:

- Calibration of the compaction energy to the measured in-hold cargo condition of the bauxites cargoes;
- Modification of the PFT methodology to ensure the PSD of the tested material is representative of the as-shipped cargo;
- Modifications to sample preparation and procedure for determining the compaction curve;
- Modifications to required equipment.

3. Results and Discussions

About 100 million tones per year of seaborne traded bauxite is transported in predominantly Panamax size vessels, although Capesize and Handymax sizes are also utilized. As observed by research on vessel motions, the smaller vessels (Handymax) are the ones that face greater accelerations and motions. However, from the regulator perspective, in order to allow a globally applicable criterion for bauxite classification, no vessel size, location of bauxite mines, routes or duration of voyages shall be taken into account as a criterion to assess risk of the cargo.

The IMSBC Code 2018, as well as its previous versions, presents a bauxite schedule containing characteristics of the cargo and listing it as a Group C cargo – no liquefaction hazard and no chemical hazard. The schedule also states that bauxite cargoes contain up to 10 % moisture content and up to 30 % of particles finer than 2.5m (figure 2). As noted by the PSD and moisture content data gathered by the GBWG, this description does not meet the characteristics of most of the bauxite shipped worldwide.

Individual schedules of solid bulk cargoes

BAUXITE

Description
A brownish-yellow clay-like and earthy mineral. Moisture content: 0% to 10%. Insoluble in water.

Characteristics

Angle of repose	Bulk density (kg/m ³)	Stowage factor (m ³ /t)
Not applicable	1190 to 1389	0.72 to 0.84
Size	Class	Group
70% to 90% lumps: 2.5 mm to 500 mm 10% to 30% powder	Not applicable	C

Figure 9. Characteristics of bauxite cargo in the IMSBC Code [9].

Taking into account the Bulk Jupiter incident, in September 2015, the IMO's Sub-Committee on Carriage of Cargoes and Containers (CCC) has issued a circular named "Carriage of bauxites which may liquefy" [12]. The document was a regulatory provision establishing that bauxite cargoes containing characteristics different than those prescribed by the Code's schedule (i.e., more than 10 % moisture and/or more than 30 % in weight passing 2.5 mm) should be shipped as Group A cargo or as Group C cargo after assessed by the competent authority and determined to be a particular cargo that does not present Group A properties. This circular remained in effect until September 2017, when it was reviewed to embrace the findings provided by the GBWG, as discussed later.

The GBWG has noted a wide range of particle size distribution (PSD) of the tested bauxites. While most ores exhibit a broad range of particle sizes, some are mostly composed of fine particles, some are dominated by coarser fractions and some are more uniformly graded due to processing applied to remove finer fractions

In order to group some finer bauxites cargoes that may become unstable in certain conditions and those coarser bauxites that may not, it was necessary to determine a sizing reference to allow easy and concise comparison between the different tested bauxites. After testing different possibilities, the GBWG proceeded its work with the 2.5 mm and 1 mm meshes, which are highly correlated, as the gradients in the PSDs curves are similar across the tested ores.

As highlighted by the GBWG, although a presentation platform based on the percentages passing 1 mm and 2.5 mm was adopted, the influence and contribution of other particle sizes on the behavior of the bauxites were considered on the tests performed.

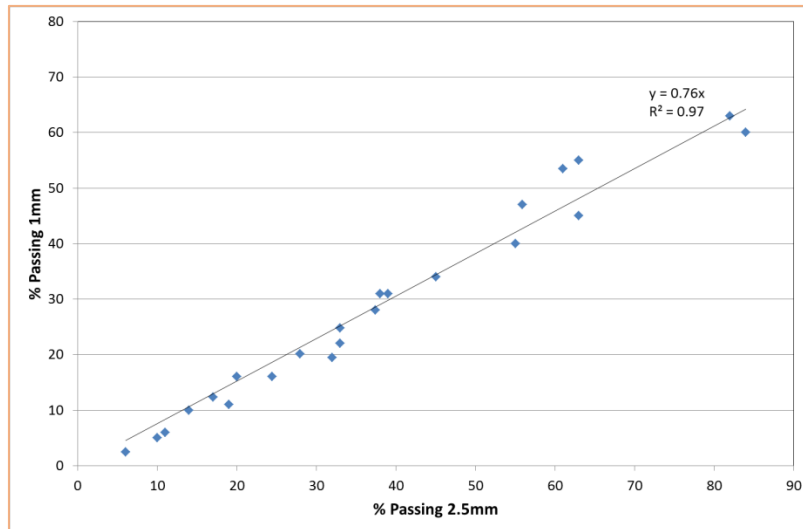


Figure 10. Chart of the relation between the percentage of weigh passing 2.5 mm and 1 mm meshes of the different bauxites tested [1].

The GBWG research investigated possible modes of instabilities of bauxites through cyclic triaxial testing (CTT) and physical modelling. The tested bauxites have not liquefied in cyclic triaxial tests conducted in undrained conditions at worst scenario of ship motions. However, some bauxites exhibited excessive straining in these tests, while physical modelling tests showed instabilities due to moisture where part of cargo’s fine particles and water come to surface forming a free slurry surface and a lower layer of unsaturated and competent solid material. This dynamic separation of the cargo is not the same mechanism of liquefaction. However, it is also driven by excessive moisture and it also may lead to a ship instability. In this sense, the same procedures applied to prevent liquefaction of bulk cargoes shall be applied to fine bauxite cargoes to avoid potential instability due to moisture. After the test work performed, the criterion to distinguish Group C and Group A bauxites was developed based on the bauxite’s propensity to strain in CTT or undergo dynamic separation in physical tests.

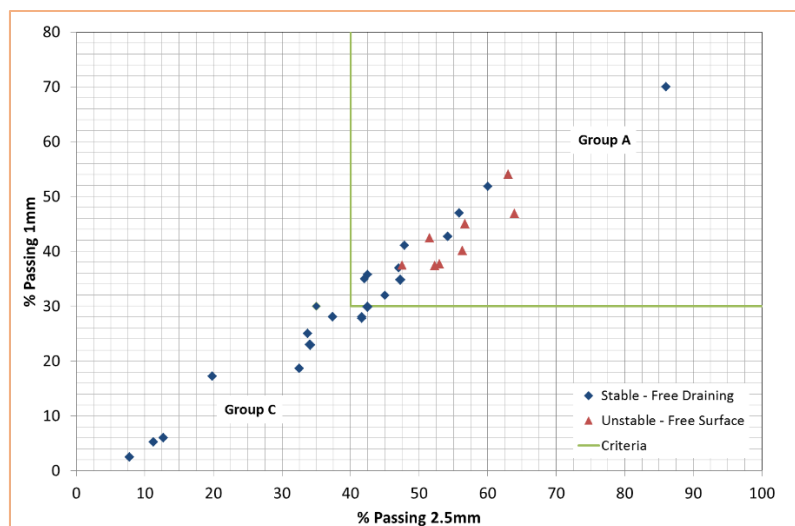


Figure 11. Chart summarizing observed behaviors of bauxites tested [1].

The summary of the bauxite behaviors presented on the “2.5 mm x 1 mm” platform allows a practical approach to classify bauxite as Group C and Group A, as the instability results (red triangles) are concentrated in an area (green square) that can be read as more than 40 % passing

2.5 mm and more than 30 % passing 1 mm, while all the stable results (blue diamonds) are found outside (i.e., less than 40 % passing 2.5 mm or less than 30 % passing 1mm).

A schematic illustration of a worst situation dynamic separation event includes adverse sea conditions leading to fine particles and water coming to surface to form a free slurry surface and a lower layer of unsaturated and competent solid material beneath it. The slurry movement above compacted cargo may destabilize the vessel, which may develop a list and capsize. This acknowledgement provides better understanding of instability mechanism and may enable for better cargo monitoring and instabilities prediction, improving safety at sea.

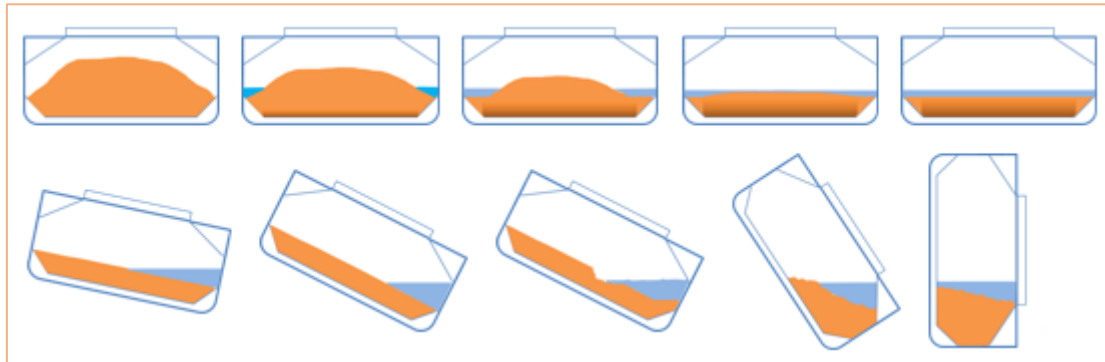


Figure 12. Schematic illustration sequence of capsize due to dynamic separation.

All the recommendations made by GBWG were approved by IMO's CCC in September 2017, when the circular "Carriage of bauxite which may liquefy" was reviewed. Since then, IMO's member states have been invited to adopt the reviewed Group C bauxite schedule, the new Group A bauxite fines schedule and the TML test procedure specific for Group A bauxite fines. The proposed Bauxite Proctor-Fagerberg Test utilizes a 150 mm "CBR" standard mold, the D Proctor-Fagerberg D hammer, and sample preparation, including sample reconstitution to ensure the TML tested material is representative of the as shipped material in regard to particle size.

As depicted from the latest circular schedules reproduced below, Group C bauxites are those coarser cargoes containing less than 40 % of particles passing 2.5 mm or less than 30 % of particles passing 1 mm. These coarser cargoes exhibit permeability enough to drain and prevent moisture related instabilities. On the other hand, Group A bauxite cargoes are those finer cargoes containing more than 40 % of particles passing 2.5 mm and more than 30 % of particles passing 1 mm.

CCC.1/Circ.2/Rev.1
Annex 3, page 1

ANNEX 3
DRAFT INDIVIDUAL SCHEDULE FOR BAUXITE OF GROUP C

Note: *The new texts are shown in grey shading and the proposed deletions are shown in struck out with grey shading, based on the existing individual schedule for bauxite in the IMSBC Code.*

BAUXITE

The provisions of this schedule shall apply to Bauxite cargoes

.1 containing either:

.1 30% or less of fine particles less than 1 mm ($D_{30} \geq 1$ mm); or

.2 40% or less of fine particles less than 2.5 mm ($D_{40} \geq 2.5$ mm); or

.3 both;

or

.2 where the shipper provides the master with a certificate, in accordance with the result of the test approved by the competent authority of port of loading, stating that the moisture of the cargo freely drains from the cargo so that the degree of saturation is not liable to reach 70%.

Description

A reddish-brown to brownish-yellow clay-like and earthy mineral. Moisture content: 0% to 40%. Insoluble in water.

Characteristics

Angle of repose	Bulk density (kg/m ³)	Stowage factor (m ³ /t)
Not applicable	1,100 to 2,000	0.5 to 0.84
Size	Class	Group
70% to 90% lumps: 2.5 mm to 500 mm 10% to 30% powder Typically up to 500 mm	Not applicable	C

Figure 13. Draft of the reviewed Group C bauxite schedule [13].

CCC.1/Circ.2/Rev.1
Annex 2, page 1

ANNEX 2
DRAFT INDIVIDUAL SCHEDULE FOR BAUXITE OF GROUP A

BAUXITE FINES

The provisions of this schedule shall apply to Bauxite cargoes containing both:

.1 more than 30% of fine particles less than 1 mm ($D_{30} < 1$ mm); and

.2 more than 40% of particles less than 2.5 mm ($D_{40} < 2.5$ mm).

Notwithstanding the above provision, Bauxite cargo meeting the above criterion may be carried as a Group C cargo in accordance with the provisions of the individual schedule for BAUXITE where the shipper provides the master with a certificate, in accordance with the result of the test approved by the competent authority of port of loading, stating that the moisture of the cargo freely drains from the cargo so that the degree of saturation is not liable to reach 70%.

Description

A reddish-brown to brownish-yellow clay-like and earthy mineral. Insoluble in water.

Characteristics

Angle of repose	Bulk density (kg/m ³)	Stowage factor (m ³ /t)
Not applicable	1,100 to 2,000	0.50 to 0.91
Size	Class	Group
More than 30% of fine particles less than 1 mm and more than 40% of particles less than 2.5 mm	Not applicable	A

Figure 14. Draft of the new Group A bauxite schedule. IMO, 2017 [13].

The GBWG also proposed consideration be given to the classification category of Group A “liable to liquefy” cargoes as other cargo instabilities due to moisture (such as the bauxite dynamic separation observed) also need to be considered. Group A classification should be for

cargoes which may have hazards arising from cargo instability due to moisture. This would be analogous to a Group B classified cargoes, which may have chemical hazards, but is not limited to one type of chemical hazard such as fire or explosion.

4. Conclusions

The GBWG findings led to recommendation to the IMO of the following amendments on regulation of bauxite maritime transportation: i) Split the existing single schedule for bauxite cargoes into Group A (bauxite fines) and Group C (bauxite); ii) Adopt the GBWG-developed TML test method (Modified Proctor-Fagerberg test procedure for bauxite) to assess the TML of Group A bauxite; and iii) consider other mechanisms for excess moisture related cargo instability within Group A in addition to classification of cargoes as “liable to liquefy”.

The compliance to the IMSBC code and the details contained in the schedules ensures that bauxite cargoes safe shipping. The research on bauxite behavior during maritime transportation has identified insights into instabilities due to moisture occurring in bauxite that offers potential safety benefits in cases where a bauxite cargo has been misdeclared. In this case, understanding the effect of a dense free slurry surface on vessel stability is paramount.

5. Acknowledgements

The authors thank the effort of the GBWG colleagues and acknowledge the support of all those who contributed representing the many companies, authorities and organizations involved.

6. References

1. Global Bauxite Working Group, 2018. Report on Research into the Behaviour of Bauxite during Shipping. Available at: http://tmltesting.com/w/images/e/e7/Global_Bauxite_WG_report_CCC_4-INF.10-Annexes.pdf
2. The Bahamas Maritime Authority, “M.V Bulk Jupiter”—Report of the Marine Safety Investigation into the Loss of a Bulk Carrier in the South China Sea on January 2nd 2015, 2015.
3. K.Terzaghi,R. Peck, and G.Mesri, *Soil Mechanics in Engineering Practice*, John Wiley & Sons, New York, NY, USA, 3rd edition, 1996
4. Munro, M.C., Mohajerani, A., 2016a. Liquefaction incidents of mineral cargoes on-board bulk carriers. *Adv. Mater. Sci. Eng.* 2016, 20. <http://dx.doi.org/10.1155/2016/5219474>
5. Ferreira, R. F. et al, 2017. Limite de Umidade Transportável de Minérios de Ferro: Aspectos Regulatórios e Técnicos. *Tecnologia em Metalurgia, Materiais e Mineração.* <http://dx.doi.org/10.4322/2176-1523.1149>
6. M. M. Rahman, M. A. L. Baki, and S. R. Lo, “Prediction of undrained monotonic and cyclic liquefaction behavior of sand with fines based on the equivalent granular state parameter,” *International Journal of Geomechanics*, vol. 14, no. 2, pp. 254-266, 2014.
7. A. L. Baki, M. Rahman, and S. R. Lo, “Cyclic instability behaviour of coal ash,” in *Proceedings of the GeoCongress 2012*, GSP 225, pp. 849-858, Oakland, Calif, USA, March 2012.
8. R. Mohamad and R. Dobry, “Undrained monotonic and cyclic triaxial strength of sand,” *Journal of Geotechnical Engineering*, vol. 112, no. 10, pp. 941-958, 1986.
9. International Maritime Organization. International Maritime Solid Bulk Cargoes Code. London: IMO; 2018
10. IOFTWG. Report 3: Iron Ore Proctor Fagerberg Test. Iron Ore Fines Technical Working Group Submission for Evaluation and Verification: Iron Ore Fines Proctor-

- Fagerberg Test. [Internet] 2013, May. Available at: <http://ironorefiners-twg.com/report-3-iron-ore-proctor-fagerberg-test/>
11. Australian Coal Association Research Program (ACARP), *TML0037 — Modified Proctor/Fagerberg Method for Coal*, Australian Coal Association Research Program (ACARP), Brisbane, Australia, 2014.
 12. Circular CCC1./ Circ.2: Carriage of bauxites that may liquefy. International Maritime Organization – IMO. London, 20th of October, 2015.
 13. Circular CCC1./ Circ.2/Rev.1: Carriage of bauxites that may liquefy. International Maritime Organization – IMO. London, 20th of September, 2017.