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Moisture Content Limits of Iron Ore Fines to Prevent Liquefaction during Transport: Review and Experimental Study

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Abstract: Iron ore is without doubt one of the most essential commodities of our time. With this, the growing demand from countries, such as China and Japan for iron ore produced in countries, such as Australia and Brazil, is only increasing. Iron Ore Fines (IOF) are a product of iron ore, commonly having a particle size less than 6.3mm, which is transported around the world in bulk carriers. Since the holds of bulk carriers are not designed to carry liquid, if liquefaction of IOF or other minerals occurs, 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 first half of this paper presents a review of the three test methods stated in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code) and the recently introduced Modified Proctor/Fagerberg test (MPFT). Along with the aforementioned tests, also reviewed are recent developments and advancements made in the field. The second half of this paper presents a comparison of the results of our experimental study with two of the three 2013 IMSBC Code tests along with the MPFT. This study shows that the three test methods which are currently used to determine the TML of minerals are not appropriate for testing of IOF and that the Modified Proctor/Fagerberg test produces a value higher than all the other test methods when used to determine the TML of IOF.

Keywords: Bulk Carriers; Iron Ore Fines; Liquefaction; Proctor/Fagerberg; TML Test Methods; Transportable Moisture Limit (TML).

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

1 Introduction

The temporary reclassification of IOF, in 2011, by the International Maritime Organization (IMO), as a 'Group A' liquefiable material [1], has initiated research into individual solid 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 [2-6].

Liquefaction is the term used to describe when a soils shear stress is reduced to near zero under cyclic, static or shock loading resulting in it behaving like a liquid. The shear strength of a soil can be reduced to near zero by the momentary prevention of water drainage under cyclic loading which causes changes in the pore pressures between the particles of the soil [7]. Sladen et al. (1985) gives a more precise definition of liquefaction; *"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" [8].*

Although minerals, such as coal, fluorspar, ilmenite and mineral concentrates (e.g. nickel [9, 10]) are more susceptible to liquefaction because of their similarity to silts and sands [11], 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 [2-6]. 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 of IOF while being transported in bulk carriers [12].

The IMSBC Code, formally the Code of Safe Practice for Solid Bulk Cargoes (BC Code) [13], which is published by the IMO, outlines the dangers associated when transporting certain types of solid bulk cargoes and provides procedures to be followed. 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 [12].

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 2015 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 [12]. The GWC is calculated as the mass of water divided by the total wet mass. This is different from the Net Water Content (NWC), which is calculated as the mass of water divided by the total dry mass. The NWC is more commonly used in geotechnical engineering than the GWC.

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 [14]. Repeated loading can increase the pore pressures of a material which contains sufficient amounts of fine particles and moisture [7]. 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 [15]. Liquefaction of a material will cause it to act like a liquid until the pore pressures dissipate, therefore normalising the shear strength. IOF after being loaded into the hold of a bulk carrier can be seen in Figure 1 [16].

Figure 1 – IOF after loading into the hold of a bulk carrier [16].

Since the holds of bulk carriers are not designed to carry liquid, if liquefaction of IOF or other minerals occurs, it may 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 [14]. 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 [17-22].

Table 1. Recent bulk carrier incidents where the suspected cause was liquefaction of the cargo of IOF [17-22].

Vessel Name	**Subclass** (See Table 2)	**Total Loss of Vessel**	**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

Recently, nickel ore has also shown similar liquefaction potential as IOF [14], but a considerably smaller quantity is transported by sea each year. In 2011, the worldwide mine production of Nickel ore was only 0.07% of iron ore [9, 10].

1.1 Transportation of Solid Bulk Cargoes

Iron ore is extracted from beneath the surface rock then crushed and mechanically divided to produce three different qualities; fines (<6.3mm), lump (6.3-31.5mm) and pellets (6-18mm) [23]. The majority of IOF produced in countries, such as Australia and Brazil, are exported to countries, such as China, Japan and South Korea, to be refined [24].

Solid bulk cargoes, such as IOF, are generally transported at sea using vessels referred to as bulk carriers. Bulk carriers refer to a class of large seagoing vessels specifically designed to carry large volumes of loose minerals and/or other commodities. Table 2 shows the four major subclasses of bulk carriers used to transport IOF along with transportation statistics of IOF [4, 18, 25, 26]. The Deadweight Tonnage (DWT) is the total maximum weight a specific vessel can safely carry, which is typically defined by the manufacturer of each vessel.

Table 2. Bulk carrier subclasses [4, 18, 25, 26].

Subclass	**Deadweight Tonnage (DWT)**	**Yearly IOF Tonnage Transported**	**Yearly IOF Voyages**	**Vessels Worldwide**

Handysize and Handymax	10,000 - 59,999	~ 1%	~ 6%	~ 39%
Panamax	60,000 - 79,999	~ 6%	~ 12%	~ 27%
Capesize	80,000 - 199,999	~ 92%	~ 82%	~ 34%

It is assumed that the density of a cargo in the hold of a bulk carrier will depend on numerous variables, including the physical properties of the cargo and system variables under which the cargo is loaded and transported. Two important system variables, which may significantly control the density of a cargo, are the loading rate and height that the cargo is loaded into the holds. Loading rates are generally specified by the manufacturers of each individual bulk carrier [27].

Along with the loading techniques varying from one port to another, this will mean that the density of IOF, in the holds of bulk carriers, may vary significantly. The maximum depth of the cargo can also vary depending on the vessel subclass, the angle of repose and the loading sequence of the cargo. The density of a cargo being transported directly relates to its liquefaction potential [14]. A typical loading profile of IOF in the hold of a Capesize bulk carrier can be seen in Figure 2 [3].

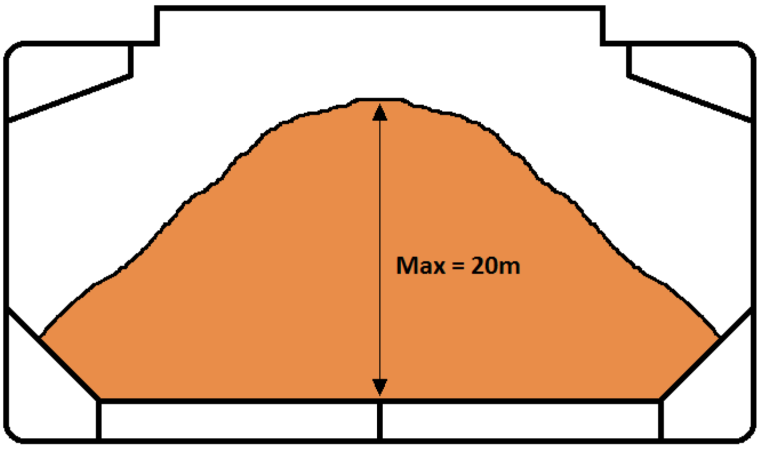

Figure 2 – Typical loading profile of IOF in the hold of a Capesize bulk carrier.

Sections 2 and 3 of this paper present a review of the three test methods stated in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code) and the recently introduced Modified Proctor/Fagerberg test (MPFT). Along with the aforementioned tests, also reviewed are recent developments and advancements made in the field. Section 4 of this paper presents a comparison of the results of our experimental study with two of the three 2013 IMSBC Code tests along with the MPFT.

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 [12]. Appendix A shows the development of these Transportable Moisture Limit testing methods in a graphical timeline, beginning in 1962. In a related publication these three original test methods are discussed in more detail [28].

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 [29]. The test method is based upon the use of the Proctor apparatus (ASTM

Standard D-698 [30]), which was developed by Ralph Proctor for use in soil mechanics [31], 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). The resulting GWC is then interpreted, from the graph, where S equals 70%. This value is referred to as the TML [12]. The PFT uses approximately 14% of the standard Proctor compaction energy and requires the specific gravity to produce the corresponding S. A typical compaction curve of IOF, produced during this study, can be seen in section 4.3 (Figure 8).

2.2 Flow Table Test (FTT)

The FTT has been widely used in the cement industry to test hydraulic cement [32]. The early IMSBC Code (the BC 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 [29]. In 2000, this method branched out into an ISO (International Organization for Standardization) guide (ISO 12742) [33].

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 $P = \rho \times d \times g$, 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 [30], *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 [12].

2.3 Penetration Test (PT)

The PT was developed in Japan at the Research Institute of Marine Engineering [34]. It was adopted by the IMO, in 1994, for determining the TML of coal and ore concentrates [35].

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 levelled [12]. 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"* [34].

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 [12].

3 Recent Developments in TML Testing

After the temporary reclassification of IOF, in 2011 [1], industry and research institutions began comprehensive research in order to understand what can cause IOF to liquefy while being transported in bulk carriers and how to prevent it from occurring in the future. 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 [2-6].

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"* [3]. The TWG is a collaboration between 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) [36].

The early implementation of the TWG's research was introduced, in 2013, by the IMO in the circular DSC.1/Circ.71 [37]. 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 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 [37]. The Australian Maritime Safety Authority (AMSA) is one governing authority that gave the option for Australian export industries to voluntarily implement the draft schedules and draft test method for IOF [38].

3.1 TWG Original Test Method Results

While evaluating the MPFT, the TWG tested the samples of IOF using the three methods stated in the 2013 IMSBC Code [2]. As seen in Table 3, the average variations from the FTT to the PFT, the PT to the PFT and the PT to FTT method was found to be approximately 8%, 27% and 18%, respectively. Figure 3 and Table 3 demonstrate the different TML values that can be produced depending on the chosen test method.

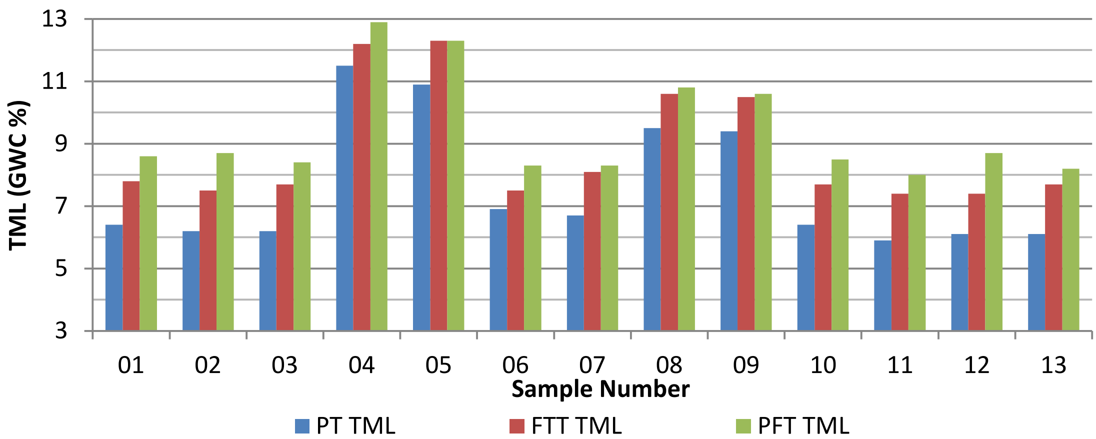

Figure 3 – IOF TML values using the PT, FTT and PFT produced by the TWG [2].

Table 3. IOF TML values using the PT, FTT and PFT and relevant increase percentages produced by the TWG [2].

Sample	PT TML (GWC %)	FTT TML (GWC %)	PFT TML (GWC %)	Increase from FTT TML to PFT TML (%)	Increase from PT TML to PFT TML (%)	Increase from PT TML to FTT TML (%)
01	6.4	7.8	8.6	10.3	34.4	21.9
02	6.2	7.5	8.7	16.0	40.3	21.0
03	6.2	7.7	8.4	9.1	35.5	24.2
04	11.5	12.2	12.9	5.7	12.2	6.1
05	10.9	12.3	12.3	0.0	12.8	12.8
06	6.9	7.5	8.3	10.7	20.3	8.7
07	6.7	8.1	8.3	2.5	23.9	20.9
08	9.5	10.6	10.8	1.9	13.7	11.6
09	9.4	10.5	10.6	1.0	12.8	11.7
10	6.4	7.7	8.5	10.4	32.8	20.3
11	5.9	7.4	8.0	8.1	35.6	25.4
12	6.1	7.4	8.7	17.6	42.6	21.3
13	6.1	7.7	8.2	6.5	34.4	26.2
Average	**7.6**	**8.8**	**9.4**	**7.7**	**27.0**	**17.9**

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 [37].

3.2 Modified Proctor/Fagerberg Test (MPFT)

In 2013, the MPFT was introduced, by the IMO, in the circular DSC.1/Circ.71 [37]. 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 [29], as seen in Table 4. Also, instead of reading the TML from the intersection of the compaction curve and Degree of Saturation (S) 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 equal to 80%, for IOF [2]. Apart from the difference in S and compaction energy, the same procedure is used for both the PFT and MPFT [37].

Table 4. Hammer masses and drop heights used by Fagerberg and Stavang, 1971 [29].

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 (C70)
D	150	150	25	5	0.22	27.59	MPFT (D80)
E	50	40	25	5	0.01	2.45	-

In 1971, Fagerberg and Stavang performed compactions on Magnetite to compare the void ratio and the water content by volume, as seen in Figure 4 and Figure 5. These compactions were compared with multiple in situ void ratios of Magnetite, measured onboard bulk carriers. From these comparisons Fagerberg and Stavang came to the conclusion that method C was adequate for replicating the density of mineral concentrates in the holds of bulk carriers and that at S equal to 70%, which is the approximate maximum density, mineral concentrates have the greatest potential to liquefy [29].

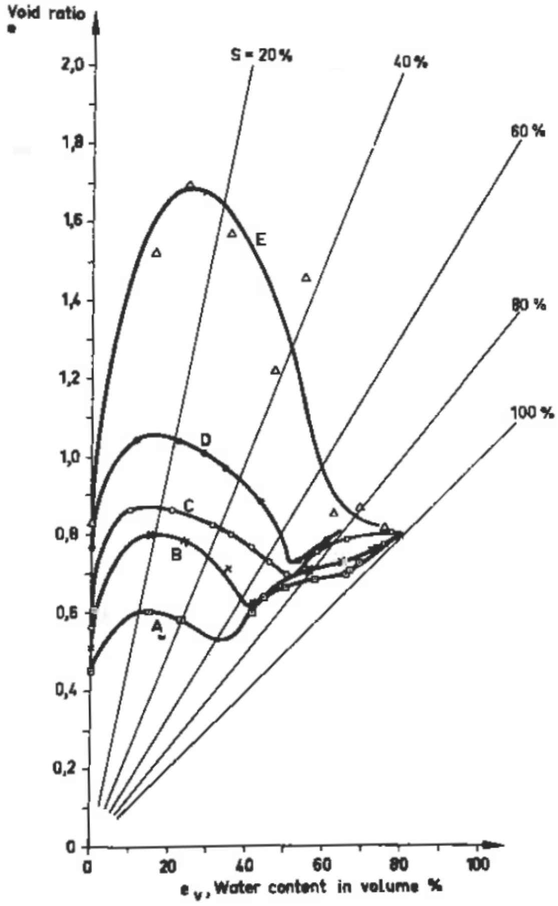

Figure 4 – Compaction test with Proctor apparatus performed on Magnetite using methods A through E performed by Fagerberg and Stavang, 1971 [29].

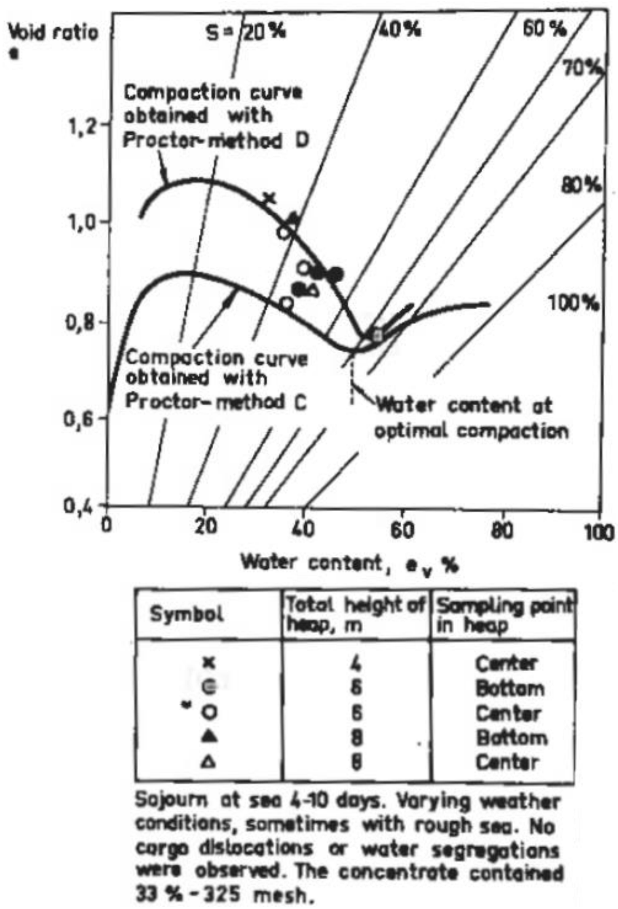

Figure 5 – Comparison of in situ void ratios of Magnetite onboard bulk carriers compared with compaction methods C and D performed by Fagerberg and Stavang, 1971 [29].

To verify this procedure the TWG measured the bulk density of IOF in the holds of multiple bulk carriers, before and after transportation, through means of height measurements, laser scanning and cone penetration testing [2, 3]. Using this data and additional bulk densities determined by drop tower testing the TWG concluded that the density produced by compaction during the MPFT or method D in Fagerberg and Stavang research [29], was more than sufficient for replicating the density of IOF in the holds of bulk carriers [3].

The TWG states that based on the research completed by Fagerberg and Stavang [29], the MPFT includes a safety factor of approximately 10-15% based on the S and approximately 10% based on the TML. This depends on the compaction curve produced by the different types of IOF. The MPFT uses around 5% of the standard Proctor compaction energy and 32% of the PFT compaction energy [2].

3.3 Particle Size Provisions

In the draft individual schedule for IOF, given in the circular DSC.1/Circ.71 [37], it is stated that when transporting iron ore cargoes containing 10% or more of fine particles less than 1mm and 50% or more of particles less than 10mm the individual schedule for IOF must be followed and therefore classified as a ‘Group A’ liquefiable material and if not then the schedule for iron ore should be followed and therefore classified as a ‘Group C’ non-liquefiable material [37]. A graphical representation of this can be seen in section 4.4 (Figure 9), where it is compared to particle size distribution results of IOF obtained during this study.

3.4 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 [3].

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 make up the structure of 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 increased [3].

In the draft individual schedule for IOF it is stated that, regardless of the particle size, 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 [37].

3.5 TWG Scale Model Testing

The TWG utilized scale models where IOF could be tested under simulated seagoing conditions. The tests were completed using hexapods along with the additional use of apparatus 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 [3].

While simulating vessel motions using the hexapod the TWG did not observe liquefaction of Australian IOF at any moisture content, but did observe cracking at the higher moisture contents along with compaction of the sample. Goethitic IOF showed no drainage and were more stable than haematitic IOF. The TWG concluded that Australian IOF were stable, even when the cargo was unconstrained, when using the hexapod [3].

Using a scale model, owned and operated by MARINTEK, the TWG also tested Brazilian IOF. They concluded that at the TML, determined by the MPFT, the samples of IOF showed no signs of failure. Typical seagoing motions also caused no failures in the samples of IOF even when the moisture content was above the TML, determined by the MPFT, but under high levels of transverse accelerations with no vertical accelerations, failure can occur if the moisture content is above the TML [3].

4 Experimental Results

The following section of this paper presents a comparison of the results of a previous experimental study with two of the three 2013 IMSBC Code test methods along with new experimental results from the newly developed MPFT.

4.1 Materials, Methods and Equipment

The IOF that were used during this study were obtained from various locations around Australia. Table 5 to Table 7 show some of the typical physical properties of the IOF used during this study as well as in the related publication [28].

Table 5. Typical properties of IOF samples used during this study as well as in the related publication [28].

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

Table 6. Properties of a typical sample of IOF that was used during this study as well as in the related publication [28].

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

Table 7. Typical particle size distribution sieve data of IOF used during this study as well as in the related publication [28].

		Percent Passing (%)		
Sieve Aperture (mm)	**Sieve Number**	**Minimum**	**Average**	**Maximum**
19.0	**3/4"**	100	100	100
13.2	**0.530"**	96	100	100
9.5	**3/8"**	87	98	100
6.7	**0.265"**	74	93	100
4.75	**No. 4**	64	85	98
2.36	**No. 8**	49	69	85
1.18	**No. 16**	36	55	71
0.6	**No. 30**	25	45	63
0.425	**No. 40**	21	40	60
0.3	**No. 50**	18	36	58
0.15	**No. 100**	11	28	51
0.075	**No. 200**	7	20	39
0.038	**No. 400**	5	13	25

A graphical representation of the particle size boundaries of 45 samples of IOF can be seen in section 4.4 (Figure 9), where they are compared to the maximum particle size of IOF classified in the draft individual schedule for IOF [37].

All the physical properties in Table 5 to Table 7 were obtained using the methods and equipment stated in AS1289 [39]. The following experimental results, which were produced during this study and the previous study, were obtained using the methods and equipment which is explained in sections 2.1, 2.2 and 3.2 for the PFT, FTT and MPFT respectively.

4.2 Flow Table and Proctor/Fagerberg Test Results Produced during Previous Study

During previous reseach, samples of IOF were tested using the FTT and the PFT as stated in the 2013 IMSBC Code [12]. These results have been presented in a related publication [28]. According to this research, when comparing the TML values produced using these two methods it can be clearly seen that there is a significant difference in the results. Seen Table 8, the results of the PFT can vary up to 16% more than the results from the FTT, with the average being 12%. This is mainly due to the difference in compacted densities that each test produces.

A graphical representation of the data from Table 8 can be seen in Figure 6. The coefficient of determination is 0.97, but the data significantly varies from the equality line.

Table 8. Comparison of IOF TML values using the PFT and FTT produced during previous reseach and presented in a related publication [28].

Sample	PFT TML (GWC %)	FTT TML (35kg.f) (GWC %)	Difference between PFT and FTT TML Values (GWC %)	Increase from PFT to FTT TML Values (%)
A	10.7	9.7	1.0	10.31
B	11.3	10.1	1.2	11.88
C	11.1	10.0	1.1	11.00
D	11.6	10.2	1.4	13.73
E	11.8	10.4	1.4	13.46
F	11.8	10.4	1.4	13.46
G	12.3	10.6	1.7	16.04
H	11.0	9.9	1.1	11.11
I	10.8	9.9	0.9	9.09
J	9.3	8.4	0.9	10.71
K	13.1	11.3	1.8	15.93
Average	**11.4**	**10.1**	**1.3**	**12.43**

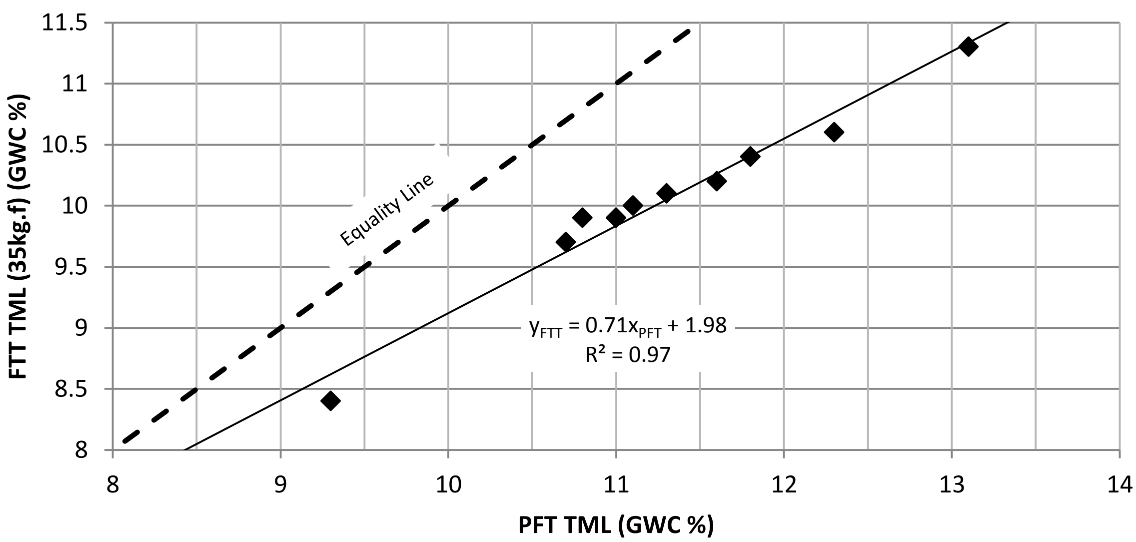

Figure 6 – Comparison of IOF TML values using the PFT and FTT produced during previous reseach and presented in a related publication [28].

Based on the data obtained during this previous research and presented in the related publication [28], the PFT will produce a consistently higher TML value than the FTT when testing samples of IOF.

4.3 Modified Proctor/Fagerberg Test Results Produced during this Study

The MPFT, created in 2013 by the TWG, is the only test method designed specifically for use with IOF [37]. For this study, compactions on samples of typical IOF were performed using the PFT and MPFT, as seen in Figure 7 and Table 9. The average variation from the PFT to the MPFT was found to be approximately 14%, which is the same variation that was seen by the TWG [3].

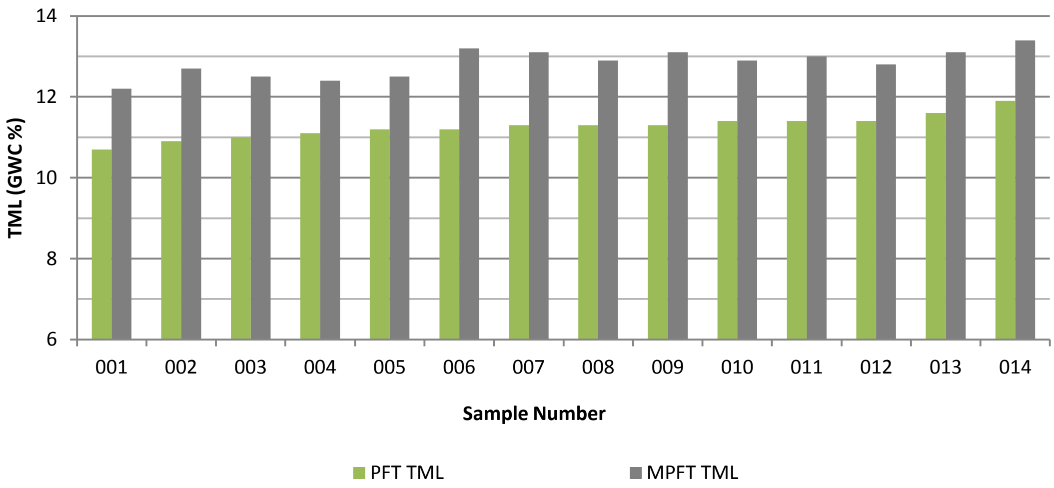

Figure 7 – IOF TML values from the PFT and MPFT produced during this study.

Table 9. IOF TML values from the PFT and MPFT produced during this study.

Sample	Standard PFT TML (GWC %)	Modified PFT TML (GWC %)	Difference between Standard and Modified PFT TML Values (GWC %)	Increase from Standard to Modified PFT TML Values (%)
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**

A graphical representation of compactions performed on sample 011 of IOF, using the PFT and MPFT test, can be seen in Figure 8. The result of using a lighter compaction hammer and a lower hammer drop height, than the PFT, and interpreting the TML from S equal to 80% instead of S equal to 70%, is 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, was used.

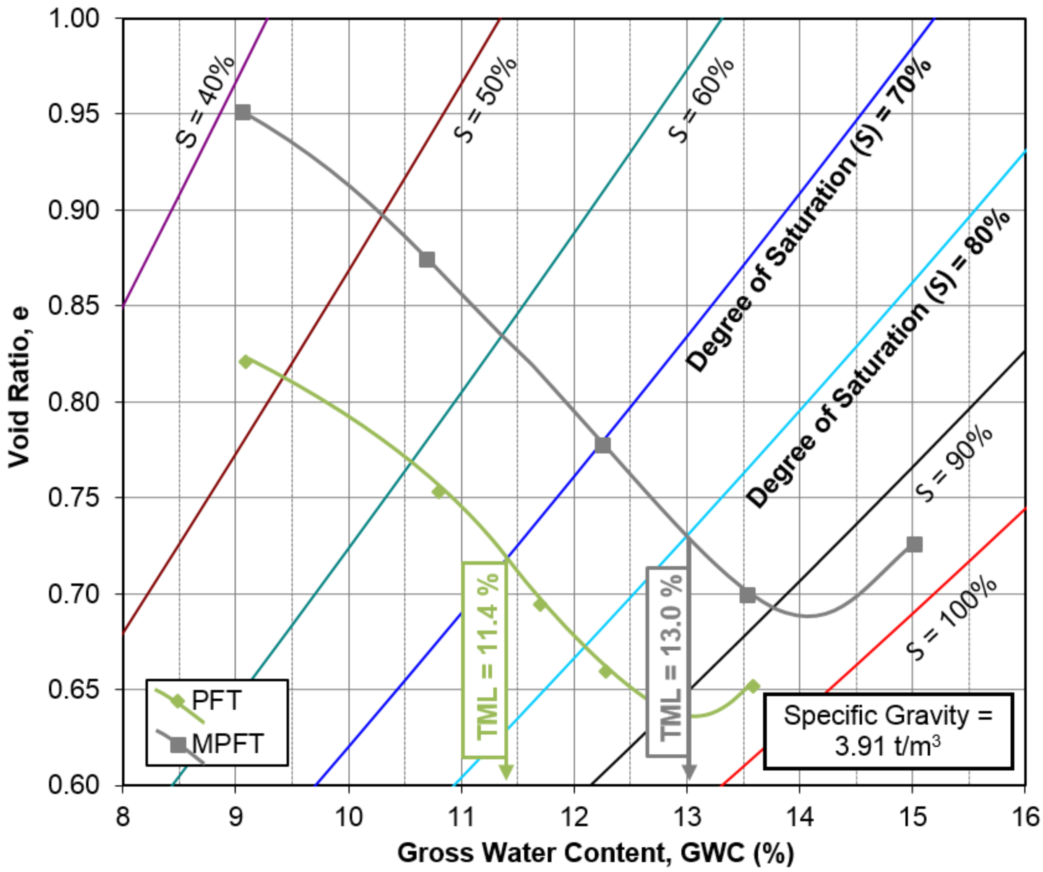

Figure 8 – Graphical representation of the compaction curves of IOF (sample 011) using the PFT and MPFT produced during this study.

4.4 Particle Size Distributions Produced during this Study

During this study the particle size boundaries of 45 samples of IOF were produced using AS 1289.3.6.1 and AS 1289.3.6.3 [40, 41]. These boundaries along with the maximum particle size of IOF, as classified in the 2013 draft schedule [37], are shown in Figure 9.

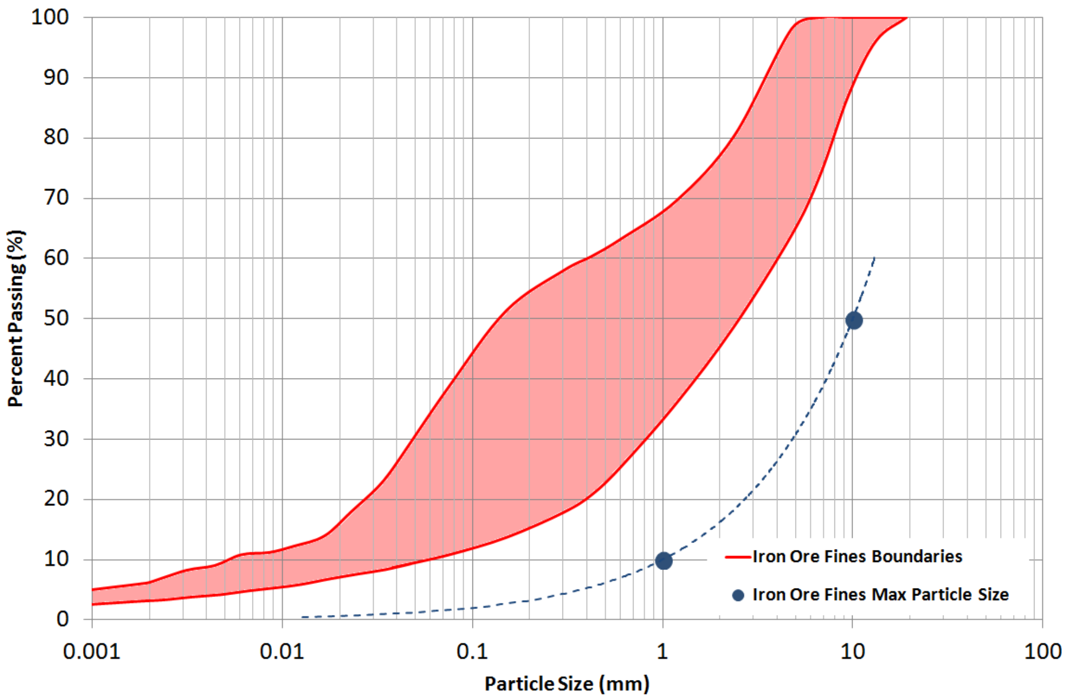

Figure 9 – Particle size boundaries of IOF, which were produced during this study, along with the maximum particle size as classified in the 2013 draft schedule [37].

If the 2013 draft schedule for IOF was used and the particle size provisions followed, as described in section 3.3, all the samples used to produce the boundaries seen in Figure 9 would be required to be transported in accordance with the draft individual schedule for IOF and therefore be classified as 'Group A' liquefiable materials [37]. This is excluding the goethite content provisions, which are described in section 3.4.

5 Conclusion

The first half of this paper presents a review of the three test methods stated in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code) and the recently introduced Modified Proctor/Fagerberg test (MPFT). Along with the aforementioned tests, also reviewed are recent developments and advancements made in the field. The second half of this paper presents a comparison of the results of our experimental study with two of the three 2013 IMSBC Code tests along with the MPFT.

Research by the TWG has produced draft schedules, in relating to TML testing of IOF, with the implementation of the MPFT, limitations on particle size and also goethite content, which are to be amended in the 2015 IMSBC Code.

The experimental results from this study, along with the results produced by the TWG, show that the original test methods, stated in the 2013 IMSBC Code, give significantly different TML values when used on IOF.

Experimental results from this study also show that typical cargoes of IOF can be transported with significantly higher moisture contents when using the MPFT to determine the TML when compared to using the three original test methods, stated in the 2013 IMSBC Code.

The introduction of the MPFT and goethite content provisions, given in the circular DSC.1/Circ.71, increases the allowable moisture content that IOF can contain when being loaded into bulk carriers and reduces the required amount of TML testing to be performed on IOF. The research that was performed is important to understand the behaviour IOF exhibit while being transported in bulk carriers.

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 investigations on the mechanism of liquefaction of IOF and other similar materials need to be explored and further research on the causes of bulk carrier incidents involving these materials is essential to prevent future loss of human life and assets.

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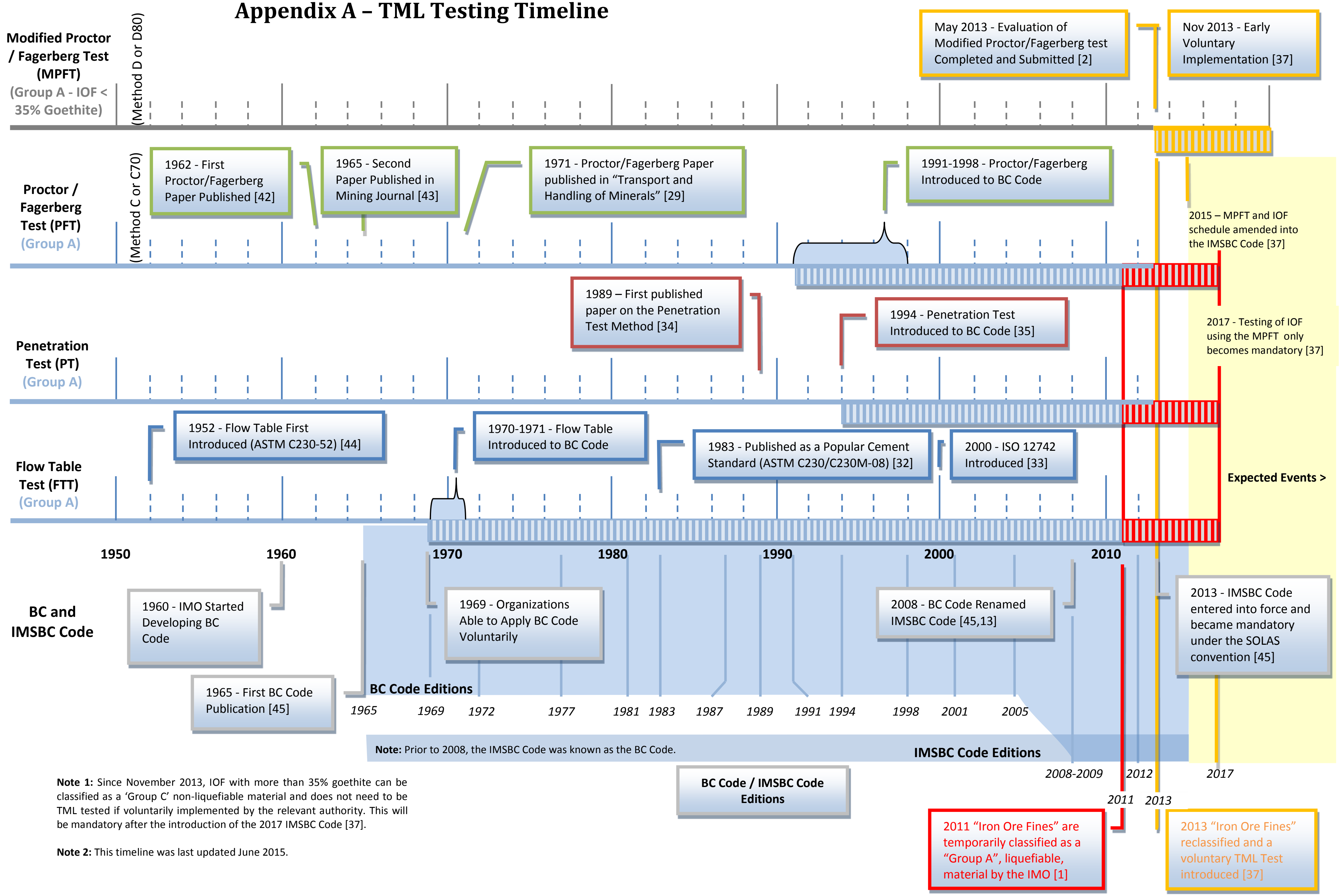
Appendix A – TML Testing Timeline



Note 1: Since November 2013, IOF with more than 35% goethite can be classified as a ‘Group C’ non-liquefiable material and does not need to be TML tested if voluntarily implemented by the relevant authority. This will be mandatory after the introduction of the 2017 IMSBC Code [37].

Note 2: This timeline was last updated June 2015.