A REVIEW OF THE NEWLY DEVELOPED METHOD USED TO PREVENT LIQUEFACTION OF IRON ORE FINES ON BULK CARRIERS

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ABSTRACT

Liquefaction is a commonly occurring problem affecting solid bulk cargoes on board bulk carriers. If liquefaction of a solid bulk cargo occurs on board a bulk carrier it can result in the vessel listing or capsizing resulting in the loss of human life and industry assets. Recent incidents involving bulk carriers transporting iron ore fines have initiated research into, and implementation of, a new test method used to determine a safe moisture content at which it can be transported without being at risk of liquefying. The new test method, known as the 'Modified Proctor/Fagerberg Test for Iron Ore Fines', has been amended in the 2015 edition of the International Maritime Solid Bulk Cargoes Code and will be entered into force in 2017. The objective of this paper is to provide a review regarding the development of the Modified Proctor/Fagerberg Test developed by the Iron Ore Technical Working Group. The review focusses on the key findings from five publicly available reports released in 2013.

Keywords: International Maritime Solid Bulk Cargoes Code; Iron Ore Fines; Liquefaction; Modified Proctor/Fagerberg Test; Technical Working Group; Transportable Moisture Limit.

Abbreviations: IMSBC Code, International Maritime Solid Bulk Cargoes Code; MPFT, Modified Proctor/Fagerberg Test for Iron Ore Fines; PFT, Proctor/Fagerberg Test; TWG, Iron Ore Technical Working Group.

1 INTRODUCTION

Liquefaction is a commonly occurring problem affecting solid bulk cargoes on board bulk carriers (Munro and Mohajerani, 2015). *"Liquefaction is a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic or shock loading, and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance."* (Sladen *et al*., 1985). If liquefaction of a solid bulk cargo occurs on board a bulk carrier it can result in the vessel listing or capsizing resulting in the loss of human life and industry assets.

The International Maritime Solid Bulk Cargoes Code (IMSBC Code), published by the International Maritime Organization, is an internationally accepted code of safe practice to be referred to when transporting solid bulk cargoes which are deemed hazardous when transporting on bulk carriers (International Maritime Organization, 2013a). Recent incidents involving bulk carriers transporting iron ore fines has initiated research into, and implementation of, a new test method used to determine a safe moisture content at which iron ore fines can be transported without being at risk of liquefying.

The new test method, known as the 'Modified Proctor/Fagerberg Test for Iron Ore Fines' and herein referred to as the MPFT, has been amended in the 2015 edition of the IMSBC Code by the International Maritime Organization and will be entered into force in 2017 (International Maritime Organization, 2015). The MPFT is specifically designed to determine the transportable moisture limit of iron ore fines. The IMSBC Code infers that the transportable moisture limit is the maximum gross water content that a cargo may contain without being at risk of liquefying.

The objective of this paper is to provide a review regarding the development of the MPFT developed by the TWG. The review focuses on the key findings from five publicly available reports released in 2013 (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e), which have been implemented in the 2015 edition of the IMSBC Code (International Maritime Organization, 2015).

2 IRON ORE FINES

In order to determine the potential risk iron ore fines pose while being transported on bulk carriers an understanding of the quantity of material being transported and vessels at risk must be determined. Iron ore is without doubt one of the most essential commodities of our time. Demand from countries such as China and Japan for iron ore produced in countries, such as Australia and Brazil, is increasing (Ridsdale & Sultan, 2011). With increasing demand also come increasing amounts being transported at sea. As iron ore fines is not a concentrate nor is it heavily refined, the geotechnical properties can vary significantly depending on where it is extracted. Various types of iron ore fines commonly transported on bulk carriers can be seen in Figure 1

Figure 1: Various types of iron ore fines commonly transported on bulk carriers.

Iron ore fines is a product of iron ore commonly having a particle size less than 6.3 mm (Bureau of Infrastructure Transport and Regional Economics, 2014). Seen in Figure 2 are typical particle size distribution boundaries of iron ore fines transported in bulk carriers, which were determined in a related publication (Munro and Mohajerani, 2015). The boundaries were determined by performing particle size distributions on 45 samples of iron ore fines using the sieve and hydrometer methods given in AS12893.6.1 and AS12893.6.3 respectively (Standards Australia, 2009, 2003a).

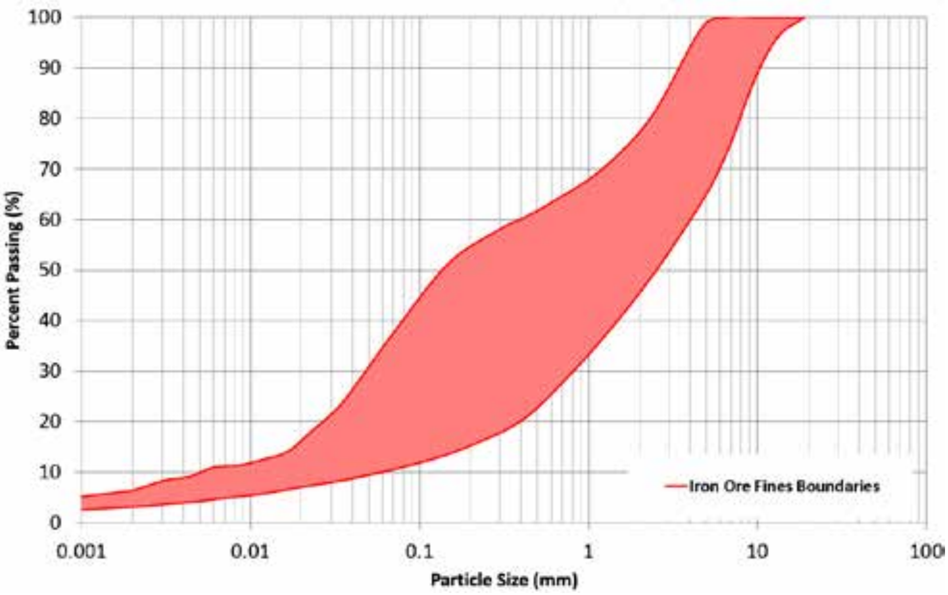

Figure 2: Particle size distribution boundaries of 45 typical samples of iron ore fines transported in bulk carriers (Munro and Mohajerani, 2015).

Because iron ore fines contains a significant amount of fine particles it allows the material to retain moisture absorbed by the environment while being extracted, stored and transported. The combination of fine particles and moisture increases the liquefaction potential of the cargo (International Maritime Organization, 2013a). Iron ore fines in the hold of a bulk carrier before and after transportation can be seen in Figure 3 and Figure 4 respectively.

Figure 3: Iron ore fines after loading in the hold of a bulk carrier (Crouch and Aamlid, 2009).

Figure 4: Iron ore fines after transportation in the hold of a bulk carrier (Crouch and Aamlid, 2009).

2.1 HISTORY

Iron ore fines were first deemed liquefiable, by the International Maritime Organization, in October 2011 in the circular DSC.1-Circ.66 where it stated "*iron ore fines may liquefy and should be treated as such, in particular the Master should refer to section 7 of the IMSBC Code, which warns about cargoes that may liquefy*" (International Maritime Organization, 2011). Not until November 2013, was iron ore fines given an individual schedule (DSC.1-Circ.71), which superseded circular DSC.1-Circ.66. From November 2013 the circular DSC.1-Circ.71 could be implemented on a voluntary basis (International Maritime Organization, 2013b). The individual schedule for iron ore fines has been adopted as part of amendment 03-15 to the 2015 edition of the IMSBC Code and the mandatory entry into force date of these amendments is 1 January 2017 (International Maritime Organization, 2013b). The considerations for amendment 03-15 was released in January 2015 as MSC 95/3/Add.1 (International Maritime Organization, 2015).

2.2 TRANSPORTATION

In order to develop a new test method for determining the liquefaction potential of iron ore fines, the TWG used transportation statistics to define the conditions under which iron ore fines are most commonly transported. Iron ore fines is generally transported at sea using vessels referred to as bulk carriers, which are specifically designed to carry large volumes of loose solid cargoes and/or other commodities in bulk. Figure 5 and Figure 6 show the four major subclasses of bulk carriers used to transport iron ore fines along with the transportation statistics, which can also be seen in Table 1. As can be clearly seen in these figures, the capesize subclass of bulk carrier transports the majority of iron ore fines around the globe.

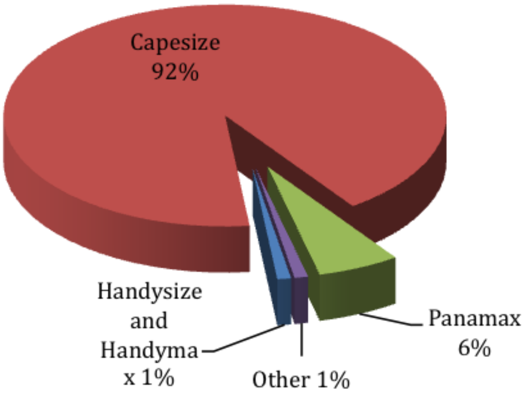

Figure 5:Approximate yearly iron ore fines tonnage transported worldwide by bulk carriers (Iron Ore Technical Working Group, 2013b).

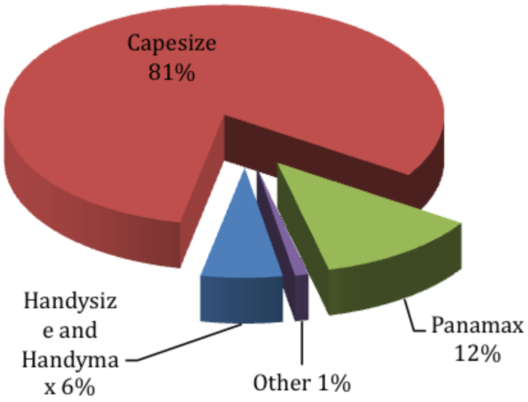

Figure 6:Approximate yearly iron ore fines voyages by bulk carriers (Iron Ore Technical Working Group, 2013b).

Table 1: Bulk carrier subclasses and subsequent transportation statistics for iron ore fines (Iron Ore Technical Working Group, 2013b; Bulk Carrier Guide, 2010; Excel Maritime Carriers Ltd, 2011; United Nations Conference on Trade and Development (UNCTAD), 2011).

Subclass	Deadweight Tonnage	Yearly Iron Ore Fines Tonnage Transported (Figure 5)	Yearly Iron Ore Fines Voyages (Figure 6)	Vessels Worldwide
Handysize	10,000 - 34,999	~ 1%	~ 6%	~ 39%
Handymax	35,000 - 59,999			
Panamax	60,000 - 79,999	~ 6%	~ 12%	~ 27%
Capesize	80,000 - 199,999	~ 92%	~ 82%	~ 34%

2.3 PRODUCTION

Recently, iron ore fines have been the focus of research due to the amount of material being transported around the world. Table 2 shows the worldwide production of nickel ore, bauxite and manganese ore in relation to the worldwide production of iron ore for the year 2011. These solid bulk cargoes have also shown similar liquefaction potential as iron ore fines but a considerably smaller quantity is transported by sea each year. These cargoes combined only form approximately 10% of the total worldwide production of iron ore. Due to this and recent incidents involving bulk carriers transporting iron ore fines, the MPFT was introduced specifically designed for use with iron ore fines.

Table 2: Worldwide production of nickel ore, bauxite and manganese ore in relation to the worldwide production of iron ore in 2011 (United States Geological Survey (USGS)).

Mineral	Major Producers (Descending order)	2011 Mine Production Worldwide (Tonnes)	Mine Production Compared with Iron Ore (%)
Iron Ore	China, Australia, Brazil, India and Russia.	2,940,000,000	100.00
Bauxite	Australia, China, Indonesia, Brazil and India.	259,000,000	8.81
Manganese Ore	South Africa, Australia, China, Gabon and Brazil.	16,000,000	0.54
Nickel Ore	Indonesia, Philippines, Russia, Canada and Australia.	1,940,000	0.07

3 MODIFIED PROCTOR/FAGERBERG TEST FOR IRON ORE FINES

The 'Modified Proctor/Fagerberg Test for Iron Ore Fines' (MPFT), not to be confused with also recently developed 'Modified Proctor/Fagerberg Test for Coal' (Australian Coal Association Research Program (ACARP), 2014), was first introduced in November 2013 in the circular DSC.1-Circ.71 where it could be implemented on a voluntary basis (International Maritime Organization, 2013b). Along with the individual schedule for iron ore fines, the mandatory entry into force date of this test would be 1 January 2017 (International Maritime Organization, 2013b) and, as previously mentioned, the considerations for the amendment 03-15, which has been implemented in the 2015 edition of the IMSBC Code, was released in January 2015 (International Maritime Organization, 2015).

3.1 HISTORY

The MPFT was developed by the Iron Ore Technical Working Group (TWG) over a two year period from May 2012 (AMIRA International, 2012). The TWG was assembled by the International Maritime Organization to *"consider the adequacy of current methods for determining transportable moisture limit for iron ore fines and consider new and/or amended existing methods to be included in appendix 2 of the IMSBC Code"* (Iron Ore Technical Working Group, 2013e).

The TWG was managed by AMIRA International and consisted of eight sponsors and five research providers. The sponsors consisted of major industries involved in the export and transportation of iron ore fines including BHP Billiton, Cliffs Asia Pacific Iron Ore, The Chamber of Minerals and Energy Western Australia, Fortescue Metals Group, The Minerals Council of Australia, Rio Tinto, Roy Hill and Vale Australia. The five research providers from Australia and New Zealand consisted of Auckland UniServices, Creative Process Innovation, the CSIRO and the universities of Auckland and Newcastle (AMIRA International, 2012).

The MPFT is based on an existing test method given in Appendix 2 of the IMSBC Code used to determine the transportable moisture limit of 'Group A' liquefiable solid bulk cargoes. The existing test, known as the

'Proctor/Fagerberg Test' and herein referred to as the PFT, was adopted by the International Maritime Organization, for use in the IMSBC Code between 1991 and 1998, to determine the transportable moisture limit of ore concentrates.

The PFT was first brought to light in a 1962 publication by Bengt Fagerberg and Kjell Eriksson (Fagerberg and Eriksson, 1962). The test was developed by a committee established by the Swedish Mining Association and several Scandinavian mining companies, which was given the task to develop a simple method for determining the transportable moisture limit of ore concentrates (Fagerberg and Stavang, 1971). The test method is based upon the use of the Proctor apparatus and procedure used in AS1289.5.1.1 and ASTM Standard D-698 (American Society for Testing and Materials, 2012; Standards Australia, 2003b), which was developed by Ralph Proctor for use in soil mechanics (Proctor, 1933).

The PFT 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 apparatus used along with a compacted sample can be seen in Figure 7 and a graphical compaction curve and resulting transportable moisture limit can be seen in Figure 8. Note that in Figure 8 the optimum moisture content of iron ore fines is at approximately 95% saturation, not 70% saturation as seen when performing the test on ore concentrates shown in Figure 9.

The compaction of the sample is executed in five layers by dropping a 350 g hammer, 25 times, through a guided pipe from a height of 200 mm. For each point the gross water content and void ratio is calculated then plotted on a graph along with the corresponding degree of saturation. The resulting gross water content is then interpreted, from the graph, where the degree of saturation equals 70%. This value is referred to as the transportable moisture limit (International Maritime Organization, 2013a). The PFT requires the specific gravity of the sample to determine the void ratio and corresponding degree of saturation. It is noted that this test method is not a direct measurement of liquefaction. More information regarding the PFT and results can be seen in two related publications (Munro and Mohajerani, 2015, 2014).

Figure 7: PFT apparatus and compacted sample of iron ore fines.

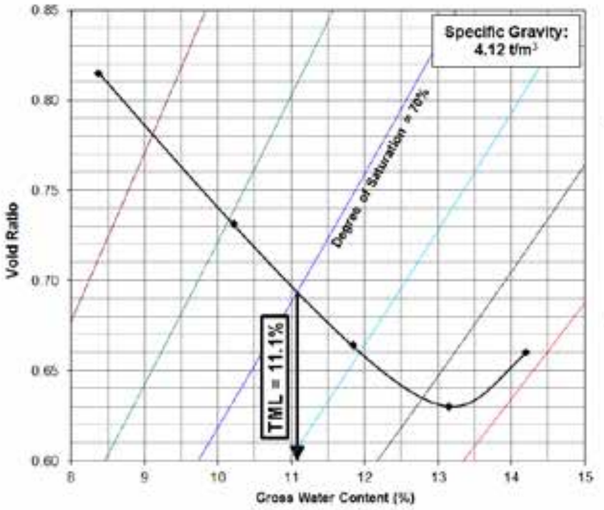

Figure 8: Example of graphical compaction curve and resulting transportable moisture limit of iron ore fines produced by the PFT.

During the development of the PFT, Bengt Fagerberg utilized five hammers with varying drop heights and weights in order to determine which best represented the density of Scandinavian ores and concentrates in the hold of a bulk carrier (Fagerberg and Stavang, 1971). The hammer weights and drop heights along with two compaction results from a sample of magnetite, including the measured density of the magnetite in the hold of a bulk carrier, can be seen in Table 3 and Figure 9 respectively.

From these results, Fagerberg decided to use compaction method C, as this compaction energy produced a lower void ratio (higher density) than the maximum density recorded on board bulk carriers, as seen in Figure 9 (Fagerberg and Stavang, 1971). The compaction method that produced a higher density was chosen because reading the transportable moisture limit from the equivalent degree of saturation equal to 70% resulted in a more conservative transportable moisture limit. Compaction method C, seen in Table 3 and Figure 9, is now referred to as the PFT in the IMSBC Code (International Maritime Organization, 2013a).

Table 3: Hammer masses and drop heights used during the research into the PFT (Fagerberg and Stavang, 1971).

Method	Hammer Mass (g)	Height of Drop (mm)	Number of Blows per Layer	Number of Layers	Compaction Energy per Blow (J)	Compaction Energy per Test (J)	Alternative Names
A	2498	305	25	5	7.47	934.27	-
B	1000	200	25	5	1.96	245.25	-
C	350	200	25	5	0.69	85.84	PFT
D	150	150	25	5	0.22	27.59	MPFT
E	50	40	25	5	0.01	2.45	-

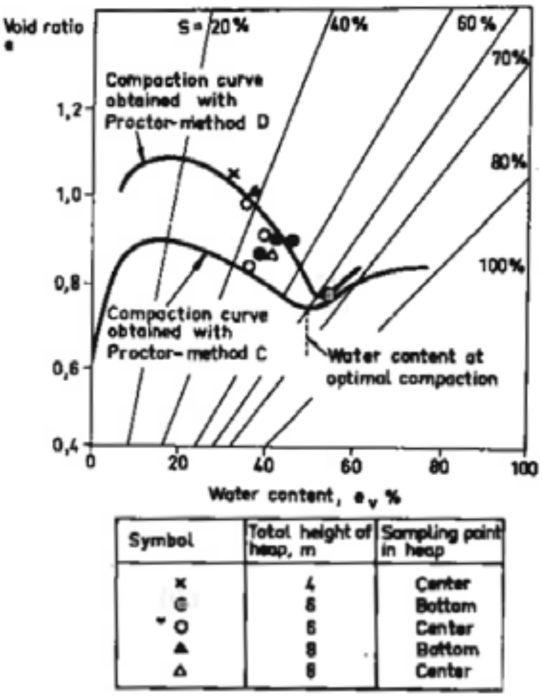

Figure 9: Comparison of *in situ* void ratios of magnetite on board bulk carriers compared with compaction methods C and D performed during the research into the PFT (Fagerberg and Stavang, 1971).

3.2 MODIFICATIONS

The TWG's decision to choose to modify the PFT over the other two methods also given in Appendix 2 of the IMSBC Code was due to it being "*an internationally recognised test that is suitable for determining the compaction curves of various materials, based on their degree of saturation*" (Iron Ore Technical Working Group, 2013a). The modifications that were made to the PFT were based off Bengt Fagerberg's original research accomplished from 1962 to 1971 (Fagerberg and Eriksson, 1962; Fagerberg and Stavang, 1971; Fagerberg, 1965) and additional research performed by the TWG, some of which is summarised herein.

Due to the significant amount of iron ore fines transported on capesize bulk carriers, as seen in Figure 5 and Figure 6, the TWG focussed on the conditions under which iron ore fines are transported in this subclass of bulk carrier to develop the MPFT. They also focussed on the handymax and handysize subclasses of bulk carriers as these have experienced the majority of liquefaction incidents (Munro and Mohajerani, 2015).

The majority of the procedure and apparatus used during the MPFT is the same of that used during the PFT, as described in Section 3.1, except two main differences. One of the decisions made was to modify the weight and drop height of the compaction hammer. The TWG determined that the density produced by the 350g hammer falling 200mm did not accurately represent the density of iron ore fines in the hold of a bulk carrier (Iron Ore Technical Working Group, 2013a).

During research into the MPFT, the TWG utilized similar methods as Fagerberg, as described in Section 3.1, to determine the compaction hammer (or method) that best represented the density of iron ore fines on board bulk carriers.

These methods included; laser scanning, cargo observations, Cone Penetration Tests and Drop Tower Tests (Iron Ore Technical Working Group, 2013a, 2013c).

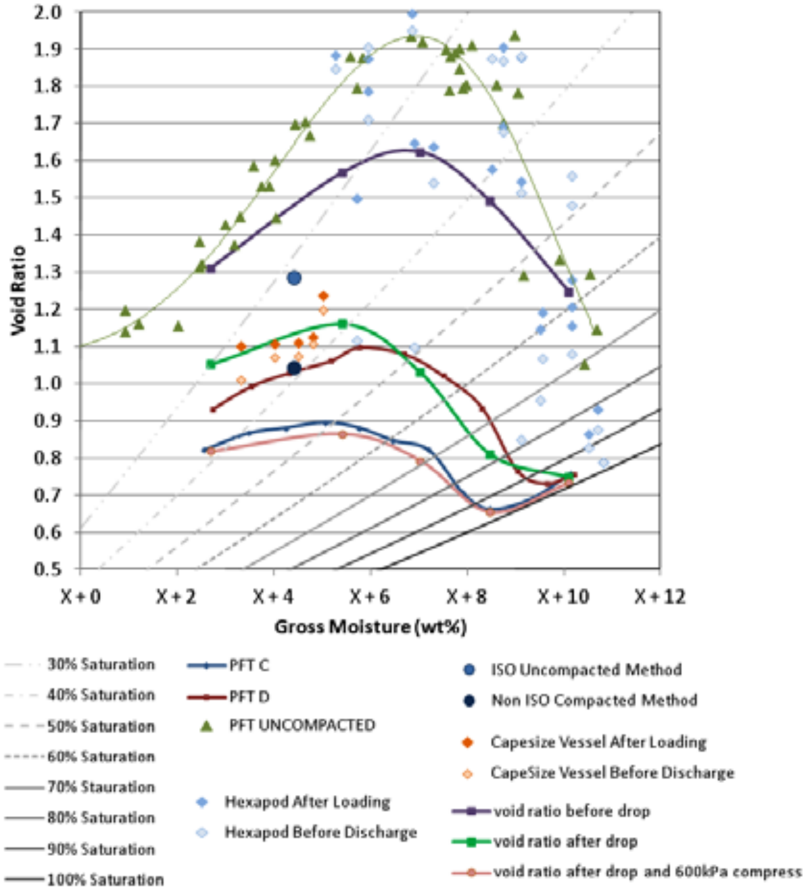

Figure 10: Compaction test results of a sample of Australian iron ore fines performed by the TWG. (Iron Ore Technical Working Group, 2013c).

Figure 10 shows the TWG's compaction results from some of the aforementioned tests for a sample of Australian iron ore fines along with the results from compaction methods C (PFT C) and D (PFT D). All the compaction results produced a higher void ratio (lower density) than compaction method D (PFT D), except from the drop tower tests ('void ratio after drop' and 'void ratio after drop and 600 kPa compress'). These tests were performed by dropping a sample at varying moisture contents from a height of 20 m and also compressing the same sample at 600 kPa after the drop. The comparable results shown in Figure 10 are the capesize vessel after loading and before discharge. These results, produced by laser scanning, show the average void ratio of the cargo on board a bulk carrier to have a greater density than those produced by compaction methods D (PFT D).

A key finding by the TWG states *"The dry density and void ratio values determined from the Proctor-Fagerberg D hammer display the closest alignment to the dry density and void ratio values measured from actual in-hold ship conditions for the iron ore fines material tested in this study."* (Iron Ore Technical Working Group, 2013a). Therefore, along with other results presented in the reports, the decision was made to use the 150 g hammer falling from 150 mm. A comparison between the hammers used for compaction methods C (PFT) and D (MPFT) can be seen in Figure 11.

Modification to the degree of saturation at which the transportable moisture limit is determined when interpreting from the graphical representation was also modified by using 80% instead of 70%. During Bengt Fagerberg's research he infers that liquefaction of the Scandinavian ores and concentrates he was studying was most likely to occur at the Optimum Moisture Content (OMC) (Fagerberg and Stavang, 1971). The OMC is the moisture content at which the minimum void ratio (maximum dry density) occurs during the compaction of a material.

Fagerberg noted that the OMC of Scandinavian ores and concentrates occurred at approximately 70% saturation and therefore the transportable moisture limit should be equal to this moisture content (Fagerberg and Stavang, 1971). The TWG showed that the OMC of iron ore fines occurs at approximately 90-95% saturation. On this basis, they decided that the transportable moisture limit should be read from the graphical representation of the compaction curve where the degree of saturation is equal to 80% to include a 10 to 15% safety factor. A comparison between the compaction curves and transportable moisture limit results produced by the PFT and MPFT on the same sample of iron ore fines can be seen in Figure 12.

Figure 11: Comparison between the compaction hammers used during the PFT and the MPFT.

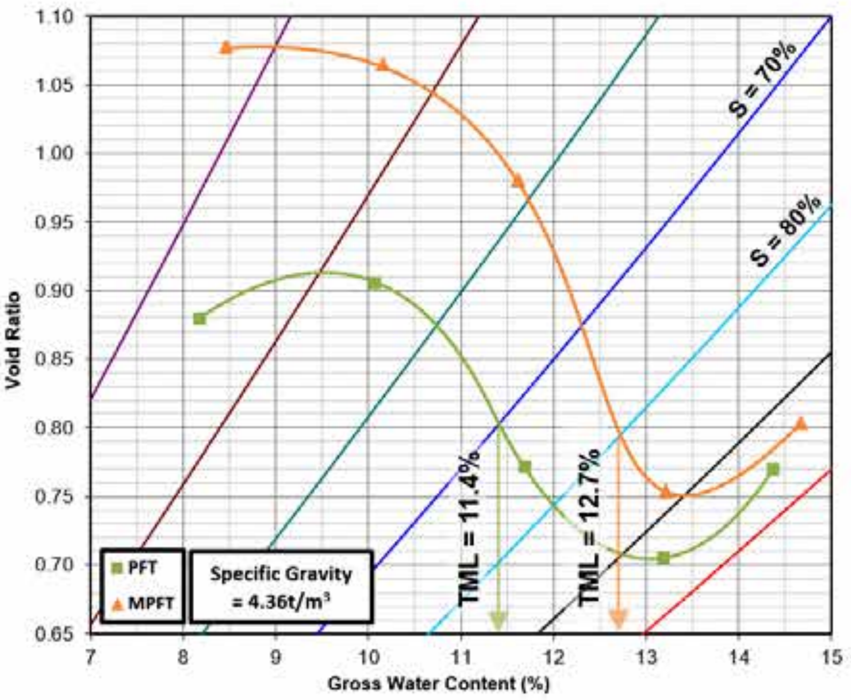

Figure 12: Comparison between the compaction curves produced by the PFT and the MPFT on the same sample of iron ore fines.

In addition to the two modification made to the PFT, the TWG performed cyclic triaxial, direct shear and centrifugal tests to determine the liquefaction resistance of iron ore fines with varying amounts of goethite (Iron Ore Technical Working Group, 2013c). The results from these tests showed that the goethite content directly relates to the surface area of the particles and volume of the pores that forms iron ore fines. The TWG demonstrated that if the goethite content of iron ore fines 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.

The TWG 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 (Iron Ore Technical Working Group, 2013c). It is inferred in the MPFT procedure that if a sample of iron ore fines contains more than 35% goethite that it can be considered a 'Group C' or non-liquefiable material and therefore the transportable moisture limit does not need to be determined (International Maritime Organization, 2015).

3.3 VERIFICATION

In order to verify that iron ore fines does not liquefy at the transportable moisture limit produced by the newly developed MPFT the TWG also performed hexapod testing and numerical modelling.

3.3.1 Hexapod Testing

The TWG utilized scale models where samples of iron ore fines could be tested under simulated seagoing conditions. The tests were completed using hexapods from supporting consultancies, such as the Norwegian Marine Technology Research Institute (MARINTEK), the Maritime Research Institute Netherlands (MARIN) and Deltares, which is also located in the Netherlands. These models incorporated six degrees of motion freedom to replicate bulk carriers seagoing motions while at sea (Iron Ore Technical Working Group, 2013c).

While simulating vessel motions using the hexapod the TWG did not observe liquefaction of Australian iron ore fines at any moisture content, but did observe cracking at the higher moisture contents along with compaction of the sample. Goethitic iron ore fines showed no drainage and were more stable than haematitic iron ore fines. The TWG concluded that all Australian iron ore fines were stable, even when the cargo was unconstrained, when using the hexapod (Iron Ore Technical Working Group, 2013c).

Using a scale model, owned and operated by MARINTEK, the TWG also tested Brazilian iron ore fines. Under typical seagoing motions, the samples of iron ore fines showed no sign of failure even when the moisture content was above the transportable moisture limit produced by the MPFT. Under high levels of transverse accelerations, with no vertical accelerations, it was noticed failure could occur if the moisture content is above the transportable moisture limit. They concluded that at the transportable moisture limit produced by the MPFT the samples of iron ore fines showed no signs of failure under any conditions (Iron Ore Technical Working Group, 2013c).

3.3.2 Numerical Modelling

Along with the hexapod testing, to further validate the MPFT, the TWG used numerical modelling to explain processes that occur within a cargo of iron ore fines. These models were based on the initial conditions of iron ore fines in the holds of bulk carriers and accelerations measured on multiple bulk carrier voyages (Iron Ore Technical Working Group, 2013b). The models calculated the simulated stress states within iron ore fines cargoes loaded in capesize, handysize and handymax subclasses of bulk carriers under a range of typical sea conditions. The TWG concluded that, under a range of cargo configurations, iron ore fines cargoes are capable of resisting the induced levels of repeated loading from the typical motions of these subclasses of bulk carriers (Iron Ore Technical Working Group, 2013c). Additionally, the TWG concluded that due to the size of capesize bulk carriers, they are inherently more stable than smaller bulk carriers when transporting iron ore fines (Iron Ore Technical Working Group, 2013b).

The TWG concluded that *"the development of a wet base in the cargo does not necessarily lead to liquefaction and, although liquefaction of the wet base was seen in some cases, it was localised and would not compromise vessel stability"*. They also concluded that "*observations of free water in the holds of vessels are not necessarily an indication of liquefaction of the cargo. Additionally the presence of free water in the corners of the hold does not necessarily mean that either saturation or liquefaction has occurred"* (Iron Ore Technical Working Group, 2013c). The TWG demonstrated that *"liquefaction of iron ore fines can only occur when the following criteria are met:*

1. *The moisture of the cargo at loading exceeds the optimum moisture content AND*
2. *The bulk of the material is saturated; AND*
3. *Moisture in the material results in excess pore water pressure AND*
4. *The induced force on the vessel and cargo (including the most extreme sea conditions) exceeds the material's resistance"* (Iron Ore Technical Working Group, 2013d).

4 DISCUSSION

The objective of this paper was to provide a review regarding the development of the 'Modified Proctor/Fagerberg Test for Iron Ore Fines' (MPFT) developed by the Iron Ore Technical Working Group (TWG). The review focussed on the key findings from five publicly available reports released in 2013, which have been implemented in the 2015 edition of the International Maritime Solid Bulk Cargoes Code (IMSBC Code) and to be made mandatory in January 2017.

Although the research performed by the TWG is an integral step in understanding the liquefaction potential of iron ore fines being transported in the hold of bulk carriers, based on continuing studies on the topic there are research aspects that need to be refined and fully understood. Further peer-reviewed, published and verified research is required to understand the process of liquefaction of iron ore fines. The varying properties of iron ore fines and variable stress states, depending on how the material is loaded and transported, are assumed to greatly influence moisture migration, local liquefaction and the overall liquefaction potential of the cargo.

The TWG has performed essential research that can be used as a foundation for future studies. Transportable moisture limit 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 iron ore fines and other minerals, while being transported, is essential to prevent future loss of human life and assets.

5 ACKNOWLEDGMENT

This review is part of an ongoing study into the liquefaction potential of mineral cargoes on board bulk carriers at RMIT University Melbourne, Australia.

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