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Evaluation on 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 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 also achieved the lowest water absorption (7.2%), which is 19% lower than the control mix (8.9%). In contrast, higher molasses levels (2.5%) resulted in reduced performance, likely due to excess sugar interfering with cement hydration. ANOVA results 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 recommended to evaluate long-term durability and environmental safety for practical deployment.

INTRODUCTION

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

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 show the technical viability of tailings recycling in construction. However, addition of GMT in concrete generally reduces the compressive strength of concrete and the result is not comparable to concrete-sand mixture (Balbin et al., 2024).

Meanwhile, the demand for cementitious materials places heavy burdens on the environment. The global construction sector consumes over 50 billion tons of sand annually (UNEP, 2014), with many sources now threatened by over-extraction. Conventional Portland cement production contributes on the order of 8% of global CO_2 emissions (Scrivener et al., 2018). These facts motivate sustainable alternatives. Natural admixtures derived from agricultural by-products are of great interest because they are low-cost 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). The study of Jumadurdiyev et al. (2004) showed that adding beet molasses to concrete increased the strength at all ages under study (Jumadurdiyev et al., 2004). These works 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 of which pose disposal challenges. Some local hollow-block makers add molasses to improve strength, but 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 is varied from 0 (control mix), 1.5%, 2.0%, and 2.5% and tested for compressive strength, and water absorption 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. Incorporating molasses is expected to improve 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 Caraga region, where artisanal and small-scale gold mining is a flourishing industry.

MATERIALS AND METHODS

Raw Materials

The GMT used in this study were 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 process 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).

For the preparation of the concrete mixtures, commercially available river sand was used as the fine aggregate and Ordinary Portland Cement (OPC) as the binder. Both materials were procured from a local construction supplier. The organic admixture, blackstrap molasses, 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.

A 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

Building on the preliminary formulation by Balbin et al. (2024), all mortar mixes were prepared using a fixed cement: GMT: sand ratio of 30:40:30 by weight. This is to test the effect on compressive strength in a mixture with higher GMT content than sand. A constant water-to-cement ratio of 0.5 was maintained across all mixes. Molasses, serving as a liquid admixture, was added at four dosage levels—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 experiment was employed, considering molasses content (0, 1.5%, 2.0%, 2.5%) and curing age (7, 14, and 28 days) as the independent variables.

Mixing and Specimen Preparation

The preparation of the concrete mixture followed 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 is maintained at 0.5 water-cement ratio 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 100mm x 100mm x 100 mm molds. Manual compaction was performed to eliminate entrapped air and ensure the mixture's proper consolidation. This procedure was consistently applied to all test specimens to maintain the reliability and comparability of the experimental results.

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

Limitations

TCLP is seen as an important part of this evaluation. However, the previous study by Balbin et al. (2024) on the cement-GMT-sand mix show that the hazardous elements present in the GMT like the 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, 28 days), samples were subjected for compressive strength testing per ASTM A55. For each mix and age, 3 specimens were tested. Water absorption was measured on samples after 7 days and 21 days of water curing (per ASTM C642): specimens were oven-dried, weighed (M1), then submerged in water for 48 hours, dried with cloth to remove water droplets and weighed again (M2). Water Absorption % is calculated as follows:

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

All data were processed statistically using ANOVA, Tukey HSD, and presented in table or 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 the 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 requirement to achieve proper coating and bonding of particles (Mindess et al., 2002; Neville, 1995). As such, concrete made with very fine aggregates like GMT often exhibits lower compressive strength unless compensated with higher cement content or the inclusion of admixtures to improve workability and cohesion (Mehta & Monteiro, n.d.). Without these modifications, the mix may suffer from poor compaction and increased porosity, which can adversely affect both strength and durability (Mehta & Monteiro, n.d.).

Table 1. Particle Size Distribution of GMT

MESH NO.	NOMINAL SIEVE OPENING (mm)	WEIGHT RETAINED (grams)	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	

The X-ray fluorescence (XRF) analysis of the gold mill tailings (GMT) in 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 is primarily composed of quartz or silicate minerals, which aligns with 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 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) at 1.15% and iron (Fe) at 5.05%, which are common in aluminosilicate and iron oxide minerals, respectively. While aluminum may slightly contribute to pozzolanic activity, the GMT is largely inert and non-cementitious.

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	-	-

Elements such as potassium (K) at 0.42% and sulfur (S) at 0.23% were also detected. The 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) problem, as S readily reacts with water and oxygen to form sulfuric acid. The sample also contained trace metals, including chromium (Cr) at 69.33 ppm, magnesium (Mg) at 63.33 ppm, mercury (Hg) at 8.67 ppm, and lead (Pb) at 57.33 ppm. Of particular concern are mercury and lead, both of which are toxic and may pose environmental and health risks if not properly encapsulated within the concrete matrix. The presence heavy metals necessitates leachability testing, such as the Toxicity Characteristic Leaching Procedure (TCLP), to determine whether the cured product can safely be 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, while also highlighting the need for further study to recover the gold, and testing to ensure its safe application in construction.

Compressive Strength

The interaction plot in Figure 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 days (9.20 MPa) to 28 days (15.83 MPa), which is 101% higher than the control mix at 28 days (7.87 MPa). This further indicates that adding molasses of 1.5% could potentially produce material passing the load-bearing bricks (minimum 13.1 MPa) based on ASTM C90.

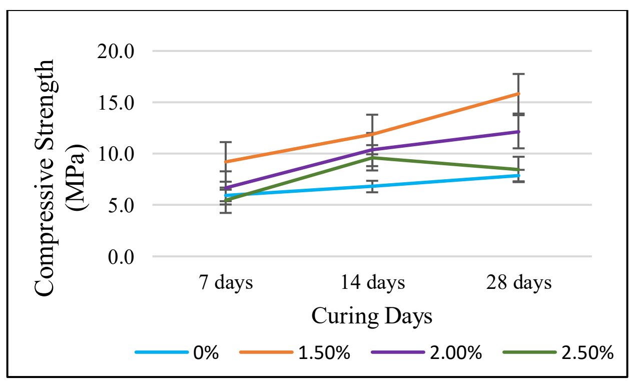

Figure 1. Interaction Plot of Compressive Strength by Curing Days and Molasses % (n=3)

In contrast, the 2.0% molasses mix showed moderate gains, and reaching 12.13 MPa by the 28th day, while the 2.5%

mix exhibited a slight decline in strength from day 14 (9.60 MPa) to day 28 (8.47MPa). The crossing of lines and divergence in trends, particularly between the 2.0% and 2.5% mixes, suggest a significant interaction—meaning the effect of molasses depends on the curing duration. Higher molasses content beyond 1.5% may retard hydration. These results underscore the importance of optimizing admixture dosage, as excessive use may compromise performance over time. The findings of this study are consistent with the results 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 in Table 3 show that 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 indicate 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 the curing time.

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			

To further determine the condition that are significantly different, a Tukey-HSD test was conducted which further give the following results: (1) there is a significant difference in compressive strength between 7 and 14 curing days ($p = 0.0266$), (2) there is a significant difference in compressive strength between 7 and 28 days ($p = 0.0008$), (3) there is no significant difference in compressive strength between 14 and 28 days ($p = 0.3791$).

The Tukey-HSD test in Table 4 further show that there is a significant difference between no molasses and mix with 1.5% molasses. Also, a significant difference was observed between mix with 1.5% molasses and 2.5% molasses. All other mixtures shows no significant difference.

The observed increase in mechanical performance maybe associated with improved matrix compaction and particle packing. The fine silt-sized particles in the gold mill tailings contribute to a denser particle arrangement, enhancing the composite's structural integrity. 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.

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			

Nevertheless, when the molasses content was increased, it negatively impact the compressive strength. Excess molasses may either 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 at 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 content demonstrates clear trends across the 7, 14, and 28 days curing periods. At all curing ages, the mix with 1.5% molasses consistently exhibited the lowest 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%) showed higher absorption values, likely due to limited flowability and less efficient compaction in the absence of any plasticizing agent.

The concrete with 2.0% molasses displayed 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. This indicates that **excess** molasses may interfere with cement hydration, either by binding available water or through the presence of unreacted sugars that delay setting and create internal voids (Yousaf et al., 2024). By 28 days, although absorption in the 2.5% mix decreased, it remained higher than in other mixes, reflecting residual porosity due to under-hydrated cement**.**

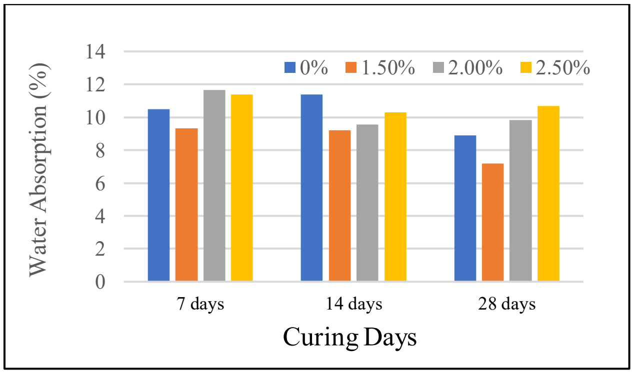

Figure 2. Water Absorption of Cement-GMT-Sand with Molasses (n=3)

These results align with findings by 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.

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				

However, the ANOVA analysis for 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 not sufficient to establish a statistically meaningful effect. Larger-scale testing is recommended to confirm this findings.

Conclusions

This study demonstrated the feasibility of using gold mill tailings (GMT) and blackstrap molasses, both industrial and agricultural by-products, in the development of sustainable cementitious composites. By employing a fixed mix proportion (30% cement, 40% GMT, 30% sand), and varying the molasses dosage from 0%, 1.5%, 2.0% and 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 moderate dosage, molasses enhances workability, matrix densification, and hydration efficiency**,** leading to a 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 affect compressive strength ($p < 0.01$), while no significant effect was found 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 gold mill tailings (GMT) (without sand) 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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