Proceedings of the 11th International Conference on Hydrodynamics (ICHD 2014)
October 19 – 24, 2014
Singapore

MOISTURE CONTENT LIMIT OF IRON ORE FINES FOR THE PREVENTION OF LIQUEFACTION IN BULK CARRIERS

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In 2013, over 500 million tonnes of Iron Ore Fines (IOF) were transported around the world using bulk carriers, more than any other unrefined mineral. Since the holds of bulk carriers have not been designed to carry liquid, if liquefaction of IOF or other minerals occur it can cause the vessel carrying the cargo to list or even capsize. Since 2006, there have been at least eight reported bulk carrier incidents possibly caused by the iron ore cargo shifting. Currently, the only available parameter used to prevent this from occurring is the Transportable Moisture Limit (TML). The TML is the maximum gross water content that certain mineral cargoes may contain, while being loaded in bulk carriers, without being at risk of liquefying during transportation. The objective of this study is to compare the three test methods stated in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code), which are used to determine the TML of IOF. They are the Proctor/Fagerberg, Flow Table and Penetration test methods. The study also covers recent developments and advancements made in the field, which includes the Modified Proctor/Fagerberg test along with goethite content provisions, which are included in the 2013 draft individual schedule for IOF, and to be amended in the 2015 IMSBC Code. This study shows that the three test methods, stated in the 2013 IMSBC Code, which are used to determine the TML of minerals, are not appropriate for testing of IOF and that recent developments, such as the Modified Proctor/Fagerberg test along with goethite content provisions, permits IOF to be transported at higher moisture contents than if one of the previous three test methods were used.

Abbreviations

FMP	- Flow Moisture Point
FTT	- Flow Table Test
GWC	- Gross Water Content
IMO	- International Maritime Organization
IMSBC Code	- International Maritime Solid Bulk Cargoes Code
IOF	- Iron Ore Fines
MPFT	- Modified Proctor/Fagerberg Test
PFT	- Proctor/Fagerberg Test
PT	- Penetration Test
S_w	- Degree of Saturation (*Volume of Water / Volume of Voids x 100*)
TML	- Transportable Moisture Limit
TWG	- Iron Ore Technical Working Group (established by the IMO)

1. Introduction

After extraction, iron ore is mechanically divided to produce three different qualities; pellets (9.5-16mm), lump (6.3-31.5mm) and fines (<6.3mm). Iron Ore Fines (IOF) make up approximately 48% of the iron ore trade, which in 2011, was approximately 1,300 million tonnes. In 2013, the majority of the 500 million tonnes of IOF that were transported around the world, using bulk carriers, were transported from Australia and Brazil.

The temporary reclassification of IOF, in 2011, by the International Maritime Organization (IMO), as a 'Group A' liquefiable material, has initiated research into individual bulk cargo behaviours while being transported at sea [1]. The focus of their research is to determine the potential risk of liquefaction that minerals, such as IOF, pose while being transported in bulk carriers. Although minerals, such as coal, fluorspar, ilmenite and mineral concentrates are more susceptible to liquefaction, under certain circumstances, IOF and other similar minerals are also vulnerable primarily due to their physical properties and the varying conditions under which they are stored, loaded and transported. There is no definitive test procedure in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code) that is applicable when determining the liquefaction potential IOF while being transported in bulk carriers.

On occasion, liquefaction of minerals being transported in bulk carriers can occur when repeated loading, produced by the ocean waves and vessels engine, are transmitted to the cargo in the hold of a bulk carrier. Repeated loading can increase the pore pressures of a material which contains sufficient amounts of fine particles and moisture. The right combination of physical properties and system variables can cause the shear strength of a material to decrease. When the shear strength reduces to near zero, it can cause the material to liquefy. Liquefaction of a material will cause it to act like a liquid until the pore pressures dissipate, therefore normalising the shear strength.

Since the holds of bulk carriers are not designed to carry liquid, if liquefaction of IOF or other minerals occur it can cause the bulk carrier, carrying the cargo, to list or even capsize. This is mainly as a result of the weight of the unconfined cargo shifting and causing a rapid change in the bulk carriers' buoyancy, which cannot be promptly corrected with ballast. Since 2006, there have been at least eight reported bulk carrier incidents possibly caused by the iron ore cargo shifting, as seen in Table 1.

Table 1. Recent bulk carrier incidents possibly caused by the iron ore cargo shifting [2-7]

Vessel Name	Subclass	Total Loss	Lives Lost	Date	Origin	Destination
Alexandros T	Capesize	Yes	26	03/05/2006	Brazil	China
Chang Le Men	Handysize	No (Listed)	0	07/09/2007	India	China
Mezzanine	Handysize	Yes	26	27/11/2007	Indonesia	China
Asian Forest	Handysize	Yes	0	17/07/2009	India	China
Black Rose	Handymax	Yes	1	09/09/2009	India	China
Sun Spirits	Handysize	Yes	0	22/01/2012	Philippines	China
Bingo	General Bulker	Yes	0	12/08/2013	India	China
Anna Bo	Handymax	No (Listed)	0	04/12/2013	Indonesia	China

The IMSBC Code, published by the IMO, outlines the dangers associated with certain types of solid bulk cargoes and provides procedures to be followed when transporting these materials [8]. Included in the 2013 IMSBC Code are test methods used to determine the Transportable Moisture Limit (TML) of 'Group A' minerals. 'Group A' minerals are those that have the potential to liquefy due to the proportion of fine particles and moisture they contain [8]. Prior to 2011, IOF were not specifically listed in the IMSBC Code. The circular (DSC.1/Circ66) sent out by the IMO, in 2011, temporarily reclassified IOF as a 'Group A', liquefiable material, until a permanent individual schedule can be agreed upon and incorporated in the IMSBC Code [1].

Currently, the only parameter used to determine a minerals potential to liquefy, while being transported in bulk carriers, is the TML. The 2013 IMSBC Code refers to the TML as the maximum Gross Water Content (GWC) that certain mineral cargoes may contain, while being loaded in bulk carriers, without being at risk of liquefying during transportation [8]. The GWC is calculated as the mass of water divided by the total wet mass. This is different from the moisture content or net water content, which is calculated as the mass of water divided by the total dry mass. Moisture content is more commonly used in geotechnical engineering than the GWC.

The objective of this study is to review the three test methods stated in the 2013 IMSBC Code, which are used to determine the TML of IOF. They are the Proctor/Fagerberg (PFT), Flow Table (FTT) and Penetration (PT) test methods. The study also covers recent developments and advancements made in the field, which includes details regarding goethite content provisions and results from the Modified Proctor/Fagerberg Test (MPFT), which are included in the 2013 draft individual schedule for IOF, and to be amended in the 2015 IMSBC Code [9].

2. Original Test Methods

In the 2013 IMSBC Code, there are three test methods used to determine the TML of 'Group A' cargoes, which are those that are potentially liquefiable. The three test methods are the Proctor/Fagerberg (PFT), Flow Table (FTT) and Penetration (PT) test methods [8]. More details in regards to the three test methods stated in the 2013 IMSBC Code can be found in the associated comprehensive comparison study [10].

2.1. *Proctor/Fagerberg Test (PFT)*

The PFT was first published in Stockholm in 1962 by Bengt Fagerberg and Kjell Eriksson as part of a committee established by the Swedish Mining Association and several Scandinavian mining companies. The committee was given the task to develop a simple method for determining the TML of ore concentrates [11].

The test method is based upon the use of the Proctor apparatus (ASTM Standard D-698), which was developed by Ralph Proctor for use in soil mechanics [12], and was adopted by the IMO, for use in the IMSBC Code, between 1991 and 1998.

The procedure involves compaction of the material, into a standard litre compaction mould, at varying moisture contents, to produce a compaction curve with a minimum of five data points. The compaction is executed in five layers by dropping a 350g hammer, 25 times, through a guided pipe from a height of 200mm. For each point the GWC and void ratio is calculated then plotted on a graph along with the corresponding degree of saturation (S_w). The resulting GWC is then interpreted, from the graph, where S_w equals 70%. This value is referred to as the TML [8]. The PFT uses approximately 14% of the standard Proctor compaction energy and requires the specific gravity to produce the corresponding S_w. A typical compaction curve of IOF, produced during this study, can be seen in Figure 1.

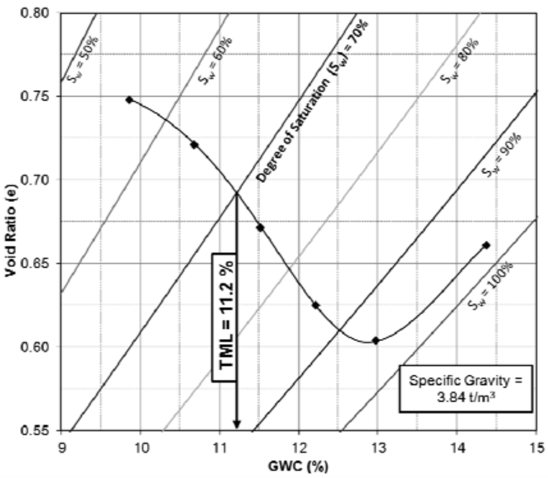

Figure 1. Graphical representation of a typical PFT compaction curve of IOF produced during this study

2.2. *Flow Table Test (FTT)*

The FTT has been widely used in the cement industry to test hydraulic cement. The early IMSBC Code included a modified procedure, created by the Department of Mines and Technical Surveys in Canada that can be used to determine the TML of ore concentrates and coal [11]. In 2000, this method branched out into an ISO (International Organization for Standardization) guide (ISO 12742).

The FTT is performed by compacting a sample, in three layers, into a conical shaped mould in the centre of the Flow Table. Compaction is performed using a tamping rod, which is set to a predetermined pressure. For a typical sample of IOF the tamping pressure used is approximately 450kPa (~33kg.f for a 30mm diameter tamper head). The tamping pressure depends on the properties of the sample being tested. The tamping pressure (P) is determined (in Pa), prior to performing the FTT, using the formula $P = \rho \ x \ d \ x \ g$, where ρ is the bulk density (in kg/m^3) obtained by performing the standard Proctor compaction, which is described in ASTM Standard D-698, d (in m) is the maximum depth of the cargo and g is the acceleration due to gravity (in m/s^2).

After compaction is complete, the mould is carefully removed. Immediately after the mould is removed, the Flow Table is raised and dropped 50 times through a height of 12.5mm at a rate of 25 times per minute. This procedure is then repeated at different moisture contents. During testing at different moisture contents, the operator visually determines whether the sample is showing plastic deformation by using height and width measurements together with observing the behaviour of the sample while the Flow Fable is being dropped. The point of change between the sample showing plastic deformation and not showing plastic deformation is referred to as the Flow Moisture Point (FMP). When a sample has been observed exceeding the FMP it is oven dried along with the previous sample, which should be just below the FMP, so that the GWC, of each, can be calculated. The mean of these two values is referred to as the FMP and 90% of the FMP is referred to as the TML [8].

2.3. *Penetration Test (PT)*

The PT was developed in Japan at the Research Institute of Marine Engineering [13]. It was adopted by the IMO, between 1991 and 1998, for determining the TML of coal and ore concentrates.

The PT is performed by compacting a sample, in four layers, into a cylindrical mould. The sample is compacted with an adjustable tamper, using a tamping pressure similar to what would be used in the FTT, so that the surface of the sample is flat and level. The developer of the test states that *"tamping does not affect the result of the PT, because the sample is quickly consolidated by vibration from the vibrating table regardless of the pressure of tamping conducted prior to the test"* [13].

After compaction is complete the mould is attached to a vibrating table and a Penetration bit is placed on the surface of the material. The vibrating table is then operated at a frequency of 50-60Hz with an acceleration of 2g rms for 6 minutes. After 6 minutes the depth of penetration, by the penetration bit, is recorded. This procedure is performed at varying moisture contents. When the depth of penetration is greater than 50mm the FMP has been exceeded and the sample is oven dried along with the previous sample, which should be just below the FMP, so that the GWC, of each, can be calculated. The mean of these two values is referred to as the FMP and 90% of the FMP is referred to as the TML [8].

3. Recent Developments in Transportable Moisture Limit Testing

After the temporary reclassification of IOF, in 2011 [1], industry and research institutions began comprehensive research in order to understand the causes of liquefaction of IOF, while being transported. The outcome of their research was to implement a new test method, specifically designed for IOF, to prevent confusion caused by determining the TML using the three test methods, stated in the 2013 IMSBC Code, which were implemented for use with coal, fluorspar, ilmenite and mineral concentrates.

Currently the most recognized research is being carried out by the Iron Ore Technical Working Group (TWG). The TWG was established by the IMO late 2012 to *"conduct research and coordinate recommendations and conclusions about the transportation of IOF"* [14]. The TWG is a collaboration of industry and research institutions managed by the Australian Mineral Industry Research Association (AMIRA). The TWG includes three of the largest iron ore producers; Rio Tinto, BHP Billiton and Vale, along with research institutions such as the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the University of Auckland and University of Newcastle (TUNRA) [15].

The early implementation of the TWG's research was introduced, in 2013, by the IMO in the circular DSC.1/Circ.71 [9]. Included in this circular are draft schedules for iron ore and IOF, it also includes the draft for a new test method for determining the TML of IOF, the Modified Proctor/Fagerberg Test (MPFT), which is discussed in section 3.2.

The circular states that although more research is required, the draft schedules and test method will be included in amendment 03-15 of the IMSBC Code in 2015 and entered into force on January 1, 2017. The Australian Maritime Safety Authority (AMSA) is one governing authority which has given the option for Australian export industries to voluntarily implement the draft schedules and draft test method for IOF [16].

3.1. *Goethite Content Provisions*

Iron ore is commonly made up of three main constituents; goethite, hematite and magnetite. The TWG performed cyclic triaxial, direct shear and centrifugal tests to determine the liquefaction resistance of IOF with varying amounts of goethite [14].

According to the research carried out by the TWG, the goethite content directly relates to the surface area of the particles and the volume of the pores that forms IOF. Furthermore, as the goethite content of IOF increases the material's ability to hold water also increases. The TWG demonstrated that if the goethite content of IOF is greater than 35% by mass then the material survived cyclic triaxial testing and became more resistant to liquefaction because of its increased water holding ability. This is also shown by the material's ability to prevent moisture migration during centrifugal testing. They also demonstrated that if the goethite content is less than 25% by mass then the material failed cyclic triaxial testing, produced more free water during centrifugal testing and therefore the potential for the material to liquefy was increased [14].

In the draft individual schedule for IOF it is stated that if the material contains more than 35% goethite by mass then the IOF can be treated as iron ore and therefore classified as a 'Group C' non-liquefiable material, otherwise the material is to be treated as IOF and therefore classified as a 'Group A' liquefiable material [9].

3.2. *Modified Proctor/Fagerberg Test (MPFT)*

In 2013, the MPFT was introduced, on a voluntary basis, by the IMO, in the circular DSC.1/Circ.71 [9]. The MPFT is the only test method specifically designed for use with IOF.

The TWG is the main driving force behind the implementation of the MPFT, which is sometimes referred to as D80. The abbreviation D80 comes from previous research carried out by Bengt Fagerberg and Arne Stavang in 1971, where compaction method D was performed using a 150g hammer falling from 150mm, instead of a 350g hammer falling 200mm, which is the PFT and method C in Fagerberg and Stavang research [11]. Also, instead of reading the TML from the intersection of the compaction curve and S_w equal to 70%, as stated in the PFT, it was recommended, by the TWG, to read the TML from the intersection of the compaction curve and S_w equal to 80%, for IOF [17]. Apart from the difference in S_w and compaction energy, the same procedure is used for both the PFT and MPFT, which can be seen section 2.1.

To verify this procedure the TWG measured the bulk density of IOF in the holds of multiple bulk carriers, before and after transportation, through the means of height measurements, laser scanning and cone penetration testing. Using this data and additional bulk densities determined by drop tower testing the TWG concluded that the density produced by compaction during the MPFT was more than sufficient for replicating the density of IOF in the holds of bulk carriers. The MPFT is said to include a safety margin of approximately 10-15%, depending on the type of IOF being tested and uses around 5% of the standard Proctor compaction energy and 32% of the PFT compaction energy [17].

3.3. *Original Test Method Results*

While evaluating the MPFT, the TWG tested the same samples of IOF using the three methods stated in the 2013 IMSBC Code [17]. The average variation from the PT to the FTT, the FTT to the PFT and the PT to PFT method was found to be approximately 18%, 8% and 27%, respectively. Figure 2,
Table 2 and

Table 3 demonstrates the different TML values that can be produced depending on the test method that is chosen.

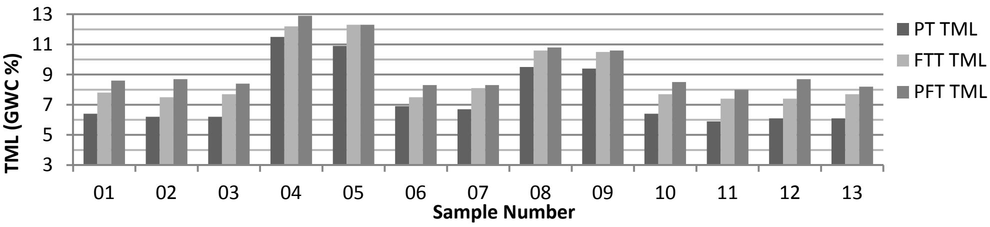

Figure 2. IOF TML values produced by the TWG using the PT, FTT and PFT [17]

Table 2. IOF TML values produced by the TWG using the PT, FTT and PFT [17]

Sample	PT TML (GWC %)	FTT TML (GWC %)	PFT TML (GWC %)
01	6.4	7.8	8.6
02	6.2	7.5	8.7
03	6.2	7.7	8.4
04	11.5	12.2	12.9
05	10.9	12.3	12.3
06	6.9	7.5	8.3
07	6.7	8.1	8.3
08	9.5	10.6	10.8
09	9.4	10.5	10.6
10	6.4	7.7	8.5
11	5.9	7.4	8.0
12	6.1	7.4	8.7
13	6.1	7.7	8.2
Average	7.6	8.8	9.4

Table 3. Increases from the TWG IOF TML values from the PT, FTT and PFT [17].

Sample	Increase from PT to FTT TML (%)	Increase from FTT to PFT TML (%)	Increase from PT to PFT TML (%)
01	21.9	10.3	34.4
02	21.0	16.0	40.3
03	24.2	9.1	35.5
04	6.1	5.7	12.2
05	12.8	0.0	12.8
06	8.7	10.7	20.3
07	20.9	2.5	23.9
08	11.6	1.9	13.7
09	11.7	1.0	12.8
10	20.3	10.4	32.8
11	25.4	8.1	35.6
12	21.3	17.6	42.6
13	26.2	6.5	34.4
Average	17.9	7.7	27.0

Due to the varying results, research into the establishment of a new test method was required, by the IMO, which is specifically designed for IOF, to prevent confusion caused by determining the TML using the three test methods stated in the 2013 IMSBC Code. Because of this requirement the TWG produced the MPFT, which can be used on a voluntary basis until amended in the 2015 IMSBC Code [9]. More comparisons, in regards to the three test methods stated in the 2013 IMSBC Code, can be found in the associated comprehensive comparison study [10].

4. This Studies Experimental Work

4.1. *Physical Properties of IOF*

Seen in Table 4 and
Table 5 are typical properties of IOF that were tested during this study and the associated comprehensive comparison study [10]. The samples of IOF were obtained from various locations around Australia.

Table 4. Properties of a typical sample of IOF that was used in this study

	Result	Standard
Minimum Dry Density (t/m^3)	2.12	AS1289.5.5.1
Maximum Dry Density (t/m^3)	3.08	AS1289.5.5.1
Liquid Limit (%)	18	AS1289.3.1.2
Plastic Limit (%)	16	AS1289.3.2.1
Plasticity Index (%)	2	AS1289.3.3.1
Standard Proctor Compaction - Optimum Moisture Content (%)	12.0	AS1289.5.1.1
Standard Proctor Compaction - Maximum Dry Density (t/m^3)	2.73	AS1289.5.1.1

Table 5. Typical ranges of properties of IOF used in this study

	Minimum	Average	Maximum	Standard
Initial Moisture Content (%)	3.4	7.9	10.3	AS1289.2.1.1
Particle Density (t/m^3)	3.78	4.27	4.91	AS1289.3.5.1
Coefficient of Uniformity (C_U)	24.9	119.3	273.2	AS1289.3.6.1
Coefficient of Curvature (C_C)	0.7	1.7	7.4	AS1289.3.6.1

4.2. *Modified Proctor/Fagerberg Test Results*

The MPFT, discussed in Section 3.2. , is the only test method designed specifically for use with IOF [9]. For this study, compactions on the same samples of typical IOF were performed using the PFT and MPFT, as seen in Figure 3 and Table 6. The average variation from the PFT to the MPFT was found to be approximately 14%. The same variation was seen by the TWG during their research into the MPFT [14].

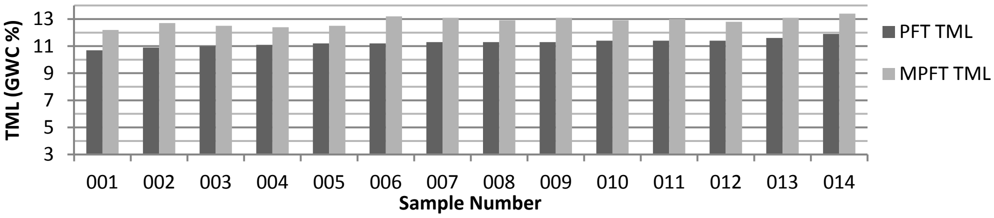

Figure 3. IOF TML values from the PFT and MPFT produced during this study.

Table 6. IOF TML values from the PFT and MPFT produced during this study

Sample	PFT TML (GWC %)	MPFT TML (GWC %)	Difference between the PFT and MPFT TML (GWC %)	Increase from PFT to MPFT TML (%)
001	10.7	12.2	1.5	14.0
002	10.9	12.7	1.8	16.5
003	11.0	12.5	1.5	13.6
004	11.1	12.4	1.3	11.7
005	11.2	12.5	1.3	11.6
006	11.2	13.2	2.0	17.9
007	11.3	13.1	1.8	15.9
008	11.3	12.9	1.6	14.2
009	11.3	13.1	1.8	15.9
010	11.4	12.9	1.5	13.2
011	11.4	13.0	1.6	14.0
012	11.4	12.8	1.4	12.3
013	11.6	13.1	1.5	12.9
014	11.9	13.4	1.5	12.6
Average	11.3	12.8	1.6	14.0

The outcome of using a lighter compaction hammer and a lower hammer drop height, than the PFT, and interpreting the TML from the Degree of Saturation (S_w) equal to 80% instead of S_w equal to 70%, all combine to produce a TML value greater than that produced by the three test methods stated in the 2013 IMSBC Code. The increased TML, produced by the MPFT, will allow IOF cargoes to be transported in bulk carriers with higher moisture contents than if one of the three test methods, stated in the 2013 IMSBC Code, were used.

5. Discussion

Since the temporary reclassification of IOF as a 'Group A' liquefiable material, by the IMO in 2011, industry and research institutions have begun widespread research into individual bulk cargo behaviours while being transported at sea. The focus of their research is to determine the potential risk of liquefaction that minerals, such as IOF, pose while being transported in bulk carriers and to re-examine whether the test methods, stated in the 2013 IMSBC Code, are acceptable when determining the liquefaction potential of IOF.

Research by the TWG has produced draft schedules, in relating to TML testing of IOF, with the implementation of the MPFT and goethite content provisions, which are to be amended in the 2015 IMSBC Code. These recent developments could potentially solve the problem of liquefaction of IOF.

This study demonstrates that the test methods, stated in the 2013 IMSBC Code, are not appropriate for testing of IOF due to the TML values varying between test methods. Limited experimental results from this study shows that typical IOF can be transported with significantly higher moisture contents based on determining the TML using the MPFT when compared to the original test methods.

The TWG has performed essential research that can be used as a foundation for future studies. TML test methods for other minerals such as bauxite, manganese ore and nickel ore, are still absent or out-dated. Further research into the cause of liquefaction of IOF and these other minerals, while being transported, is essential to prevent future loss of human life and assets.

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