



Evaluation of the Effect of Molasses on Compressive Strength and Water Absorption of Cement-Gold Mill Tailings-Sand Mixture

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ABSTRACT

This study investigates the effect of molasses as a natural admixture on the compressive strength and water absorption of a cementitious mix incorporating gold mill tailings (GMT) and sand. A constant mix ratio of 30% cement, 40% GMT, and 30% sand by weight was used, with molasses incorporated at varying dosages (0%, 1.5%, 2.0%, and 2.5% by total solid mass). The resulting mortar samples were evaluated for compressive strength and water absorption at 7, 14, and 28 days of curing. The results showed that a 1.5% molasses dosage produced the highest 28-day compressive strength (15.83 MPa), representing a 101% increase over the control mix (7.87MPa). The 1.5% molasses dosage also achieved the lowest water absorption (7.2%), which was 19% lower than that of the control mix (8.9%). In contrast, higher molasses levels (2.5%) resulted in reduced performance, likely because excess sugar interfered with cement hydration. Analysis of variance revealed that molasses dosage and curing age had a statistically significant effect on compressive strength ($p < 0.01$), while no significant difference was found for water absorption. These findings highlight the potential of combining GMT and molasses to produce sustainable, low-cost cementitious materials for non-structural applications, such as masonry blocks. The use of molasses not only improves performance but also offers a viable alternative to synthetic admixtures, supporting circular economy and waste valorization goals. Further research is warranted to evaluate long-term durability and environmental safety for practical applications.

INTRODUCTION

Gold mill tailings (GMT) are abundant residual wastes generated after gold ore processing. Each year, tens of billions of metric tons (MT) of mill tailings are produced worldwide, and these are often stored in impoundments that pose environmental risks. (Edraki et al. 2014, Hudson-Edwards et al. 2011, Vallero & Blight 2019). In the Caraga region, it is estimated that approximately 500,000 metric tons (MT) of gold ore is processed annually. (Mines and Geosciences Bureau (Philippines) 2024), which corresponds to the amount of waste generated because of the very small amount of gold recovered for every ton of ore processed (approximately 5 g/ton).

The utilization of tailings for construction materials is viewed as an alternative pathway to reduce the amount of waste in storage facilities and eventually mitigate the hazards associated with GMT (Binnemans et al. 2015, Korhonen et al. 2018, Mandpe et al. 2023). In particular, the use of tailings as fine aggregates or even as reactive precursors has been widely studied (Aseniero et al. 2018, Ikotun et al. 2024, Preethi et al. 2017, Roy et al. 2007, Wei et al. 2021). Recent reviews note that mine tailings can serve as partial sand substitutes in cement-based concretes or as inputs to alkali-activated binders (geopolymers) (Aseniero et al. 2018, Balegamire et al. 2022., Ikotun et al. 2024). These studies demonstrate the technical viability of tailings recycling in the construction industry. However, the addition of GMT to concrete generally reduces its compressive strength, and the results are not



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comparable to those of concrete–sand mixtures (Balbin et al. 2024).

Meanwhile, the demand for cementitious materials places a heavy burden on the environment. The global construction sector consumes over 50 billion metric tons of sand annually (UNEP 2014), and many sources are threatened by over-extraction. Conventional Portland cement production contributes approximately 8% of global carbon dioxide emissions (Scrivener et al. 2018). These facts motivate sustainable alternatives. Natural admixtures derived from agricultural by-products are of great interest because they are inexpensive and eco-friendly (Akar & Canbaz 2016, Vignesh et al. 2015). For example, sugarcane derivatives (molasses) have been studied as cement retarders or plasticizers (Akar & Canbaz 2016). Jumadurdiyev et al. (2004) demonstrated that adding beet molasses to concrete increased the strength of the concrete at all ages (Jumadurdiyev et al. 2004). These studies highlight that small doses of sugar-rich admixtures can improve mechanical performance.

In the Philippines, sugar mills and small-scale miners produce vast quantities of molasses (a viscous sugar by-product) and gold mill tailings (GMT), respectively. Both pose disposal challenges. Some local hollow-block makers add molasses to improve strength; however, no rigorous study has quantified its effects in a GMT-cement mixture. The present research investigates whether blackstrap molasses can enhance the performance of a cement-GMT-sand composite. Using a controlled mix (30% cement, 40% GMT, 30% sand by weight) (Balbin et al. 2024), the amount of molasses was varied from 0 (control mix), 1.5%, 2.0%, and 2.5%, and the compressive strength and water absorption were tested after 7, 14, and 28 days. This study aims to: (1) evaluate the effect of molasses incorporation into a cement-GMT-sand mixture on the compressive strength and water absorption of the composite, (2) determine the amount of molasses dosage that gives the best results for compressive strength and water absorption, and (3) compare the experimental results with findings from related studies utilizing natural admixtures and tailings-based concrete.

This work is significant since it targets to combine two waste materials, gold mill tailings and molasses, in a cementitious product, linking waste valorization with green admixture technology. Incorporation of molasses is expected to improve the workability and later-age strength of concrete (Aseniero et al. 2018, Ikotun et al. 2024). Moreover, the potential utilization of both molasses and GMT can help reduce the volume of waste requiring storage, particularly in the Caraga region, where artisanal and small-scale gold mining is a flourishing industry.

MATERIALS AND METHODS

Raw Materials

The GMT used in this study was collected from an artisanal and small-scale gold-processing (ASGM) site located in Rosario, Agusan del Sur, Philippines (coordinates: 8°58'N, 125°58'E). These tailings, a by-product of the cyanide and amalgamation processes commonly employed in ASGM operations, were gathered from existing tailings piles within the vicinity of the processing facility. To ensure consistency and minimize moisture-induced variability during testing, the GMT samples were oven-dried at 105 °C until a constant weight was achieved, in accordance with standard drying procedures for mineral aggregates. (Amacher & Brown 2000).

Commercially available river sand was used as the fine aggregate and ordinary Portland cement (OPC) as the binder to prepare the concrete mixtures. Both materials were procured from a local construction supplier. Blackstrap molasses, an organic admixture, was sourced from a local hollow-block maker. Tap water, drawn from the municipal supply network, was used throughout the mixing and curing processes.

The selection of these locally sourced materials aligns with the study's goal of developing economical and regionally accessible construction solutions, particularly for application in rural and mining-affected communities. Furthermore, using indigenous materials, such as GMT and molasses, supports the principles of waste valorization, circular economy, and sustainable construction.

Material Characterization

To assess the suitability of gold mine tailings (GMT) as a partial replacement for fine aggregates in concrete mixtures, two primary characterization methods were employed: particle size analysis and elemental composition analysis.

Sieve analysis was conducted on the GMT to determine its particle size distribution. This analysis is critical for evaluating the grading and classification of the material (ASTM, n.d.). The particle size distribution provides insights into the fineness, uniformity, and potential packing density of the tailings when used in cementitious mixes. Fine particles typically influence the workability, water demand, and strength development of concrete (Mindess et al. 2002, Neville, 1995). To complement the physical characterization, the GMT underwent elemental analysis using X-ray fluorescence (XRF) spectroscopy (Amacher & Brown 2000). This non-destructive analytical technique provides a quantitative understanding of the major and trace elements present in the tailings.

Mix Design

Following Balbin et al. (2024), all mortar mixes were prepared using a fixed cement:GMT:sand weight ratio of 30:40:30. This was done to evaluate the effect of a higher GMT content than that of sand on the compressive strength. A constant water-to-cement ratio of 0.5 was maintained for all mixes. Molasses, serving as a liquid admixture, was added at four dosage levels i.e., 0%, 1.5%, 2.0%, and 2.5%- based on the total solid mass (cement + GMT + sand). These mixtures were designated as MOL-0, MOL-1.5, MOL-2.0, and MOL-2.5, respectively. A full factorial design of experiments was employed, considering molasses content (0, 1.5%, 2.0%, and 2.5%) and curing age (7, 14, and 28 days) as the independent variables.

Mixing and Specimen Preparation

The concrete mixture was prepared following the standard procedures outlined in ASTM C305 to ensure consistency. Initially, the dry components, including cement, gold mine tailings (GMT), and commercially available sand, were thoroughly mixed to achieve a uniform distribution of materials (Almeida et al. 2020). After the dry components were adequately blended, a solution of molasses dissolved in water was gradually added. The amount of water was maintained at a water-cement ratio of 0.5 throughout all the mixes. Continuous stirring was maintained to ensure homogeneity and to prevent the formation of lumps.

Once the desired consistency was obtained, the fresh concrete was carefully placed into 100 mm × 100 mm × 100 mm molds. Manual compaction was performed to eliminate entrapped air and ensure proper consolidation of the mixture. This procedure was consistently applied to all test specimens to maintain the reliability and comparability of the experimental results.

The curing conditions were room temperature ranging from 25 to 30°C and humidity of 70-85%.

Limitations

TCLP is considered to be an important part of this evaluation. However, a previous study by Balbin et al. (2024) on cement-GMT-sand mixes showed that hazardous elements present in the GMT, such as lead and mercury, were immobilized. The results also showed that it is non-reactive and non-corrosive (Balbin et al. 2024).

It is also worth noting that the sugar content of the molasses was not quantified in this study, which represents a limitation and a potential variable affecting the consistency and performance of the final mixture.

Testing and Data Analysis

At each test age (7, 14, and 28 days), the samples were subjected to compressive strength testing according to ASTM A55. For each mix and age, three specimens were tested. Water absorption was measured on samples after 7 and 21 days of water curing (according to ASTM C642): the specimens were oven-dried, weighed (M1), then submerged in water for 48 h, dried with a cloth to remove water droplets, and weighed again (M2). Water absorption was calculated as follows:

$$\text{Water Absorption, \%} = \frac{M2 - M1}{M1} \times 100\%$$

All data were processed statistically using ANOVA and Tukey HSD, and are presented in tables, bar graphs, or plots.

RESULTS AND DISCUSSION

Material Characterization

Particle size analysis, as presented in Table 1, reveals that approximately 90% of the GMT passed through a 200- μm (No. 75) sieve, which corresponds to the typical grind size used in gold ore processing operations. This particle size distribution classifies the material predominantly as fine sand to silt or clay, according to the Unified Soil Classification System (USCS). The fine nature of GMT presents both opportunities and challenges when incorporated into cementitious systems.

From a concrete performance perspective, finer particles generally lead to a higher surface area, which in turn increases water demand and cement paste requirements to achieve proper coating and bonding of particles (Mindess et al. 2002, Neville, 1995). Consequently, concrete made with very fine aggregates, such as GMT, often exhibits lower compressive strength unless compensated with a higher cement content or the inclusion of admixtures to improve workability and cohesion (Mehta & Monteiro, n.d.).

Table 1: Particle size distribution of GMT.

| Mesh No. | Nominal Sieve Opening [mm] | Weight Retained [g] | Retained [%] | Passing [%] |
|----------|----------------------------|---------------------|--------------|-------------|
| 40 | 0.425 | 78.0 | 5.9 | 94.1 |
| 60 | 0.250 | 44.6 | 3.4 | 90.7 |
| 70 | 0.212 | 7.0 | 0.5 | 90.2 |
| 100 | 0.150 | 91.4 | 6.9 | 83.3 |
| 200 | 0.075 | 549.5 | 41.5 | 41.9 |
| 325 | 0.045 | 324.7 | 24.5 | 17.4 |
| 400 | 0.038 | 50.3 | 3.8 | 13.6 |
| PAN | | 179.8 | 13.6 | |

Table 2: Elemental Composition of GMT by XRF (n=3).

| Element | Average [%] | Element | Average [ppm] |
|---------|-------------|---------|---------------|
| Si | 34.01 | Cr | 69.33 |
| Al | 1.15 | Mg | 63.33 |
| Fe | 5.05 | Au | 2.67 |
| Ca | 0.51 | Hg | 8.67 |
| K | 0.42 | Pb | 57.33 |
| S | 0.23 | - | - |

Without such modifications, the mix may suffer from poor compaction and increased porosity, which can adversely affect both strength and durability (Mehta & Monteiro, n.d.).

X-ray fluorescence (XRF) analysis of the gold mill tailings (GMT, Table 2) revealed that the material is predominantly siliceous, with silicon (Si) comprising 34.01% of the total composition. This high silica content suggests that the GMT primarily comprises quartz or silicate minerals, which aligns with the typical residual mineralogy from gold ore processing. The abundance of silica makes the material suitable as a partial fine aggregate replacement in cementitious systems, contributing to the packing density and dimensional stability (Mehta & Monteiro, n.d.). Notably, gold (Au) was detected at 2.67 ppm, indicating inefficient recovery in the ore processing stage and suggesting that the tailings may still hold residual economic value for metal recovery. Other major components include aluminum (Al, 1.15%) and iron (Fe, 5.05%), which are common in aluminosilicate and iron oxide minerals, respectively. Although aluminum may slightly contribute to pozzolanic activity, the GMT is largely inert and non-cementitious.

Elements, such as potassium (K, 0.42%) and sulfur (S, 0.23%), were also detected. Low sulfur content is advantageous, as it reduces the risk of sulfate-related durability issues in concrete (Mindess et al. 2002). However, long storage of GMT may drive acid mine drainage (AMD)

problems, as S readily reacts with water and oxygen to form sulfuric acid. The sample also contained trace metals, including chromium (Cr, 69.33 ppm), magnesium (Mg, 63.33 ppm), mercury (Hg, 8.67 ppm), and lead (Pb, 57.33 ppm). Mercury and lead are of particular concern, as they are both toxic and may pose environmental and health risks if not properly encapsulated within the concrete matrix. The presence of heavy metals necessitates leachability testing, such as the Toxicity Characteristic Leaching Procedure (TCLP), to determine whether the cured product can be safely used in open environments.

Overall, the XRF results support the feasibility of using GMT as a partial sand replacement in concrete from a physical and mineralogical perspective, and highlight the need for further studies to recover gold and test its safe application in construction.

Compressive Strength

The interaction plot in Fig. 1 reveals that both molasses content and curing duration significantly influence the compressive strength of cement–gold mill tailings–sand composites, with a clear interaction effect between the two factors. Among the dosages tested, 1.5% molasses consistently yielded the highest compressive strength across all curing periods, indicating its effectiveness in enhancing the hydration process and improving matrix bonding. The strength for 1.5% molasses increased from 7 to 28 days (9.20 MPa to 15.83 MPa), which is 101% higher than the control mix at 28 days (7.87 MPa). This further indicates that adding 1.5% molasses could potentially produce materials that pass the load-bearing bricks (minimum 13.1 MPa) based on ASTM C90.

In contrast, the 2.0% molasses mix showed moderate gains, reaching 12.13 MPa by day 28, while the 2.5% mix exhibited a slight decline in strength from day 14 (9.60 MPa) to day 28 (8.47 MPa). The crossing of lines and divergence

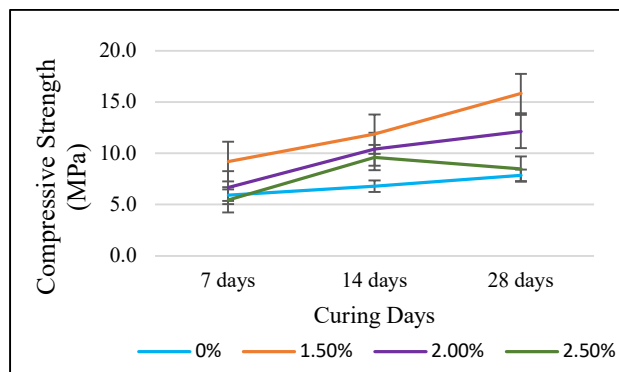


Fig. 1: Interaction plot of compressive strength by curing days and molasses % (n=3).

in trends, particularly between the 2.0% and 2.5% mixes, suggest a significant interaction, indicating that the effect of molasses depends on the curing duration. A higher molasses content beyond 1.5% may retard hydration. These results underscore the importance of optimizing the admixture dosage, as excessive use may compromise performance over time. The findings of this study are consistent with those of Harriet et al. (2021), who reported that the incorporation of molasses as an admixture can enhance the mechanical strength of cement-based materials up to an optimal dosage, beyond which performance may decline. (Harriet et al. 2021).

The two-way ANOVA results shown in Table 3 indicate statistically significant differences across all three tested factors: molasses % ($p < 0.01$), curing days ($p < 0.01$), molasses % and curing days (interaction) ($p < 0.01$). This result indicates that molasses content significantly influences compressive strength, and there is a significant effect of curing days on compressive strength. Moreover, a statistically significant interaction exists between molasses dosage and curing days, indicating that the effect of molasses depends on curing time.

To further determine the conditions that were significantly different, a Tukey–HSD test was conducted, which yielded the following results: (1) a significant difference in compressive strength between 7 and 14 days of curing ($p = 0.0266$), (2) a significant difference in compressive strength between 7 and 28 days of curing ($p = 0.0008$), and (3) no significant difference in compressive strength between 14 and 28 days of curing ($p = 0.3791$).

The Tukey–HSD test in Table 4 further shows that there is a significant difference between no molasses and the mixture with 1.5% molasses. In addition, a significant

difference was observed between the mixture with 1.5% molasses and that with 2.5% molasses. All other mixtures showed no significant difference.

The observed increase in mechanical performance may be associated with improved matrix compaction and particle packing. Fine silt-sized particles in gold mill tailings contribute to a denser particle arrangement, enhancing the structural integrity of the composite. However, such fineness also increases the specific surface area, thereby requiring additional water to achieve adequate workability and full cement hydration (Mehta & Monteiro, n.d.). The introduction of molasses as a natural plasticizer helps mitigate this by improving flowability and reducing water demand at moderate dosages.

Nevertheless, an increase in the molasses content negatively impacts the compressive strength. Excess molasses may reduce the availability of free water or introduce surplus unhydrated sugars, which can interfere with the formation of calcium-silicate-hydrate by blocking active hydration sites (Yousaf et al. 2024). This phenomenon likely accounts for the reduced strength and increased water absorption observed with a 2.5% molasses content. At this concentration, the high presence of organic retarders may have led to incomplete cement hydration, resulting in increased porosity and internal voids within the hardened matrix (Yousaf et al. 2024).

Water Absorption

The water absorption behavior of the concrete samples with varying molasses contents demonstrated clear trends across the 7, 14, and 28 days of curing. At all curing ages, the mix containing 1.5% molasses consistently exhibited the lowest

Table 3: Analysis of Variance for Compressive Strength.

| Source of Variation | SS | df | MS | F | P-value | F crit |
|---------------------|--------|----|--------|-------|----------|--------|
| Molasses % | 154.58 | 3 | 51.52 | 44.75 | 5.53E-10 | 3.01 |
| Curing days | 112.95 | 2 | 56.478 | 49.05 | 3.32E-09 | 3.40 |
| Interaction | 33.711 | 6 | 5.6186 | 4.88 | 0.002174 | 2.51 |
| Within | 27.63 | 24 | 1.1513 | | | |

Table 4: Summary of Tukey–HSD test results.

| Molasses % group 1 | Molasses % group 2 | p-value | curing days 1 | curing days 2 | p-value |
|--------------------|--------------------|---------|---------------|---------------|---------|
| 0 | 1.5 | 0.0001 | 7 | 14 | 0.027 |
| 0 | 2.0 | 0.0630 | 7 | 28 | 0.001 |
| 0 | 2.5 | 0.8107 | 14 | 28 | 0.379 |
| 1.5 | 2.0 | 0.1117 | | | |
| 1.5 | 2.5 | 0.0017 | | | |
| 2.0 | 2.5 | 0.3319 | | | |

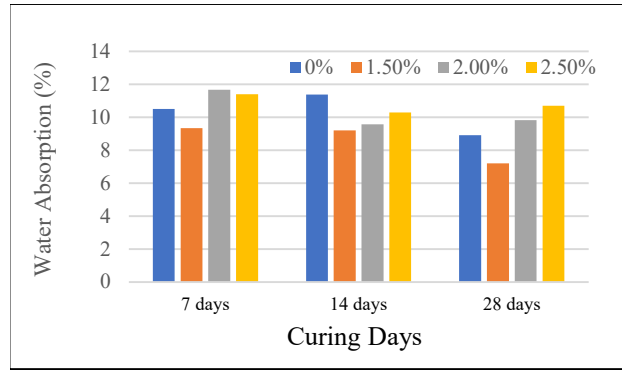


Fig. 2: Water absorption of cement-GMT-sand with molasses (n=3).

Table 5: ANOVA analysis for water absorption.

| Source of Variation | SS | Df | MS | F | P-value | F crit |
|---------------------|--------|----|------|------|---------|--------|
| Molasses % | 8.516 | 3 | 2.84 | 3.98 | 0.071 | 4.76 |
| Curing Days | 5.004 | 2 | 2.50 | 3.51 | 0.098 | 5.14 |
| Error | 4.274 | 6 | 0.71 | | | |
| Total | 17.795 | 11 | | | | |

water absorption, indicating a denser and less permeable concrete matrix (Mehta & Monteiro, n.d.). This suggests that at this dosage, molasses effectively improved workability and compaction, leading to better particle packing and reduced capillary voids. In contrast, the control mix (0%) exhibited higher absorption values, likely due to limited flowability and less efficient compaction in the absence of any plasticizing agent.

The concrete containing 2.0% molasses exhibited moderate absorption values, suggesting marginal benefits over the control, but not as effective as the 1.5% dosage. Meanwhile, the 2.5% molasses mix consistently showed the highest water absorption, particularly at 7 and 14 days (Fig. 2). This indicates that excess molasses may interfere with cement hydration, either by binding available water or by the presence of unreacted sugars that delay setting and create internal voids (Yousaf et al. 2024). By 28 days, although the absorption in the 2.5% mix decreased, it remained higher than that in the other mixes, reflecting residual porosity due to under-hydrated cement.

These results align with the findings of Yousaf et al. (2024), who reported that while molasses can improve concrete durability at optimal dosages, excessive use can lead to incomplete hydration (Akar & Canbaz 2016, Harriet et al. 2021). Overall, the trend observed in this study supports the conclusion that 1.5% molasses offers the best balance for enhancing durability performance in GMT-based concrete through reduced water absorption.

However, the ANOVA analysis of water absorption in Table 5 revealed that there were no statistically significant differences in water absorption attributable to either curing duration or molasses dosage at the 95% confidence level. This suggests that while observable trends exist in the data, the variations across different curing days and molasses percentages are insufficient to establish a statistically meaningful effect. Larger-scale testing is recommended to confirm these findings.

CONCLUSIONS

This study demonstrated the feasibility of using gold mill tailings (GMT) and blackstrap molasses, both industrial and agricultural by-products, to develop sustainable cementitious composites. By employing a fixed mix proportion (30% cement, 40% GMT, and 30% sand) and varying the molasses dosage from 0% to 2.5%, the effects on compressive strength and water absorption were systematically evaluated in a small-scale laboratory study.

The results indicate that incorporating 1.5% molasses yielded the most favorable performance, achieving a 28-day compressive strength of 15.83 MPa, which is 101% higher than the control mix at 28 days (7.87 MPa). The 1.5% mix also achieved the lowest water absorption at 7.2%. This suggests that at a moderate dosage, molasses enhances workability, matrix densification, and hydration efficiency, leading to stronger and less permeable concrete. However, higher dosages (2.5%) showed diminished benefits, likely

due to retardation effects and excess sugar content that interfered with cement hydration, causing increased porosity and reduced strength.

Statistical analysis confirmed that molasses content, curing duration, and their interaction significantly affected compressive strength ($p < 0.01$), whereas no significant effect was observed on water absorption. These findings support the conclusion that molasses can be a viable natural admixture when properly dosed, particularly in GMT-rich mortar mixes.

From a sustainability perspective, this work contributes to waste valorization by repurposing two underutilized waste materials, GMT and molasses, into a functional and potentially cost-effective construction product. For future research, it is recommended to explore molasses dosages lower than 1.5% to determine whether further improvements in strength or durability can be achieved at minimal concentrations. Additionally, trials using mixes composed solely of cement and GMT (without sand) should be conducted to assess the standalone potential of GMT as a fine aggregate substitute and to evaluate its compatibility with molasses in simplified binder systems. Field trials within mining communities, along with investigations on long-term durability and leaching behavior, should be conducted at a larger scale to validate the findings and assess the practical feasibility of implementing this study in real-world applications.

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