The 56th International October Conference on Mining and Metallurgy
22-25 October 2025, Bor Lake, Bor, Serbia
www.ioc.tfbor.bg.ac.rs

DOI: 10.5937/IOC25211M

Original scientific paper

SAFETY CHALLENGES IN TRANSPORT OF COPPER CONCENTRATE: TML AS A BOUNDARY PARAMETER OF MARITIME CARGO STABILITY

Dušica Mirović[1a], Yuankun Yang[1b], Shengli Yu[1c]
[1] Serbia Zijin Mining doo Bor, Cvetna šuma, 19210 Bor, Serbia
[1a] dusica.mirovic@zijinmining.rs, 0009-0006-5149-7071
[1b] yang.yuankun@zijinmining.rs, 0009-0006-7701-7275
[1c] yu.shengli@zijinmining.rs, 0009-0001-8044-2022

Abstract
Transportable Moisture Limit (TML) is a boundary safety parameter in maritime transport of bulk cargoes. This paper integrates the IMSBC Code framework, laboratory methodologies, and experimental results for Serbia Zijin copper concentrates. Results show that TML is influenced primarily by sulfide content and mineral composition, while granulometry and flotation reagents have limited effects. A novel microstructural hypothesis is introduced, suggesting that inter-particle correlations, capillary forces, and surface energy significantly affect TML values. Preliminary indications also suggest potential for industrial application through surface modification approaches. Integrating standard IMSBC methods with micro-scale analysis may improve predictive accuracy and enhance maritime safety.

***Keywords**: TML, IMSBC Code, copper concentrate, sulfides, liquefaction, maritime safety*

1. INTRODUCTION

Copper concentrate export from Serbia Zijin exceeds 95% of production, mainly by sea. Ensuring safe transport requires strict control of cargo moisture. If the moisture exceeds TML, the concentrate may behave like a liquid under ship motions, producing free-surface effects and loss of stability [1].

Since 2021, winter shipments have repeatedly exceeded TML values due to rainfall during handling. Corrective actions such as re-blending, lime addition, or overturning of cargo in ports generate delays, economic losses, and safety risks.

2. WHAT IS TML AND WHY IT IS IMPORTANT

TML is defined as 90% of the Flow Moisture Point (FMP). Exceeding this limit can cause liquefaction, leading to catastrophic ship accidents. Historical incidents with nickel ore illustrate the consequences of improper TML determination [5].

In addition to defining the critical moisture threshold, TML also serves as a practical tool for risk management, since it provides ship operators and shippers with a measurable boundary parameter that must be respected during loading.

2.1 Fundamental mechanism of liquefaction (ISO N1166)

According to ISO N1166, a wet granular material consists of solid particles and voids filled with water and air. Under cyclic loading, particle rearrangement tends to reduce pore volume. If the voids are water-filled and drainage is restricted, pore pressure rises, leading to a potential loss of shear strength. This mechanism provides the physical foundation of liquefaction, directly linking moisture content, pore water pressure, and cargo instability. This mechanism is of particular importance in maritime transport, since cyclic ship motions continuously generate such pore pressure build-up.

3. IMSBC CODE: RULES AND SAFETY REQUIREMENTS

The International Maritime Solid Bulk Cargoes (IMSBC) Code governs safe transport. Copper concentrates fall into Group A cargoes (prone to liquefaction). Testing must be performed by accredited laboratories. Misjudgment of TML can determine the difference between safe voyage and disaster [1].

The Code also emphasizes the responsibility of shippers to provide accurate laboratory certificates, and of carriers to verify that the cargo complies with declared moisture limits.

3.1 Implications for Maritime Transport

Lower TML values directly increase liquefaction risks. Even a shipment loaded with 1% moisture above the TML threshold could destabilize a vessel in heavy seas. While ship design features (double hulls, drainage systems) provide mitigation, precise laboratory determination remains the most reliable safeguard.

Seasonal variations and precipitation during transport highlight the importance of continuous moisture monitoring and application of corrective measures.

4. LABORATORY METHODS FOR DETERMINING TML

Several laboratory methods are prescribed under the IMSBC Code to establish TML values:

- Flow Table Test: simulates cargo vibration to determine the Flow Moisture Point.
- Penetration Test: measures the depth at which moisture triggers collapse or flow.
- Proctor/Fagerberg Test: evaluates compaction, porosity, and density changes under applied load.
- Gravimetric Method: determines the actual water content of samples.

In this study, the Proctor/Fagerberg method was selected due to its higher accuracy for sulfide-rich concentrates [2]. The test involves controlled compaction of prepared samples while progressively increasing their moisture content. Measurements of bulk density and pore volume allow precise identification of the saturation threshold at which liquefaction becomes possible. This method is especially suitable for fine-grained concentrates, where micro-pores and sulfide minerals strongly affect water retention. In practice, the selection of method depends on cargo mineralogy, particle size distribution, and available laboratory capacity.

5. EXPERIMENTAL ANALYSIS

Three types of concentrates were analyzed: VK (coarser particles), direct-milled (medium particles), and flotation (finest particles). Multi-element and granulometric analyses were combined with TML measurements.

Table 1. Copper concentrates analysis results

Concentrate type	Granulometry	Main minerals	TML (%)
VK concentrate	Coarser	Chalcopyrite, pyrite, quartz, aluminosilicates	14.2
Direct-milled conc.	Medium	Covellite, tetra-chalcopyrite, pyrite, alunite	9.2
Flotation concentrate	Finest	Covellite, tetra-chalcopyrite, pyrite, alunite	7.7

The results revealed pronounced differences among the three concentrate types. The VK concentrate exhibited the highest TML value (14.2%), despite its relatively coarse texture. Direct-milled samples showed intermediate stability (9.2%), whereas flotation concentrate—although expected to yield higher TML values due to its finer granulometry—displayed the lowest value (7.7%).

Contrary to the expected trend, finer particle size did not result in higher TML values. Instead, mineralogical composition, particularly sulfide content, exerts a stronger influence. Higher sulfide content correlates with lower TML values, as observed in flotation and direct-milled concentrates. Granulometry showed only a limited effect, while flotation reagents had no significant impact on TML values. This suggests that surface chemistry and particle interactions play the dominant role [2,4].

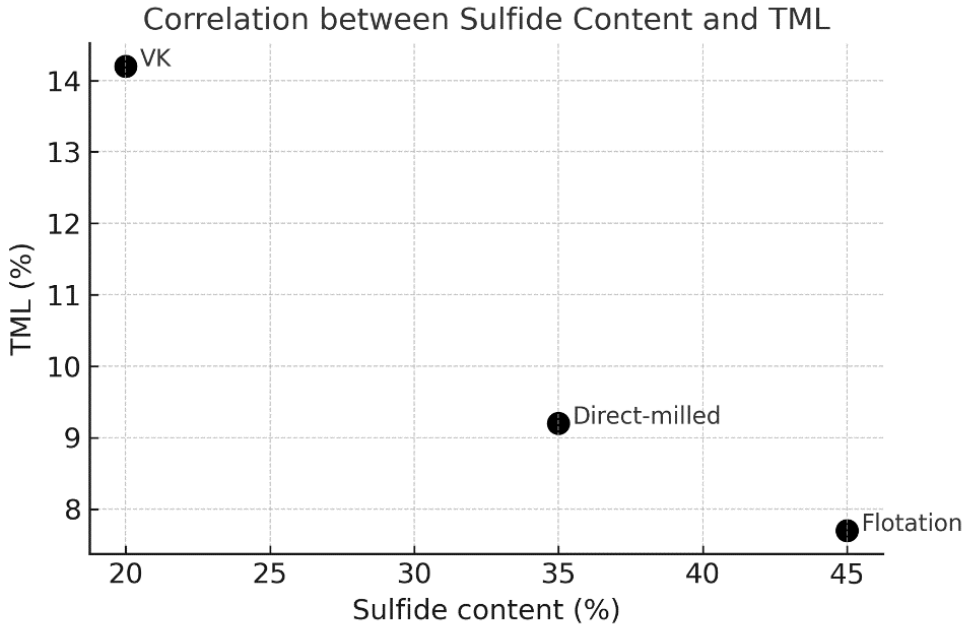

Figure 1. Correlation between sulfide content and TML values for VK, direct-milled, and flotation concentrates.

These findings provided the basis for developing a microstructural hypothesis: that inter-particle correlations, capillary forces, and surface energy effects—rather than granulometry alone—govern the moisture behavior of sulfide concentrates.

6. NEW THEORY: MICROSTRUCTURAL INTERACTIONS

Laboratory results indicate that TML is not simply a function of particle size or water content. Microstructural interactions between fine particles strongly influence the behavior of concentrates.

Aggregates of chalcopyrite and pyrite modify pore structures and capillary effects, reducing TML even for finer fractions.

Surface energy and capillary bridges between particles contribute to water retention in ways not detected by classical methods.

This explains why flotation concentrates, although finer, often display unexpectedly low TML values. Further work should apply SEM imaging, surface energy measurements, and computational modeling to validate these assumptions and improve predictive models [4].

7. CONCLUSION

This study showed that TML determination is shaped by particle size, mineral composition, and especially sulfide content. Experimental results confirmed that VK concentrate has the highest

TML (14.2%), direct-milled intermediate (9.2%), and flotation the lowest (7.7%). Sulfide minerals exert the strongest influence, while granulometry and flotation reagents have only limited effects.

Microstructural interactions—particle correlations, surface energy, and capillary effects—emerged as critical hidden factors. The most promising industrial approach is the addition of surface-active agents into concentrate mixing tanks, as this modifies particle interactions without disrupting current operations [3].

Integrating micro-scale analysis with IMSBC Code testing can improve predictive accuracy, reduce liquefaction risks, and enhance maritime safety.

Collaboration with research institutions is planned to further validate this method, with the goal of enabling industrial application.

ACKNOWLEDGEMENTS

The authors acknowledge Serbia Zijin Mining and partner institutions for support in experimental and analytical work.

REFERENCES

[1] IMO, International Maritime Solid Bulk Cargoes (IMSBC) Code, latest edition.
[2] J. Li, P. Zhang., Miner. Eng., 135 (2019) 25–34.
[3] A.S. Patra., Miner. Eng., 81 (2016) 62–69.
[4] M. Garshasb, R. Saulters., Physical and Mineralogical Impact of Copper Concentrate on Transportable Moisture Limit (TML), Canadian Institute of Mining, Metallurgy and Petroleum, 2019.
[5] IMO, Case studies of maritime accidents caused by cargo liquefaction, IMO Safety Reports.