

The Influence of Moisture Content on the Occurrence of Liquefaction During the Transport of Bulk Cargos by Ship

Jasmina Nešković #, Pavle Stjepanović, Klara Konc Janković,
Dejan Lazić, Veselin Anđelković

Mining Institute Ltd. Belgrade

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ABSTRACT

One of the most common methods for transporting large quantities of solid bulk cargo is by ship. This mode of transport involves certain risks because the cargo is loaded in bulk, without additional packaging. As a result, it can become further moistened by atmospheric precipitation, since ships are generally not covered. Moisture in the cargo is the most significant risk factor leading to liquefaction. Excessive moisture content in the cargo can cause liquefaction, which may result in the cargo shifting to one side of the ship, compromising the stability of the ship and in the worst case, causing it to capsize.

One of the most important safety measures for this mode of transport is controlling the permissible moisture limit (TML). By reducing the initial moisture content in the bulk cargo before loading - through drying or proper storage - the risk of liquefaction can be minimized or prevented.

In this paper, the critical (FMP) and permissible (TML) moisture content in a sample of fine-grained copper concentrate from Bor was determined using a standard method to ensure safe transport of bulk cargo by ship.

Test results for a copper concentrate sample, with an initial moisture content of 11.49 %, show that with the standard addition of water in increments of 0.4 % to 0.5 % per cycle, the obtained TML values are above the initial moisture content.

The concentrate is suitable for transport by ship with appropriate precautions.

1. Introduction

Ore concentrates and other fine-grained cargoes are most often transported by ships in bulk, without additional packaging in bags. This type of transport can be risky due to the possibility of cargo shifting inside the ship's hold (Ferreira et al., 2019).

The majority of solid bulk cargo carriers reach their

destination without incident; however, the number of overturned ships and lost human lives is not negligible. One of the main risks is liquefaction caused by excessive moisture in the fine-grained cargo, which is responsible for most of these disasters. In the past 15 years, there have been more than 30 incidents with human casualties on ships carrying bulk cargo (Ferreira et al., 2019; Kowalczyk and Gourvenec, 2025).

Corresponding author: jasmina.neskovic@ribeograd.ac.rs

The transport of bulk cargo by ship is regulated by the International Maritime Organization (IMO) through the International Maritime Solid Bulk Cargo Code (IMSBC Code). This code has been mandatory since 2011 under the SOLAS convention and it defines the Transferable Moisture Limit (TML) as a measure to reduce the risk of liquefaction for cargoes classified as Group A (Ferreira et al., 2019; Ferreira and Lima, 2023). The code classifies solid bulk cargoes into three groups: Group A includes liquefiable cargoes that may liquefy, Group B includes cargoes that present a chemical hazard, and Group C includes cargoes that are not prone to liquefaction and do not present a chemical hazard. The code specifies the characteristics of different types of cargo and the recommendations that should be applied for their safe handling and transport (Ferreira et al., 2019).

Liquefaction during the transport of bulk cargo by ship directly affects the stability of the vessel, leading to tilting and capsizing. Due to ship's motion, the cargo can shift in one direction but cannot return in the opposite direction with the same movement (Ferreira et al., 2019; Kowalczyk and Gourvenec, 2025; Ferreira and Lima, 2023; Zhao et al., 2025; Wu et al., 2025). Figure 1 shows the fine fraction of iron ore before and after liquefaction (Tugan and Colak, 2015).



Figure 1. Iron ore fines before and after liquefaction (Tugan and Colak, 2015).

Liquefaction is a hazardous process in which wet mineral cargo changes from a solid to a viscous, flowing liquid (Figure 2). Triggered by the cyclic motion of a ship

at sea, the cargo compacts, increasing internal water pressure until the solid particles lose friction and stability, posing severe risks to the vessel. The transformation of solid bulk cargo into a liquid slurry on board a ship can be divided into these primary stages (Ferreira et al., 2019):

- *Initial State:* Granular mineral cargoes remain stable due to the structural friction and pressure between individual solid particles.
- *Compaction and Vibration:* The continuous, cyclic motion of a ship at sea acts as dynamic stress, causing the loosely stacked cargo to compact and contract.
- *Pressure Build-Up:* As the cargo settles, it reduces the volume of empty spaces (voids) between the solid particles. If these spaces are saturated with water, the solid particles transfer their weight to the water.
- *Loss of Friction:* This transfer generates a surge in excess pore water pressure. As this pressure builds, it pushes the solid grains apart and reduces the internal friction (effective stress) holding the mass together.
- *Liquefaction:* When the pore water pressure equals the initial structural pressure of the particles, the material loses all shear strength. The grains become suspended in the water, and the cargo behaves like a heavy, viscous liquid (Ferreira et al., 2019).

Jianjun Wu, in his article, reports the results obtained by Shen, Wang, Popek, and Altun (Popek, 2010; Shen, 2012; Wang et al., 2016; Wu et al., 2020; Altun and Göller, 2013). Specifically, Shen discovered that the actual moisture content of the cargo must be less than the transportable moisture limit (TML) to prevent liquefaction. However, when it comes for bauxite with an initial moisture content lower than the TML, liquefaction can still occur during transport if there is a change in temperature and moisture (Shen, 2012; Wu et al., 2020).

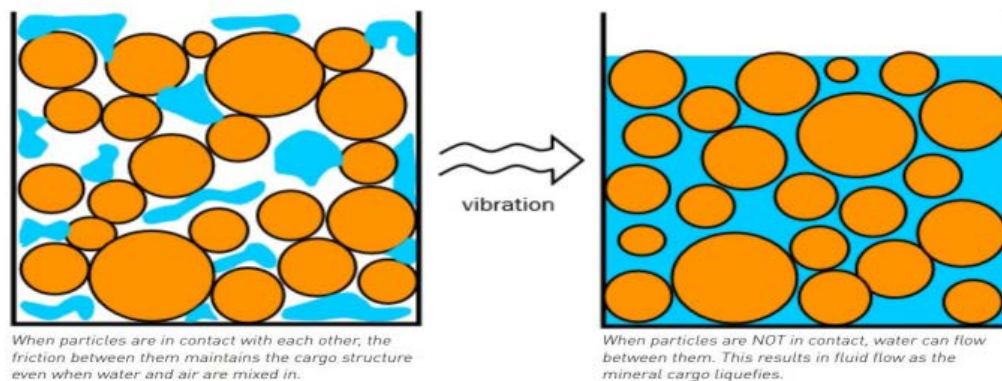


Figure 2. The occurrence of liquefaction (Bin Suhrab and Rodzi, 2021)

Wang concluded that saturation and compactness are key factors in measuring the degree of liquefaction. Higher moisture content or saturation increases the risk of liquefaction, and it is crucial to prevent any additional increase in moisture content during loading and transportation by ship (Wang et al., 2016; Wu et al., 2020). Furthermore, Popek proposed using biodegradable thermoplastic polymer material as an addition to the concentrate, which would absorb moisture from the granular pores and prevent the flow of the concentrate during transport (Popek, 2005; Popek, 2010; Wu et al., 2020). Altun advanced this research by adding chemical auxiliaries to the filtration process, achieving a 10 % - 15 % reduction in moisture content from the TML in various mineral concentrates (Altun and Göller, 2013; Wu et al., 2020). Most researchers in this field conclude that the cargo's resistance to liquefaction during transport can be increased by reducing the initial moisture content below the prescribed limit, which also accounts for unpredictable factors, such as hydrometeorological conditions (Wu et al., 2020).

In addition to liquefaction, accidents during the transport of fine-grained cargoes are influenced by several other factors, and their recognition and monitoring are essential (Wu et al., 2020):

Seawater intrusion: Wave overflow during storms causes water to penetrate the holds, directly increasing the moisture content of the cargo and endangering navigational safety (Wu et al., 2020).

Aerodynamic and hydrodynamic forces: Wind directly reduces speed and increases heel angle (Montewka et al., 2015), while stochastic waves in the open sea cause extreme rolling, which can lead to capsizing (Wang and Tan, 2010; Ren et al., 2014).

Loss of static stability: The initial displacement of cargo after liquefaction, combined with pitching moments from wind and wave action, results in loss of stability and capsizing (Zhao and Meng, 2012).

Kinematics and acceleration: Ship acceleration and wave kinematics directly affect the internal stability of the cargo (Holmes et al., 2016).

Structural and mechanical vibrations: Hull vibrations caused by rolling and operation of the propulsion system, not only threaten the structural integrity of the ship (Ding, 2017) but also alter the rheological properties of the cargo (Munro and Mohajerani, 2016), which further intensifies the liquefaction process (Drzewieniecka, 2014).

Previous research on liquefaction remains insufficient, despite significant interest from researchers. To the author's knowledge, copper concentrates have not yet

been tested, although coal, aluminum, iron, and nickel concentrates have been studied.

2. Materials and methods

The sample used in this study is a copper ore concentrate obtained after the flotation and filtration process from Bor. The copper content in the sample was 10 %.

2.1. Testing methods

The procedure for determining the maximum allowable moisture (TML) involves first measuring the initial moisture level in the sample, followed by a moisture flow point (FMP) test according to the recommended methods of the international IMSBC Code (ASTM C230 / C230M - 13, 2013, IMSBC Code 2023).

The initial moisture in the sample was calculated by measuring the mass of the sample before and after drying in an oven (Tomanec, 2000).

The standard "Flow Table" method (ASTM C230 / C230M - 13, 2013) was used to determine the FMP (flow moisture point) of the copper ore concentrate sample. The equipment used is shown in Figure 3. This method applies to solid bulk cargoes with a particle size of less than 1 mm intended for transport by ship. The aim of the test is to determine the cone diameter after 50 impacts, as this parameter directly depends on the change in moisture content in the sample (ASTM C230 / C230M - 13, 2013; IMSBC Code 2023).



Figure 3. Laboratory mixer and "Flow Table"

2.2. Sample preparation

After determining the initial moisture content in the sample, two groups of experiments are performed:

- The first group (preliminary test) identifies the location of the Flow Moisture Point (FMP) and indicates how much water should be added to determine the FMP. Water is added in increments of approximately 0.4 % to 0.5 % of the total sample mass per cycle.

- The second group (main test) begins with sample whose moisture content is set to about 2 % below the FMP. The procedure is the same as in the first group, but water is added in amounts 50 % smaller per cycle to achieve a more accurate FMP determination.

The experiment is conducted as follows:

First step: A representative sample of the tested material is placed in a mixing bowl and thoroughly mixed with a laboratory mixer. Three sub-samples, A, B, and C, are separated from the container after mixing. Sample A is immediately weighed and placed in an oven to determine its moisture content. Sample B is used for the preliminary FMP test, while sample C is used for the main FMP determination.

Second step: Filling the mold. The mold is placed in the center of the "Flow Table" and filled in three stages with material from the mixing bowl. After tamping, the first charge should fill the mold to approximately one-third of its depth. After compaction, the second charge should fill the mold to about two-thirds of its depth, and the third and final charge should reach a height just below the top of the mold. The objective of compaction is to achieve a degree of compaction similar to that at the bottom of a ship's load of the tested material. The compaction pressure can be determined by calculation or by using the values specified in the standard (ASTM C230 / C230M - 13, 2013, IMSBC Code 2023).

The number of tamping operations (applying accurate, steady pressure each time) should be about 35 for the bottom layer, 25 for the middle layer, and 20 for the top layer, gradually tamping across the surface to the edges of the mold to achieve an evenly flat surface for each layer.

Third step: Removing the mold. After filling, the mold is tapped on the side with a wooden object until the sample is loosened. The mold is then carefully removed, leaving the sample in the form of a truncated cone on the "Flow Table" (ASTM C230 / C230M - 13, 2013, IMSBC Code 2023).

2.3. Preliminary test

Immediately after removing the mold, 50 shakes are performed at a height of 12.5 mm and a rate of 25 times per minute. If the material has moisture below the FMP, it typically crumbles and separates into fragments with successive drops of the "Flow Table". In this cycle, the "Flow Table" is stopped, all the material is weighed, and then returned to the mixing vessel. Next, 0.5 % water by mass of the sample is added and thoroughly mixed in a laboratory mixer, and the process is repeated. If the flow state does not develop, the process is repeated with further additions of water until the flow state is reached (ASTM C230 / C230M - 13, 2013, IMSBC Code 2023).

Flow state recognition

The impact action of the "Flow Table" causes the grains to rearrange and compact the mass. As a result, the fixed volume of moisture in the material at any level increases as a percentage of the total volume. The flow state is considered reached when the moisture content and compaction of the sample produce a level of saturation that allows plastic deformation. At this stage, the molded sides of the sample can be deformed, resulting in a convex or concave profile.

With repeated action of the "Flow Table", the sample continues to fall and flow out. A template that, for example, indicates an increase in diameter of up to 3 mm in any part of the cone is a useful guide for this purpose. When the increased moisture content approaches the FMP, the sample cone begins to show a tendency to stick to the mold. Additionally, when the sample is pushed off the table, it may leave traces (streaks) of moisture on the table. If such streaks are observed, the moisture content may be above the FMP; however, the absence of streaks does not necessarily indicate that it is below the FMP (ASTM C230 / C230M - 13, 2013, IMSBC Code 2023).

The diameter of the cone, at the base or at half height, is recorded. By adding water in increments of 0.4 % to 0.5 % for each subsequent cycle and applying 25 "Flow Table" shocks, the first increase in diameter will be between 1 and 5 mm. With further increases in water content, the base diameter will expand by 5 to 10 mm when the test is considered complete. After the test, a diagram is drawn showing the increase in the diameter of the sample at the base in relation to the moisture content. A straight line drawn through the two points will intersect the moisture content axis near the FMP.

After the FMP (Flow Moisture Point) value is determined, the TML (Transportable Moisture Limit) is calculated using the formula (ASTM C230 / C230M - 13, 2013, IMSBC Code 2023):

$$TMP = FMP \cdot 0.9 \quad (1)$$

2.4. Main test

After the first round of FMP testing is completed, the main test sample is adjusted to the required moisture content level, approximately 1 % to 2 % below the liquefaction point determined in the initial tests. This is recommended to avoid starting the main examination too close to the FMP. The final test is then performed on this adjusted sample in the same manner as the preliminary test, but in this case with the addition of water in increments of no more than 0.5 % by weight of the test material. If the "initial" FMP is lower, the smaller increments of water addition should be used. After each stage, the entire sample is weighed immediately and the sample are separated for moisture measurement. This is necessary if the sample has flowed or if the next slightly

wetter sample is flowing. If not needed, it can be returned to the mixing bowl.

When the flow state is reached, the moisture content should be determined on two samples, one with a moisture content just above the FMP and one with a moisture content just below the FMP. The difference between these two values should be 0.5 % or less, and the FMP is taken as the mean of these two values.

3. Results and discussion

In a representative sample of copper concentrate from Bor, an initial moisture content of 11.49 % was determined using the previously described method.

For the initial test and a rough determination of the onset of liquefaction, two measurements with recorded plastic deformations on the sample are sufficient. This sample was separated from the series of measurements and is presented in this paper. The same procedure was used for the main test.

3.1. Preliminary test results

Figure 4 shows the process of the preliminary experiment with the initial sample. Figures 4a and 4b show the mold being filled in layers. Figure 4c shows a sample with the initial moisture content that has been removed from the mold and is ready to begin the preliminary test. Figure 4d shows the appearance of the sample after 50 shakes on the "Flow Table". No plastic deformation is present - the specimen has fractured.

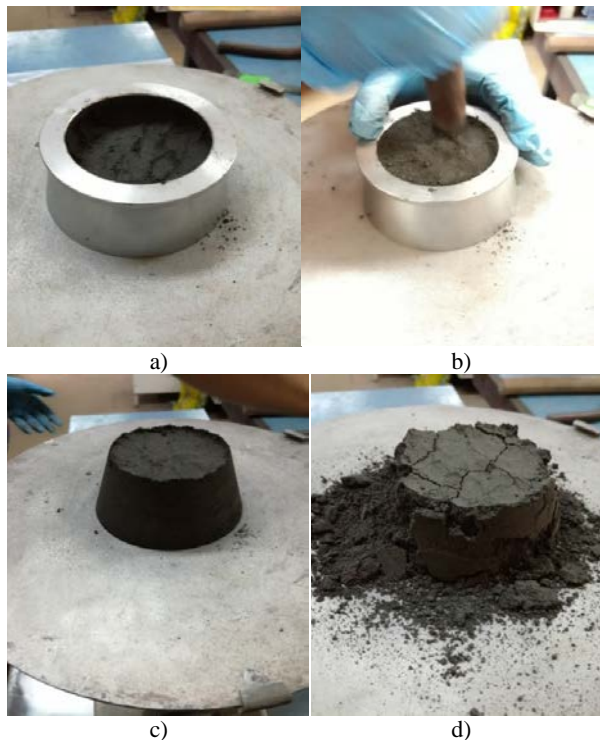


Figure 4. Flow of the preliminary test

Water was gradually added to the sample in 0.5 % increments. When the water content reached 4 % of the total sample mass, a distortion was observed, characterized by a decrease in height and an increase in bottom diameter, as shown in Figure 5. Figure 5a shows sample after removal from the mold, while Figures 5b and 5c show the changes in the sample after stress and strain measurements.

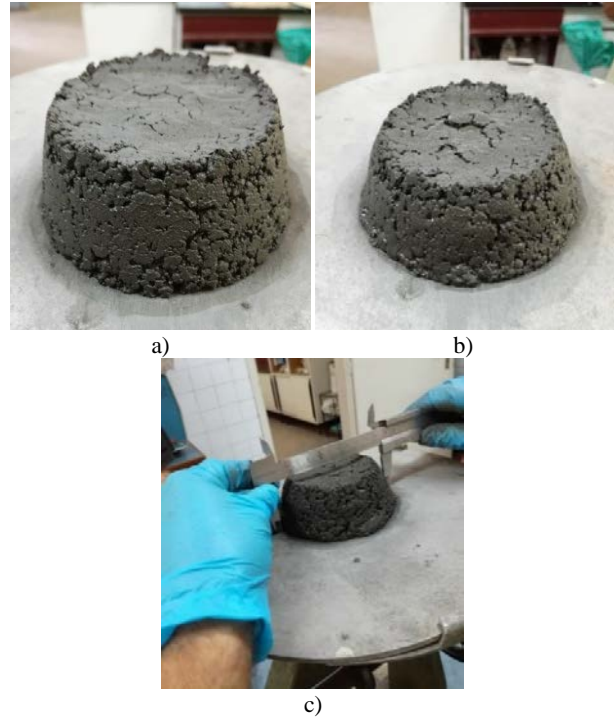


Figure 5. Preliminary test flow of the sample to which 4 % water was added

The gradual addition of water in 0.5 % increments continued. When the water content reached 5 % of the total sample mass, greater plastic deformation was observed, indicated by a decrease in height and an increase in bottom diameter, as shown in Figure 6. Figure 6a shows the sample after homogenization in a laboratory mixer. Figure 6b shows the mold with the sample after filling. Figure 6c shows the sample after removal from the mold, and Figure 6d shows the measurement of the bottom diameter after shaking and distortion.

The results from the cycles in which changes in the sample diameter were recorded are shown in Table 1.

Table 1
Measured moisture values and changes in diameter for the examined sample in the preliminary test

Parameter/Preliminary test	Moisture W (%)	Change in diameter R (mm)
Cycle 1 (added 4 % H ₂ O)	14.76	11.2
Cycle 2 (added 5 % H ₂ O)	16.00	23.4

Based on the obtained values, a diagram was drawn (Figure 7) from which the FMP point can be identified.

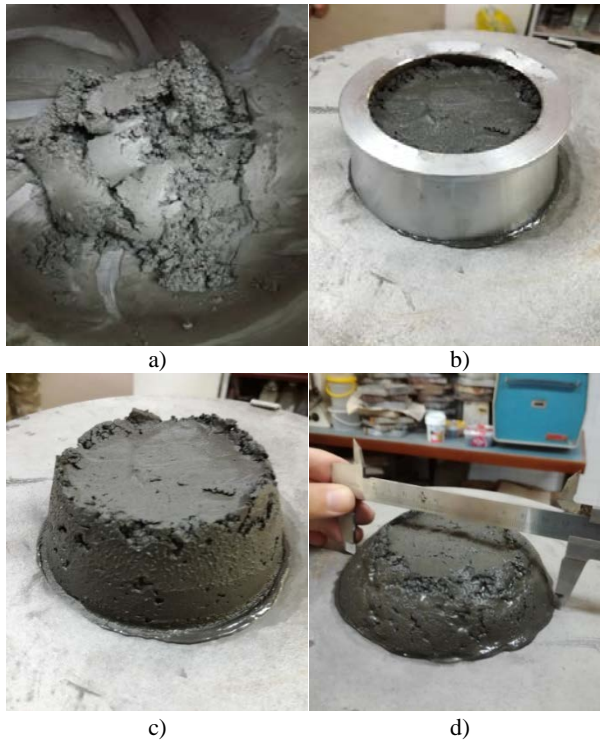


Figure 6. Preliminary test flow of the sample to which 5 % water was added

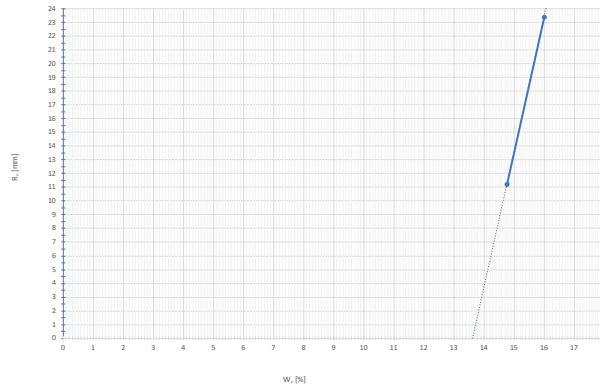


Figure 7. FMP diagram for the test sample - preliminary test

The value of FMP (Flow Moisture Point) was read from the diagram as 13.60 %. The value of TML (Transportable Moisture Limit) was then calculated as follows:

$$TML = 0.9 \cdot FMP = 12.24 \% \quad (2)$$

3.2. Main test results

In the first main test, 4 % water was added. After the test, slight distortion of the sample was observed. Figure 8a shows the sample before the test, while Figure 8b shows the diameter measurement on the deformed sample after the test.

In the second main test, with the addition of 4.5 %

water, greater plastic deformation was observed as a decrease in height and an increase in bottom diameter, as shown in Figure 9. Figure 9a shows the sample after removal from the mold, and Figure 9b shows the measurement of the bottom diameter after stressing and deformation.

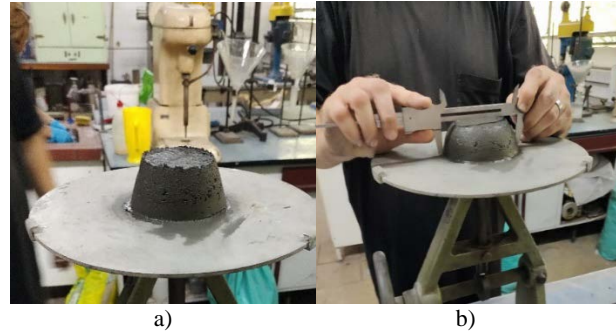


Figure 8. Flow of the main test sample to which 4 % water was added

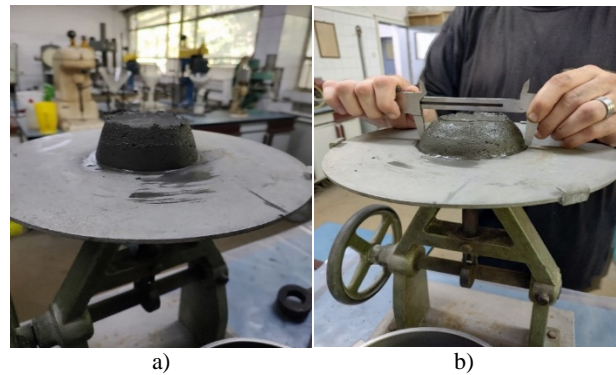


Figure 9. Flow of the main test sample to which 4.5 % water was added

The results from the main test for changes in the sample diameter are shown in Table 2.

Table 2

Measured values of moisture and changes in diameter for the main test sample

Parameter/Preliminary test	Moisture W (%)	Change in diameter R (mm)
Cycle 1 (added 4 % H ₂ O)	14.33	8.4
Cycle 2 (added 4.5 % H ₂ O)	14.89	14.3

Based on these values, a diagram was created (Figure 10) from which the FMP point can be determined.

The FMP (Flow Moisture Point) value was read from the diagram as 13.52 %. The TML (Transportable Moisture Limit) value was then calculated as follows:

$$TML = 0.9 \cdot FMP = 12.7 \quad (3)$$

The variance between the TML values for copper concentrate in the preliminary test (12.24 %) and the main test (12.17 %) is marginal (0.07 %). This minimal deviation confirms the high repeatability and technical

reliability of the testing procedure. The critical concern is not the variance between the two tests, but that the actual moisture content for copper concentrate is only 0.68 % - 0.75 % below the allowable TML. In industrial practice, this indicates that the cargo (copper concentrate) is on the verge of instability.

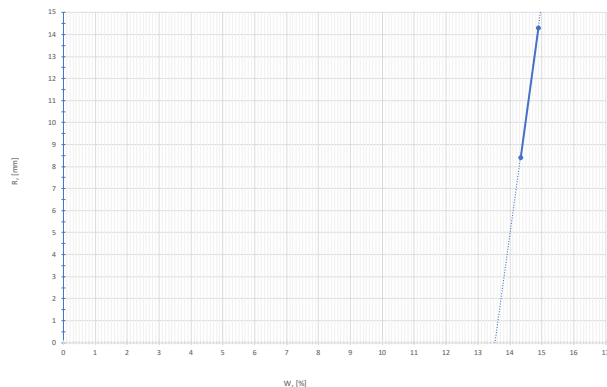


Figure 10. FMP diagram for the tested sample - the main test

According to the International Maritime Solid Bulk Cargoes (IMSBC) Code, copper concentrate is classified as a Group A cargo (cargoes that may liquefy). International maritime regulations strictly prohibit the loading of Group A cargoes if their actual moisture content exceeds the TML. While this specific cargo (copper concentrate) legally complies with the rule, the safety buffer is significantly tighter than standard industry recommendations.

Copper concentrate must not be left exposed to weather elements without protection before loading onto a ship. Even minimal summer rain or high moisture during rail or truck transit can raise the moisture content by more than the critical 0.68 %, making the cargo (copper concentrate) automatically unsafe for loading onto a ship.

These findings indicate that the mine's filtration plant must operate at maximum efficiency to further reduce the initial moisture level and establish a more robust safety margin.

4. Conclusion

In this study, the Transportable Moisture Limit (TML) for the copper concentrate obtained in the preliminary test is 12.24 %, which is 0.75 % higher than the initial moisture content. The TML value from the main test is 12.17 %, or 0.68 % above the initial moisture content.

For the overall safety assessment, the actual moisture content of the cargo is less than 1 % below its Transportable Moisture Limit (TML), placing this material in a high-risk category for logistical management. Under the IMSBC Code, the cargo technically meets the legal criteria for maritime transport; however, this minimal safety margin allows no room for operational error. Any exposure to precipitation during

open storage or inland transit could easily increase the moisture content beyond the critical TML threshold. Therefore, mandatory, continuous moisture monitoring of copper concentrate immediately before and during loading into the ship's holds is highly recommended.

Further research should focus on monitoring other material parameters and risk factors that affect transport.

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Uticaj sadržaja vlage na pojavu likvefacije tokom transporta rasutih materijala brodom

Jasmina Nešković #, Pavle Stjepanović, Klara Konc Janković,
Dejan Lazić, Veselin Anđelković

Rudarski Institut d.o.o. Beograd

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IZVOD

Jedan od najčešće korišćenih načina transporta velikih količina čvrstog rasutog tereta jeste pomorski transport. Ovakav vid transporta nosi sa sobom određene rizike jer je materijal koji se tovari na brod u rasutom stanju, bez dodatne ambalaže. Usled izloženosti atmosferskim padavinama, teret može dodatno da se ovlaži, naročito kada se prevoz obavlja na brodovima sa otvorenim skladišnim prostorima. Upravo je vlaga u materijalu najvažniji faktor rizika koji dovodi do pojave utečnjavanja (likvefacije). Naime, povećan sadržaj vlage u transportovanom materijalu može izazvati pomeranje tereta ka jednoj strani broda, čime se narušava stabilnost broda, a u najgorem slučaju može dovesti do prevrtanja broda.

Jedna od najvažnijih mera bezbednosti u pomorskom transportu rasutih tereta jeste kontrola dozvoljenog sadržaja vlage (TML). Smanjenjem početnog sadržaja vlage u rasutom teretu pre utovara na brod sušenjem ili adekvatnim skladištenjem, rizik likvefacije se svodi na minimum, odnosno može da se spreči. U ovom radu je standardnom metodom određen kritični (FMP) i dozvoljeni (TML) sadržaj vlage u uzorku sitnozrnog koncentrata bakra iz Bora, radi procene njegove pogodnosti za bezbedan pomorski transport.

Rezultati ispitivanja uzorka koncentrata bakra, sa početnim sadržajem vlage od 11,49 %, pokazuju da su pri standardnom dodavanju vode u koracima od 0,4 % do 0,5 % po ciklusu, dobijene TML vrednosti iznad početnog sadržaja vlage. Na osnovu dobijenih rezultata zaključeno je da je koncentrat pogodan za transport brodom, uz primenu odgovarajućih mera predostrožnosti.