Iron Ore Technical Working Group Submission for Verification

Research Synopsis and Recommendations

June 2013

All participants of the Technical Working Group (TWG) operate under the international and their respective national anti-trust laws and regulations. Suitable controls are in place to ensure all meetings are minuted and discussions and material exchanged do not transgress anti-trust requirements. All participants of the TWG have access to in-house competition law advice, operate at all times under all applicable international and national competition laws and regulations and have been cautioned accordingly.

Introduction

At the 17th session of the Sub-committee on Dangerous Goods, Solid Cargoes and Containers, Member States directed the Correspondence Group (CG) on the transportation of the iron ore fines (established at DSC 16) to continue its work with updated Terms of Reference to:

.1) consider the adequacy of current methods for determining transportable moisture limit (TML) for iron ore fines and consider new and/or amended existing methods to be included in appendix 2 of the IMSBC Code – to be completed by end of May 2013 (DSC 17/4/34 and DSC 17/INF.9);

.2) consider the evaluated and verified research into Iron Ore Fines – to be completed by end of May 2013;

.3) prepare draft individual schedule(s) for iron ore fines and any required amendments to appendix 2, taking into account .1 and .2 above and review the existing iron ore schedule, as necessary; and

.4) submit a report to DSC 18.

In an effort to ensure the CG's deliberations are informed by the latest scientific insights, the three largest iron ore producers (with the support of their respective Competent Authorities) committed to form an Iron Ore Technical Working Group (TWG). The TWG has coordinating research efforts into the transportation of iron ore fines to provide independently "evaluated and verified" findings that can serve as the basis for decision making.

To this end, the TWG produced the following reports:

- Report #1: "Terms of Reference .1" – This report assesses the adequacy of current IMSBC Code methods for determining the TML of Iron Ore Fines (IOF).
- Report #2: "Marine Report" – This document reports the characteristics of vessel motions and forces imposed on IOF cargoes during transit; the impacts of vessel size and sea conditions (swell, sea and wind); and, the stability of vessels in various cargo behaviour scenarios.
- Report #3: "Iron Ore Fines Proctor-Fagerberg Test"– Building on the outcomes of Report #1, this document explores potential adjustments to one of the existing routine IOF test methods – or a new test – to better reflect actual in-hold shipping conditions and observations.
- Report #4: "Reference Tests" – This report provides further evidence to substantiate the applicability of the routine IOF test method identified in Report #3 through the material's performance in real-world conditions using a variety of well-established geotechnical methods, numerical modelling and cargo observation.
- Report #5: "Research Synopsis and Recommendations"– This report will integrate the results of all of the preceding research into a series of recommendations that can inform the deliberations of the CG.

The TWG have appointed external experts (Prof Kenji Ishihara, Prof Junichi Koseki and Dr Kourosh Koushan) in the relevant disciplines to verify each of the reports. This evaluation was followed by an independent scientific review process undertaken by reviewers from Imperial College London (Dr Stephen Neethling and Professor Velisa Vesovic) and for vessel stability (Marine Report) by University of Strathclyde (Professor Dracos Vassalos) under the direction of the International Group of P&I Clubs (IG). The IG represents a group of industry NGOs that includes BIMCO, Intercargo, International Chamber of Shipping and IFAN . Dr Ken Grant (Minton, Treharne and Davies, Singapore) assisted IG by reviewing those TWG responses to the reviewers from Imperial College that were related to TML methods. The finalized reports were then submitted to the CG, fulfilling the requirement for “evaluated and verified” research.

Context and Work Programme

1 Context

The interest of the International Maritime Organization in the safe transport of solid bulk cargoes that may liquefy began after incidents involving iron ore fines (IOF) that led to loss of life and vessels. Incidents also occurred involving nickel ore and other bulk cargoes. The two incidents involving iron ore occurred in India in 2009. The ship types involved in all of these accidents were handysize, handymax and supramax bulk carriers.

In the case of iron ore fines, following a decision by DSC15*,* a circular was issued (DSC/1/63) warning Masters that some shippers were wrongly declaring this cargo as “iron ore”, a Group C cargo as set out in the IMSBC Code. In the absence of an agreed upon definition of IOF, however, this measure caused confusion amongst shippers and operators alike.

DSC16 then issued a new circular (DSC/1/66), to serve as an interim measure until a definition of iron ore fines could be agreed and incorporated into the IMSBC Code. DSC16 also established a CG.

In 2012, DSC17 considered the report from the CG, along with submissions from Brazil and Australia on their respective research programs. Brazil’s submission included a proposal for a new method for TML determination. Australia’s submission recommended an extension of the research period to DSC18, to provide the opportunity for validated research to inform the development of a new schedule for iron ore fines. Based on these inputs, DSC17 determined that a better understanding of the critical factors related to safe seaborne carriage of IOF was required before a decision on a new schedule(s) could be taken.

Accordingly, DSC17 re-established the CG to finalize IOF schedule(s) with the following Terms of Reference:

i. consider the adequacy of methods for determining IOF TML and consider new and/or amended methods to be included in Appendix 2 of the IMSBC Code;

ii. consider the evaluated and verified research into IOF;

iii. prepare drafts of individual schedule(s) for IOF and any required amendments to Appendix 2 taking into account i. and ii. above and review the existing iron ore schedule, as necessary; and

iv. submit a report to DSC18.

2 Technical Working Group (TWG): Program of Work

At DSC17, the Chair of DSC facilitated an agreement among interested parties to assist the exchange of technical information into the safe shipping of iron ore fines and accelerate consensus on key issues. To this end, the three largest iron ore producers (BHP Billiton, Rio Tinto and Vale), with the agreement of their Competent Authorities and support of relevant maritime industry Non-Government Organizations (NGOs), established an Iron Ore Technical Working Group (TWG) [1] to conduct research and coordinate recommendations and conclusions about the transportation of IOF.

The TWG's research program was comprehensive in examining the critical factors related to safe seaborne carriage of IOF. The program of work focused on the following issues:

- test methodologies applicable to IOF
- effect of mineralogy on liquefaction potential
- impact of saturation levels on liquefaction
- relevance of vessel size and stability on the safe carriage of IOF

This research drew on an array of approaches and tools to generate results. These included review of scientific literature and research on IOF; laboratory testing, measurement and analysis; real-time monitoring of vessels; cargo observation; scale model testing and numerical modelling.

The TWG's research provided a comprehensive examination of seaborne-traded IOF, covering different continents and including a full spectrum of commercial mineralogies. The vessel sizes studied ranged from handysize to capesize.

In addition to this report, the TWG produced four reports of technical research and submitted them to the CG. These reports were prepared with the support of technical specialists from the mining industry, accredited laboratories and external consultants, as well as a panel of geotechnical and marine experts.

In addition, under the auspices of the International Group of P&I Clubs (acting on behalf of a group of shipping industry NGOs), reviewers from Imperial College London carried out an independent review of TWG's research findings. In particular they verified that the conclusions drawn were consistent with the data presented in each Report. The evaluated results from this research form the basis of findings and recommendations in this document as the basis for amendments to the IMSBC Code.

[1] *All participants of the TWG operate under the international and their respective national antitrust laws and regulations. Suitable controls are in place to ensure all meetings are minuted and discussions and material exchanged do not transgress anti-trust requirements. All participants of the TWG have access to in-house competition law advice, operate at all times under all applicable international and national competition laws and regulations and have been cautioned accordingly*

3 Introduction

The four TWG reports entitled Terms of Reference 1, Marine Report, Iron Ore Fines Proctor-Fagerberg Test, and Reference Tests present a comprehensive picture of:

- the interaction between vessel and IOF cargo behaviour;
- the implications of these interactions and, finally;
- the combinations of conditions required to produce liquefaction.

4 TWG Report 1: Terms of Reference 1

Report 1: Terms of Reference 1 (TOR1) addresses the adequacy of current TML determination methods, and particularly their applicability to IOF. This was completed for the purpose of considering “new and/or amended existing methods to be included in Appendix 2 of the IMSBC Code.”

The report found that there is a need to augment the existing three tests used to determine TML to better match the characteristics of IOF.

The Proctor-Fagerberg Test (PFT) method was identified as the test best able to be calibrated to the actual bulk densities and real-world transit conditions for IOF. A cornerstone of the PFT involves using the Optimum Moisture Content (OMC) of an ore to establish an appropriate saturation level for testing. The TWG research found that the OMC of IOF differed significantly from the OMC contained in the IMSBC Code (which is focussed on the OMC of mineral concentrates from Fagerberg’s original research). Accordingly, any potential modifications to this test should better reflect the actual OMC of IOF products. Notwithstanding these observations about the need to enhance the existing testing regime with modifications to account for IOF, the TWG’s research did not discount the value of the existing TML tests for other products.

5 TWG Report 2: Marine Report

Report 2 establishes the characteristics of vessel motions and forces imposed on IOF cargoes during transit, the impacts of vessel size and sea conditions (swell, sea and wind) and cargo observations and the stability of vessels.

The outcomes from this research provided quantitative inputs for the testing and numerical modelling used in TWG Report on Reference Tests. In addition to this, it produced the following findings:

- Capesize vessels generate a lower energy input into the cargo than handysize vessels.

- Vessel intact stability is higher in a capesize than a handysize vessel.

- Where free water exists, not trimming to level, i.e. limiting trimming to the natural angle of repose, impedes the surface impacts of free water.

6 TWG Report 3: Iron Ore Fines Proctor-Fagerberg Test

TWG Report 3 explores in detail, specific aspects of the PFT methodology, using the existing Appendix 2 of the IMSBC Code as a basis to determine if modification could match "the actual bulk densities and real-world transit conditions for IOF."

The results of the TWG samples tested (representing a comprehensive picture of seaborne-traded IOF, covering different continents and including a full spectrum of commercial mineralogies) are presented. Results included:

- The OMC of IOF occurs between 90-95% saturation.

- Matching the necessary compaction energy of a sample to determine TML (a necessary requirement to match the bulk density) required a relatively simple change to the IMSBC Code's Appendix 2. This involved changing the hammer weight to a standard Proctor D 150g hammer and its drop height of 150 mm.

- Some further modifications to the existing PFT procedure are required, namely, using recognized standard methods for determining specific gravity and moisture. These were found to improve the precision of the test.

In order to reflect the differing OMC of IOF, compared with those of the mineral concentrates used to develop the original PFT, the saturation level for the test was set at 80%. Given that the OMC of IOF was identified as occurring between 90 – 95% saturation, this 80% intersect provides a safety margin of 10-15%. This safety margin was consistent with the philosophy of a 10% safety margin used in the Flow Table Test (FTT) and Penetration Test (PT) in the IMSBC Code. This 80% intersect was taken forward as the point for TML determination in the IOF PFT (PFT-D 80) procedure to be substantiated further through for reference testing (TWG Report 4).

7 TWG Report 4: Reference Tests

The findings of Report 4 substantiate the applicability of the IOF test method described in TWG Report 3. Using a variety of well-established geotechnical methods, numerical modelling and cargo observation, the TWG was able to test and validate the material's performance in real-world conditions. In addition, this Report outlines the transit conditions (sea states, material properties and vessel sizes) in which IOF would be liable to potentially liquefy, as well as the effect of mineralogy on the liquefaction potential of IOF. The findings of this report draw significantly on results in each of the three preceding reports.

The TWG concluded that the Proctor-Fagerberg D hammer at 80% saturation, as outlined in TWG Report 3, is an appropriately conservative method for the determination of the liquefaction potential of IOF for the materials tested by the TWG. Report 4 details the Cyclic Triaxial Testing (CTT) and numerical modelling work that validates this conclusion.

The numerical modelling explained the processes that could occur within the cargo, subject to the initial conditions of the cargo and accelerations experienced on voyages. In the case of IOF cargo, it assessed the overall cargo behaviour based on the parameters determined in the laboratory analysis. The numerical modelling quantified the stress states within cargoes loaded in capesize and handysize vessels during a range of sea states that can be expected to arise (based on published sea state data). When assessing the cargo's resistance against the induced cyclic forces that a vessel experiences, this work finds that IOF products are able to resist the induced Cyclic Stress Ratios (CSR) from vessel motions of both capesize and handysize vessels over a large range of cargo conditions.

Numerical modelling also establishes that the development of a wet base in the cargo does not necessarily lead to cargo instability; although liquefaction of the wet base is possible, this modelling demonstrates it is localised and does not compromise the stability of the cargo or the intact stability of the vessel. In addition, the presence of free water is not necessarily an indicator of liquefaction. As outlined in the cargo observations in TWG Report 2, Australian ores do not exhibit wet base.

The TWG research, involving the laboratory testing and numerical modelling, has been able to determine the conditions under which liquefaction is likely to occur. Liquefaction of IOF can only occur when all of the following criteria are met:

- The moisture of the cargo at loading exceeds OMC; AND
- The bulk of the material is saturated; AND
- Moisture in the material results in excess pore water pressure; AND
- The induced force on the vessel and cargo (including the most extreme sea conditions) exceeds the material's resistance.

The materials tested by the TWG within the research have defined that certain IOF mineralogies exhibit liquefaction resistance – a factor closely linked to mineralogy, namely the iron oxide species of goethite. Goethite's properties result in high water holding ability preventing moisture migration during sustained cyclic loading. IOF with increasing goethite content have higher liquefaction resistance.

The laboratory testing program (CTT and PFT-D80) has identified a goethite content threshold above which IOF show higher resistance CSRs, bulk strength, and moisture holding ability. This research showed that material with 35% goethite content survived CTT, but material with 25% goethite content failed.

Conclusions

8 Liquefaction

Laboratory testing and modelling indicate that IOF cargo instability due to liquefaction requires that a combination of factors coincide (TWG Report 4).

TWG Reports 2 and 4 found that small failures around the flanks do not compromise vessel stability and safety. IOF material at slightly greater than OMC may result in flank failure, but these are minor block failures and the bulk is stable. In cases where a flank failure may occur, vessel stability is not compromised as it involves only a small proportion of the cargo.

The TWG's research also indicated that the combination of conditions required for liquefaction is not attained in IOF with goethite content that is above a minimum threshold – even when this material is tested in fully saturated conditions. The research showed that material with 35% goethite content survived CTT, but material with 25% goethite content failed.

9 Proctor Fagerberg Test Modifications recommended for Iron Ore Fines TML determination

The results from the research show that it is appropriate for an additional TML test to be used to reflect the characteristics of IOF. The recommended improvements to the test procedure reflect the characteristics of IOF and based on the results in TWG Report 3, for all the materials tested, the PFT-D 80 was sufficiently conservative.

Detailed CTT and numerical modelling support the appropriateness of PFT-D 80 for testing the liquefaction potential of IOF.

The TWG recommends modification of Appendix 2 of the IMSBC Code with a PFT as a discrete test procedure (see Annex B) for IOF. Other IMSBC Code Appendix 2 amendments will need to be undertaken to integrate that change.

The TWG recommends modification of Appendix 2 of IMSBC Code with an IOF PFT with specific requirement to a recognised international standard to undertake density determination.

The TWG recommends before applying this method, in keeping with the existing code requirement "an extensive investigation for adoption and improvement of the method" is required to be conducted to determine if the OMC is equal to, or greater than, 90%.

10 TML experimental errors

Regardless of the test used, errors such as sampling and moisture determination are common to all methods. The largest error is associated with sampling. The TWG addressed this in Report 1 by emphasizing the need to follow Section 4.7 of the IMSBC Code as well as recommending the use of ISO standards. Specific Gravity (SG) can have a large effect on the TML result, which can be mitigated by using a recognized standard method.

The calibration of the PFT D-80 against the actual OMC of IOF results in a 10 to 15% safety margin between the saturation at OMC and the TML determined by the 80 % saturation intercept. This translates into a safety factor in TML (moisture at 80% saturation verses moisture at OMC) of around 10%, the exact number depending upon the shape of the compaction curve and the location of the OMC.

11 Mineralogy

The research output demonstrated that the IOF tested by TWG behave differently as regards liquefaction potential. Different mineralogies (predominantly goethite) have a bearing on liquefaction potential. IOF with increasing goethite content have higher liquefaction resistance. Some of the properties that arise from different mineralogies i.e. chemical and physical (including pore size, surface area etc) affect the behaviour of the ore in terms of its bulk strength, water holding ability and drainage. These distinctions influence characteristics such as resistance to liquefaction, as well as the presence or absence of free surface water, water at the base of a hold, and the resistance of the material during various reference tests.

The TWG recommends goethite content should be determined using an internationally recognised procedure.

12 Vessel Size and Assessment of cargo stability related to liquefaction

Cargo observations in TWG Reports 2 and 4 provide qualitative support for the stability of the cargo below TML. The small-scale modelling, numerical modelling and CTT in Report 4 also provides the stability boundary in cases where the cargo is above TML and demonstrates that for cargo near TML, cargo remains stable and does not compromise vessel intact stability. The stability section of TWG Report 2 also indicates the reserve stability of various vessels in fully liquefied cargo conditions. This provides an indication of the fraction of the cargo that would need to become unstable to compromise vessel intact stability.

IOF have a safety margin against liquefaction which is higher in a capesize vessel compared to a handysize. TWG Report 2 found that handysize vessels encounter large roll events more frequently than capesize vessels. Roll events of 20^{o} and 30^{o} were examined and safety factors for cargo bulk were determined. In each case the Stability Safety Factor (SSF) was greater than 1 for the cargo bulk indicating material has higher resistance to the induced stress. While SSF determined for specific points in the cargo surface and subsurfaces can be less than 1 (indicating that localised slip failure may occur under such conditions), the overall stability of the cargo was maintained and vessel intact stability was not compromised.

The TWG recommends that a new IRON ORE FINES schedule (Group A) contained in the IMSBC Code contain a specific exemption for IOF cargoes with a minimum goethite content with a critical value within the range of 25%<x<35% (where x is to be finalized), AND are being transported in vessels that have a gross tonnage (GT) rating greater than XX,000. Cargoes that meet these criteria should be categorized as Group C.

The TWG recommends that the goethite content of the material be declared as part of the cargo information supplied in writing in appropriate shipping documents prior to loading.

The TWG recommends that a new IRON ORE FINES schedule (Group A) contained in the IMSBC Code contains specific wording that deals with the situation where a cargo, previously categorised as Group C (based on the mineralogy and vessel size criteria detailed above), is subsequently transshipped in a vessel with a GT equal to or less than XX,000, then the cargo shall revert to a IRON ORE FINES (Group A) category.

13 Wet base, free water and appropriate loading conditions

IOF with different mineralogies perform differently in respect to the absorption and drainage of moisture. As a consequence of these differences, Australian ores do not develop a wet base or surface water (either tested, modelled or observed), while Brazilian ores can experience free water collecting in the corners of the hold.

Even when shipped below TML, Brazilian ores can experience the development of a wet base, which indicates that there is a saturated layer present. The saturated IOF has a potential to liquefy locally under shipping conditions. However, even if this layer is liquefied, Finite Element Modelling, model scale testing and cargo observations demonstrate that Brazilian IOF cargoes remain fully stable and that these conditions do not constitute a “dangerous wet base”, i. e. Brazilian IOF wet base will not lead to instability of the cargo or the ship.

These models show that, if a cargo were loaded at the TML then the maximum wet base that could possibly form in the cargo would be below 2m in a capesize vessel (proportionately less in a handysize vessel). Even in this extreme situation, the modelling shows that the cargo would remain stable. Furthermore, the numerical models also find that these IOF cargoes would remain fully stable even if the wet base reached a level of 3m in a capesize vessel.

Some of the Brazilian IOF’s have characteristics that allow moisture to drain, possessing sufficient permeability that water can migrate within the cargo, resulting in free water collecting in the corners of the hold. The shape of stow and trimming practice encourages water containment in the corners of the hold and its subsequent removal through regular bilge pumping. To reinforce the requirements of the IMSBC Code for Group A cargoes it should be highlighted to vessel masters carrying particular iron ore products, that the management of water collecting within the corners of the holds is important.

14 Other Findings and Recommendations

The TWG identified several technical requirements within Appendix 2 that have been reviewed and evaluated to be considered for modification.

All three TML test methods should reference internationally recognised standards. e.g.

Moisture Determination for Iron Ore - ISO3087; and

Density of the Solid Material – ASTM D5550 & AS1289

The TWG proposed two minor wording considerations to the proposed IRON ORE FINES (Group A) Schedule;

- Remove the term ironstone out of the “Description” provision as there is an existing BCSN “IRONSTONE”.
- Insert the term “yellow” into the Description” provision to better reflect the range of IOF colours.

Annex A – Schedule

Proposed Iron Ore Fines Schedule

BCSN

IRON ORE FINES

This schedule shall not apply to IRON ORE FINES when:

i. The total goethite content exceeds [x% - in the range of 25% to 35%, to be defined], and

ii. the cargo is to be carried in bulk carriers of [XX,000] gross tonnage or greater where the deadweight is [XX,000] tonnes or greater;

The shipper shall provide the master with a declaration detailing the goethite content of the material to be shipped. Cargoes that meet both the above criteria together with the shipper's declaration shall be shipped under the IRON ORE (Group C) schedule.

If the carriage of this cargo is to be shipped in a bulk carrier equal to, or less than [XX,000] gross tonnage where the deadweight is equal to, or less than [XX,000] tonnes, the provisions of this schedule shall apply.

DESCRIPTION

Iron ore fines vary in colour from dark grey, rusty red to yellow and comprise of hematite, goethite and magnetite with varying iron content.

IRON CONCENTRATE is a different cargo (see schedule "MINERAL CONCENTRATES")

CHARACTERISTICS

ANGLE OF REPOSE	BULK DENSITY (kg/m^3)	STOWAGE FACTOR (m^3/t)
Not applicable	1,500 to 3,850	0.26 to 0.67
SIZE	**CLASS**	**GROUP**
10 % or more of fine particles less than 1 mm, and 50 % or more of particles less than 10 mm	Not applicable	A

HAZARD

This cargo may liquefy if shipped at moisture content in excess of its transportable moisture limit (TML). See section 7 of this Code.

This cargo may affect magnetic compasses.

This cargo is non-combustible or has low fire-risks.

STOWAGE & SEGREGATION

No special requirements

HOLD CLEANLINESS

No special requirements

WEATHER PRECAUTIONS

When a cargo is carried in a ship other than a specially constructed or fitted cargo ship complying with the requirements in subsection 7.3.2 of this Code, during loading and unloading operations, the following provisions shall be complied with:

.1 the moisture content of the cargo shall be kept less than its TML during loading operations and the voyage;

.2 unless expressly provided otherwise in this individual schedule, the cargo shall not be handled during precipitation;

.3 unless expressly provided otherwise in this individual schedule, during handling of the cargo, all non-working hatches of the cargo spaces into which the cargo is loaded or to be loaded shall be closed;

.4 the cargo may be handled during precipitation under the conditions stated in the procedures required in subsection 4.3.3 of this Code; and

.5 the cargo in a cargo space may be discharged during precipitation provided that the total amount of the cargo in the cargo space is to be discharged in the port.

LOADING

Trim in accordance with the relevant provisions required under sections 4 and 5 of the Code. When the shipper's cargo declaration states that the cargo is likely to exude free water on passage, the cargo shall not be trimmed to level. As the density of the cargo is high, due consideration shall be paid to ensure that tanktop is not overstressed during voyage and during loading by a pile of the cargo.

PRECAUTIONS

Loading rates of this cargo are normally very high. Due consideration shall be given to the ballasting operation in developing the loading plan required by SOLAS regulation

VI/7.3. Bilge wells shall be clean, dry and covered as appropriate to prevent ingress of the cargo.

VENTILATION

No special requirements

CARRIAGE

It is recommended the appearance of the surface of this cargo should be checked regularly during voyage, although this may not always be possible, for example in heavy weather. Cargo hold bilges shall be sounded at regular intervals and pumped out as necessary.

When the shipper's cargo declaration states that the cargo is likely to exude free water on passage and free water is collected at the corners of the cargo spaces, bilge water pumping needs to be reinforced.

If a fluid state of the cargo bulk is observed or free water is observed above the cargo bulk during voyage, the master shall take appropriate actions to prevent cargo shifting and give consideration to seeking emergency entry into a place of refuge.

DISCHARGE

No special requirements

CLEAN-UP

No special requirements

Annex B –Changes to Appendix 2 of IMSBC Code

1.4 Iron Ore Fines (IOF) Proctor/Fagerberg test procedure

1.4.1 *Scope*

.1 Proctor/Fagerberg specific to iron ore fines, does not exclude existing TML tests in the Code.

.2 Test method for Iron Ore Fines (IOF) materials with 10% or more of fine particles less than 1mm, and 50% or more of particles less than 10mm. It is necessary that Optimum Moisture Content (OMC) of the IOF tested occur at saturation levels greater than or equal to 90 %.

.3 The transportable moisture limit (TML) of a cargo is taken as equal to the critical moisture content at 80% degree of saturation according to the IOF Proctor/Fagerberg method test.

1.4.2 *IOF Proctor/Fagerberg test equipment*

.1 The Proctor apparatus (see figure 1.4.2) consists of a cylindrical iron mould with a removable extension piece (the compaction cylinder) and a compaction tool guided by a pipe open at its lower end (the compaction hammer).

.2 Scales and weights (see 3.2) and suitable sample containers.

.3 A drying oven with a controlled temperature interval from 100°C to maximum 105°C.

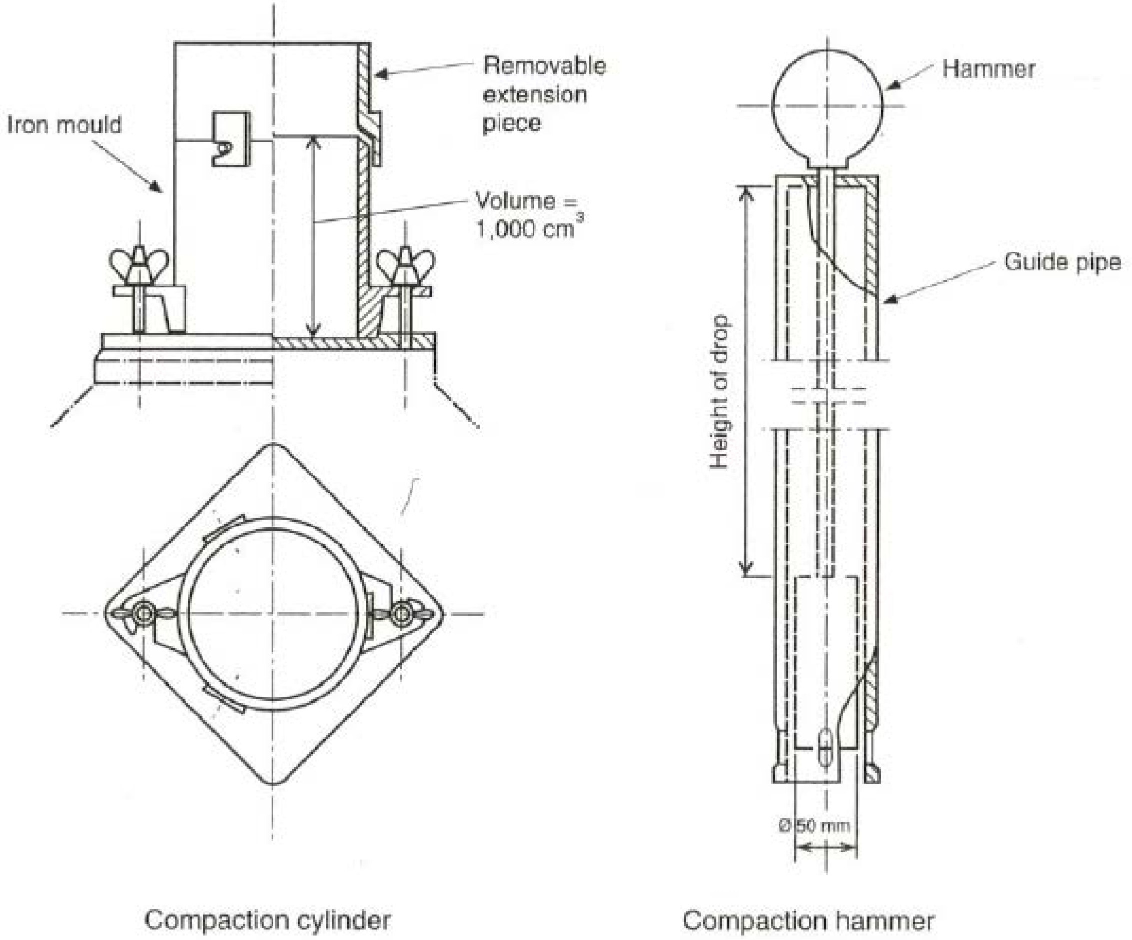
.4 A container for hand mixing. Care should be taken to ensure that the mixing process does not reduce the particle size by breakage or increase the particle size by agglomeration or consistency of the test material.

.5 A gas or water pycnometry equipment to determine the density of the solid material as per a recognised standard (i.e ASTM D5550, AS1289)

1.4.3 *Temperature and humidity (see 1.1.3)*

1.4.4 *Procedure*

.1 *Establishment of a complete compaction curve*. A representative sample according to a relevant standard (see section 4.7 of the IMSBC Code) of the test material is partially dried at a temperature of approximately 60°C or less to reduce the samples moisture to a suitable starting moisture, if needed. Note: no full drying for IOF samples are to be carried out. The total quantity of the test material should be at least three times as big as required for the complete test sequence. Compaction tests are executed for five to ten different moisture contents (five to ten separate tests). The samples are adjusted in order that partially dry to almost saturated samples are obtained. The required quantity per compaction test is about 2,000 cm^3.



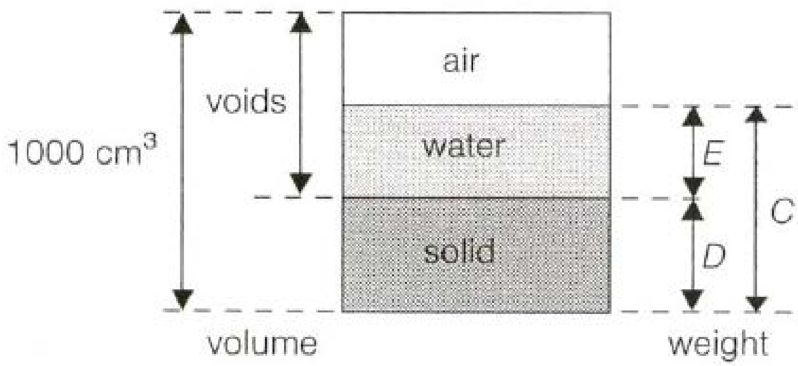


Figure 1.4.2

At each compaction test a suitable amount of water is added to the sample of the test material. The sample material is gently mixed before being allowed to rest and equilibrate. Approximately one fifth of the mixed sample is filled into the mould and levelled and then the increment is tamped uniformly over the surface of the increment. Tamping is executed as per the Proctor – Fagerberg method D, by dropping a 150g hammer 25 times through the guide pipe, 0.15 m each time. The performance is repeated for all five layers. When the last layer has been tamped the extension piece is removed and the sample is levelled off along the brim of the mould with care, ensuring to remove any large particles that may hinder levelling of the sample, replacing them with material contained in the extension piece and re-levelling. When the weight of the cylinder with the tamped sample has been determined, the cylinder is emptied, the sample is dried at 105°C as per ISO moisture determination standard for iron ore (ISO 3087) and the weight is determined. The test then is repeated for the other samples with different moisture contents.

.2 *Definitions and data for calculations (see figure 1.4.2)*

- empty cylinder, mass in grams: A

- cylinder with tamped sample, mass in grams: B

- wet sample, mass in grams: C

  C = B – A

- dry sample, mass in grams: D

- water, mass in grams (equivalent to volume in cm^3): E

  E = C – D

Volume of cylinder: 1000 cm^3

.3 *Calculation of main characteristics*

- density of solid material, g/cm^3 (t/m^3): d

- dry bulk density, g/cm^3 (t/m^3): γ

  $\gamma = D/1000$

- net water content, volume %: e_v

  $e_v = E/D \times 100 \times d$

- void ratio: e (volume of voids divided by volume of solids)

  $e = d/\gamma - 1$

- degree of saturation, percentage by volume: S

$S = e_v/e$

- gross water content, percentage by mass: W_1

$W_1 = E/C \times 100$

- net water content, percentage by mass: W

$W = E/D \times 100$

.4 *Presentation of the compaction tests*

For each compaction test the calculated void ratio (e) value is plotted as the ordinate in a diagram with net water content (e_v) and degree of saturation (S) as the respective abscissa parameters.

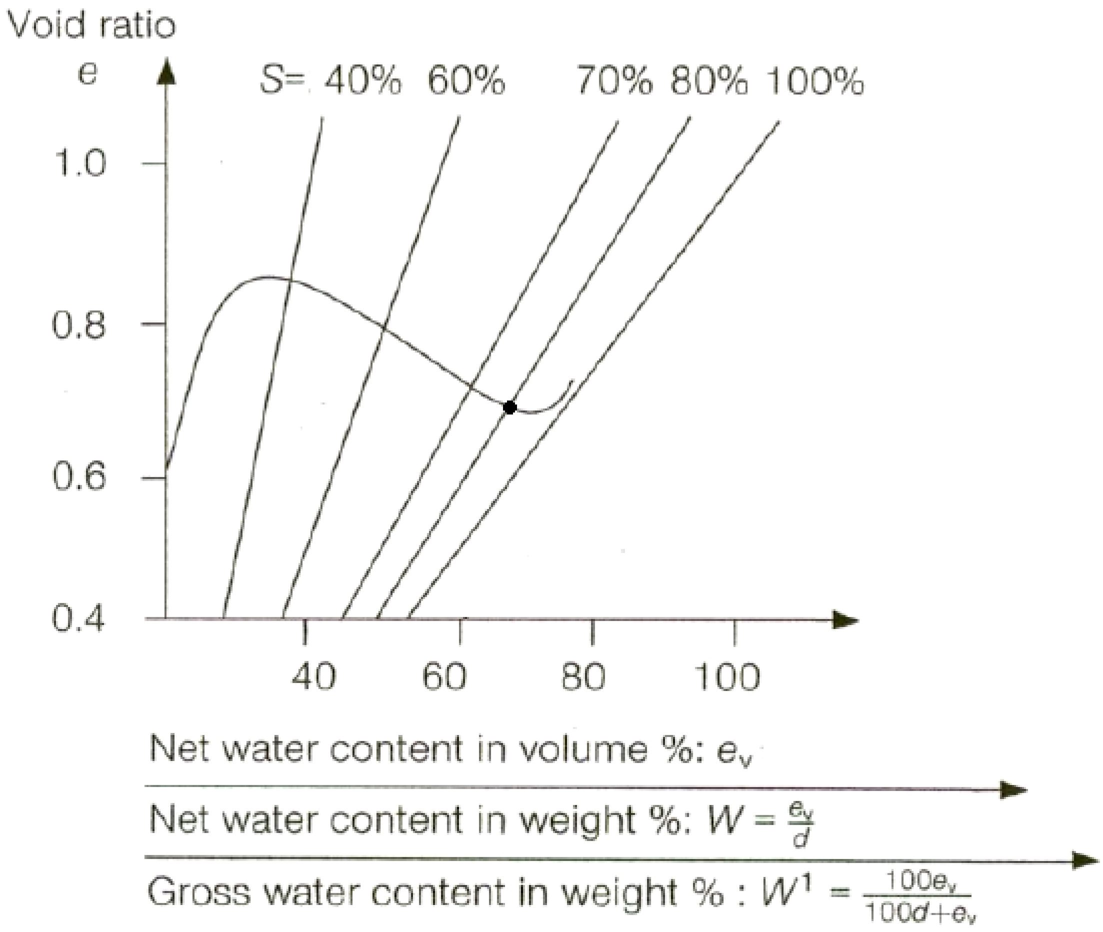


Figure 1.4.3

.5 *Compaction curve*

The test sequence results in a specific compaction curve (see figure 1.4.3).
The optimum moisture content (OMC) of IOF should occur above 90% saturation.

The critical moisture content is indicated by the intersection of the compaction curve and the line S = 80% degree of saturation. The transportable moisture limit (TML) is the critical moisture content.