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# MANUFACTURE OF LIGHTWEIGHT PREFABRICATED PANELS EMPLOYING MINE TAILINGS

Fabricación de paneles prefabricados ligeros utilizando jales mineros

Fermín RAMÍREZ-CRESCENCIO, Jaime PARRA-VÉJAR, Verónica LOERA-CASTAÑEDA, Luis Antonio AGUILAR-PÉREZ and Ignacio VILLANUEVA-FIERRO*

Instituto Politécnico Nacional, CIIDIR Unidad Durango, calle Sigma 119, Fraccionamiento 20 de Noviembre II, 34220, Durango, Durango, México.

*Author for correspondence: ifierro62@yahoo.com

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Key words: tailings reutilization, foamed concrete, fiber reinforced concrete.

## ABSTRACT

The present study describes the incorporation of mine tailings from the silver mine La Guitarra in the manufacture of lightweight prefabricated panels (LPPs). Tailings have concentrations of heavy metals below the maximum permissible levels according to Mexican regulations. Their acidity potential (AP) of 2.22 kg of $CaCO_3$ per tailings ton, along with their lack of neutralization potential (NP), indicates a possibility for the generation of acid mine drainage (AMD). It was reported that concrete could be employed to prevent AMD, thus we proposed to stabilize mine tailings with different concrete ratios and employ these mixtures to fabricate concrete panels. To obtain lightweight panels, a foaming agent was added to the tailings/concrete mixture. Then, a fiberglass mesh was employed to reinforce the final structure. The resulting LPPs (dimensions: 254 × 139.7 × 12.7 mm) showed a flexural strength of 5.80 ± 0.06 MPa, bulk density of 712 ± 104 kg/m$^3$, thermal conductivity of 0.159 ± 0.004 W/m K, mass water absorption of 59 ± 10 %, and net neutralization potential (NNP = NP/AP) > 1.2. According to Mexican regulations, these LPPs are not potential generators of AMD.

Palabras clave: reuso de jal de mina, concreto celular, concreto reforzado con fibra.

## RESUMEN

El presente estudio describe la incorporación de jales mineros de la mina de plata La Guitarra en la fabricación de paneles prefabricados ligeros (PPL). Estos jales tienen concentraciones de metales pesados inferiores al límite máximo permisible de acuerdo con la normatividad mexicana. Sin embargo, su potencial de acidez (PA) de 2.22 kg de $CaCO_3$ por tonelada de jal, aunado a la ausencia de potencial de neutralización (PN), indica que pueden generar drenaje ácido. Se ha informado que el concreto se puede utilizar para prevenir la generación de drenaje ácido, por lo que se propuso estabilizar los jales mineros con diferentes proporciones de concreto y emplear estas mezclas para fabricar paneles de concreto. Para obtener paneles ligeros se añadió un agente espumante a la mezcla de jales/concreto y se utilizó una malla de fibra de vidrio para reforzar la estructura final. Los PPL resultantes (dimensiones: 254 × 139.7 × 12.7 mm) mostraron una resistencia a la flexión de 5.80 ± 0.06 MPa, densidad aparente de 712 ± 104 kg/m$^3$, conductividad térmica de 0.159 ± 0.004 W/m K, absorción de agua en masa de 59 ± 10 %, y potencial neto de neutralización (PNN = PN/PA) > 1.2. De acuerdo con la normatividad mexicana, este valor de PNN implica que los PPL no son potenciales generadores de drenaje ácido.

## INTRODUCTION

There is a growing interest in the development of sustainable options for the mining activity (Gorman and Dzombak 2018). Therefore, management of mining waste has become increasingly important (Aznar-Sánchez et al. 2018). Mine tailings are produced after separation of the valuable products from a mineral ore. A 2016 estimate calculates their production rate from five to 14 billion tons per year (Schoenberger 2016). Large companies store the mine tailings behind dammed impoundments, often termed as tailing ponds or tailing dams (Kossoff et al. 2014). Unfortunately, the frequency of dam failures is high resulting in both economic and environmental issues (Páez-Osuna et al. 2015, Schoenberger 2016, Jain and Das 2017).

The chemical composition of tailings depends on several factors of the mineralogy of the ore body, the processing fluids used to extract the economic metals, the efficiency of the extraction process, and the degree of weathering during storage (Kossoff et al. 2014). The presence of sulfide minerals is common, such as pyrite ($FeS_2$), pyrrhotite ($Fe_{1-x}S$), galena ($PbS$), sphalerite ($ZnS$), chalcopyrite ($CuFeS_2$), or arsenopyrite ($FeAsS$). Sulfide minerals lead to the formation of acid mine drainage (AMD) by exposition to atmospheric oxygen, oxygenated waters, and bacteria (Lawrence and Scheske 1997, Plumlee 1999, Kefeni et al. 2017). AMD represents an environmental problem due to its high acidity, toxic metals, and sulfate contents. When deposits of calcite ($CaCO_3$), dolomite ($CaMg[CO_3]_2$), and magnesite ($MgCO_3$) occur in proximity of acid-generating sulfide minerals, they can react and consume some of the acid generated during sulfide oxidation (Plumlee 1999). Otherwise, to fully suppress AMD generation, it is necessary to protect sulfide minerals from air, water, and bacteria (Kefeni et al. 2017).

Portland cement was previously reported as an excellent alternative for the encapsulation, as well as chemical fixation, of the toxic mobile elements in tailings (Nehdi and Tariq 2007, Rachman et al. 2018). Examples of its application include the fabrication of synthetic gravel (Zuccheratte et al. 2017), concrete pavements (Gayana and Chandar 2018), and cemented paste backfill (Lu et al. 2018). It is known that Portland cement can be mixed with aggregates (sand, gravel, and rock), water, and small amounts of chemical admixtures to make concrete (Aljerf 2015). Hence, our research interests are focused on the utilization of tailings as aggregates in the fabrication of concrete, particularly foamed concrete.

Foamed concrete is obtained by adding a foaming agent to the concrete mixture, resulting in a product with high flowability, low cement content, low aggregate usage and excellent thermal insulation (Amran et al. 2015). In the construction industry, prefabrication and modularization are preferred because they improve worksite productivity, decrease waste generation in site, and improve project return on investment (Construction 2011). In consequence, we proposed the fabrication of lightweight prefabricated panels (LPPs) that involve the use of tailings as replacement of aggregates in the foamed concrete. To further improve the concrete post-crack performance, polypropylene fibers are added during the preparation (Yin et al. 2015) and a fiberglass mesh is employed as reinforcement element.

## MATERIALS

Mine tailings were provided from La Guitarra, a silver mine located at the Temascaltepec municipality, State of Mexico, Mexico, owned by First Majestic Silver (2015). The chemical analysis of the tailings was performed by the company following procedures according to the Official Mexican Standard NOM-141-SEMARNAT-2003 (SEMARNAT 2004). Contents of metals were determined by extraction and subsequent analysis through atomic absorption spectroscopy (AAS) whereas the neutralization and acidity potentials were determined by the modified acid base accounting (ABA) procedure. Both methodologies are based on the ASTM D3987 (ASTM 2012) and the modified ABA test (Lawrence and Wang 1997), respectively. Characterization details are summarized in **tables I** and **II**.

**TABLE I.** HEAVY METALS CONCENTRATION IN MINE TAILINGS DETERMINED BY ATOMIC ABSORPTION SPECTROSCOPY (AAS).

| Element | Measured concentration by AAS (mg/L) | MPL[a] (mg/L) |
|---|---|---|
| As | < 0.005 | 5.0* |
| Ba | 0.24 | 100.0* |
| Be | < 0.005 | 1.22† |
| Cr | < 0.005 | 5.0* |
| Ag | < 0.005 | 5.0* |
| Pb | < 0.005 | 5.0* |
| Se | < 0.005 | 1.0* |

[a]Maximum permissible limit according to Mexican standards *NOM-052-SEMARNAT-2005 (SEMARNAT 2006), †NOM-157-SEMARNAT-2009 (SEMARNAT 2011).

**TABLE II.** NEUTRALIZATION POTENTIAL (NP), ACIDITY POTENTIAL (AP), PH, AND HUMIDITY PERCENTAGE IN MINE TAILINGS OBTAINED FROM LA GUITARRA.

| NP (kg of $CaCO_3$/ton) | AP (kg of $CaCO_3$/ton) | pH | Humidity (%) |
|---|---|---|---|
| 0 | 2.22 | 3.89 | 14.3 |

Because of their high water content, tailings were first sun-dried. Then, larger aggregates were separated using a sieve (mesh size of 2.5 mm).

Type II Portland cement (CEMEX, Monterrey, Mexico), fiber glass mesh (60 g/m$^2$, FIBRAMALLA), foaming agent (Barracel, BASF), polypropylene fiber (Sika Fiber, SIKA), and vinyl sealant (Daraweld BA3S, GRACE) were bought at local hardware stores. Potable water was employed in all procedures.

Molds for the LPPs fabrication were built using four pieces of galvanized steel angle (3/4 × 3/4 × 1/8 in). These molds were secured with hexagonal bolts and nuts to obtain a rectangular form of 254 × 139.7 × 12.7 mm (length × width × height). It is highly important that molds are greased before the application of the concrete mixture to facilitate their cleaning and reuse.

## METHODS

### Determination of the neutralization potential of LPPs

Specimens were tested according to NOM-141-SEMARNAT-2003 (SEMARNAT 2004), which is based on the modified ABA test (Lawrence and Wang 1997), following the same procedure as in the tailings characterization.

### *General procedure for LPPs fabrication*

The quantities employed to obtain the different test specimens are summarized in **table III** and were based on the previous experience of one of the authors in the masonry work with concrete (I.V.F.). Typically, mine tailings, polypropylene fiber, and cement are dry mixed in a bucket until a homogeneous mixture is obtained. Then, water and vinyl sealant are added. The mixing continues until a uniform paste forms. The foaming agent and water were mixed in a separate container until homogenization prior to their addition to the paste. The resulting product is poured into the molds to form their final shape. Afterwards, the fiberglass mesh (254 cm x 139.7 cm) is placed into the mold. Finally, the concrete is cured every 24 hours with water for three days.

**TABLE III.** MATERIALS EMPLOYED IN THE FABRICATION OF DIFFERENT TEST SPECIMENS OF LPPs. NUMBERS CORRESPOND TO THE WEIGHT PERCENTAGE.

| Material | Test specimen | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Cement | 27.7 | 24.7 | 24.4 | 26.5 |
| Tailings | 41.6 | 44.4 | 44.0 | 47.7 |
| Water | 20.3 | 21.7 | 21.5 | 17.0 |
| Water/foaming agent | 5.5 | 5.9 | 4.9 | 5.3 |
| Foaming agent | 0.3 | 0.3 | 0.2 | 0.3 |
| Vinyl sealant | 4.6 | 3.0 | 4.9 | 3.2 |

### *Characterization of LPPs*

The apparent density, thermal conductivity, water vapor permeability, humidity adsorption, and water absorption were measured for the LPPs because Mexican Official Standard NOM-018-ENER-2011 (SENER 2011) requires them to be reported for the commercialization of thermal insulating materials, with no specified reference values. Additionally, the flexural strength of panels was determined.

The apparent density is defined as the ratio between the apparent volume (i.e., including voids) and the mass of the sample. The following equation was employed:

$$\rho_{ap} = \frac{m}{V} \quad (1)$$

where $\rho_{ap}$ is the apparent density (kg/m$^3$), $m$ is the mass of the specimen (kg), and $V$ is the volume of the specimen (m$^3$).

Thermal conductivity was determined by using a quasicubic arrangement, as proposed by Díaz and Tibaquirá (2008). Five sides of the cube consist of expanded polystyrene (thermal insulator) with a panel that is placed at the top side. A lamp, inside the cube, was used as the heat source, and temperature differences were measured using an infrared thermometer. Finally, thermal conductivity was estimated using the Fourier's equation of heat conduction:

$$Q_{cond} = -kA\,\frac{\Delta T}{\Delta X} \quad (2)$$

where $Q_{\mathrm{cond}}$ is the heat flow rate by conduction (W), $k$ is the thermal conductivity of the panel (W/m K), $A$ is the cross-sectional area normal to direction of heat flow (m$^2$), $\Delta T$ is the temperature difference (K), and $\Delta X$ is the panel thickness (m).

For water absorption experiments, test specimens were submerged horizontally in a container with water at 20 ± 1 ºC. After 24 h, water was removed and the specimen suspended to drain for 10 min. The weight difference, before and after submersion, corresponds to the water absorbed by the panel.

Moisture adsorption was determined by placing the specimens inside an aluminum chamber with relative humidity of 100 % and temperature of 20 ºC for 24 h. The weight difference, before and after the treatment, corresponds to the moisture adsorbed by the specimen.

Water vapor permeability was measured following a procedure similar to the ASTM E96/E96M method (ASTM 2016a). A test dish impermeable to water was filled with distilled water and the test specimen was attached to the dish by sealing. Distance from the water level to the test specimen was 20 mm. This assembly was placed on a horizontal surface and weighed periodically to determine the change in mass as a function of time. A slope value was determined from the linear regression of the straight line obtained. When the slope value is divided by the test area (cup mouth area), the rate of water vapor transmission (WVT) of the specimen is obtained. Later, permeance was obtained using the following equation:

$$Permeance = \frac{WVT}{S(R_1 - R_2)} \quad (3)$$

where $S$ is the saturation vapor pressure at the test temperature (25 ºC), $R_1$ is the relative humidity in the dish, and $R_2$ is the relative humidity at the vapor sink.

Finally, tension tests were carried out using an INSTRON 3360 Series Dual Column Tabletop Testing System. A given panel was supported near the ends (2.54 cm) and a central load was applied at 50 mm/min until the specimen fracture.

## RESULTS AND DISCUSSION

### Toxicity of LPPs

From data in **table I**, it is clear that mine tailings from La Guitarra do not represent a hazardous waste in terms of their metals' content according to Mexican standards (SEMARNAT 2004). However, their lack of neutralization potential along with their acidity potential (2.22 kg of $CaCO_3$ per ton of tailings) made necessary to stabilize them by making foamed concrete. After fabrication of the LPPs, the NP and AP of the panels were determined to evaluate their potential as generators of AMD. A value of NNP = 193 ± 1.5 was obtained, which indicates that LPPs do not represent a hazardous waste in terms of the Mexican standards (SEMARNAT 2004). It has been mentioned that the effectiveness of Portland cement to stabilize mine tailings is mainly derived by the encapsulation, as well as chemical fixation, of their toxic components (Nehdi and Tariq 2007, Rachman et al. 2018).

### Characterization of LPPs

The properties measured for every test specimen after characterizations are shown in **table IV**.

It is worth to mention that early experiments lead us to the use of a fiberglass mesh as reinforcement element in the panels. The mesh accounted for up to 95 % of the flexural strength in the panels. As can be seen in **table IV**, minimal variations between the test specimens were found; also, if the mesh is not used, cracks appear in the PPLs. Thus, we decided to use the mesh, then statistical changes were difficult to observe. The properties of foamed concrete as a function of their composition was previously reviewed in the literature (Amran et al. 2015, Ma and Chen 2016) and a similarly extensive study was not considered necessary for LPPs.

According to their apparent density values (< 1800 kg/m$^3$), LPPs correspond to lightweight concrete. In general, flexural strength in concrete is about 10 to 20 % of its compressive strength (NRMCA 2000). This indicates that specimens 1-4 are not suitable for structural applications neither by density (ASTM 2016b) nor strength (NRMCA 2003). However, LPPs are not intended for a structural application, but as

**TABLE IV**. PROPERTIES MEASURED FOR THE TEST SPECIMENS OBTAINED.

| Test specimen | Flexural strength (MPa) | Apparent density ($kg/m^3$) | Water absorption (% mass) | Humidity absorption (% mass) | Permeance (perm) | Thermal conductivity (W/m K) | NNP |
|---|---|---|---|---|---|---|---|
| 1 | 5.76 | 613.4 | 71.9 | 14.2 | 31.47 | 0.162 | 195 |
| 2 | 5.78 | 656.7 | 59.3 | 8.2 | 26.9 | 0.163 | 192 |
| 3 | 5.78 | 853.1 | 46.4 | 2.1 | 43.54 | 0.159 | 192 |
| 4 | 5.89 | 725.0 | 59.4 | 5.4 | 22.01 | 0.153 | 194 |

NNP: net neutralization potential.

an alternative for non-structural applications such as housing (insulating walls, sidings, or roof material).

Thermal conductivity values ($k$) are not directly comparable with other foamed concrete systems. This is due to the addition of mine tailings as aggregates. The comparison of typical thermal conductivity values for foamed concretes (Asadi et al. 2018) in the density range of 400-1600 $kg/m^3$ (0.15 - 0.57 W/m K) indicates that LPPs 1-4 are similar in terms of thermal behavior (0.15 - 0.16 W/m K). Foamed concrete is considered an excellent thermal insulator because of its low $k$ values. Such behavior is mainly due to the enhanced amount of air inside the cement matrix (Asadi et al. 2018).

The lack of water and moisture absorption studies in foamed concrete with tailings made necessary to compare our results with nearly equivalent systems. Ma and Chen (2016) have reported the properties of foamed concrete (target density: 550 $kg/m^3$) made of ordinary Portland cement, silica fume, water, polypropylene fiber, a type of naphtalene-based superplasticizer and foam stabilizer agents. Water absorption, by volume, determined after 48 h of concrete soaking is 68.5 % and the moisture absorption value obtained at 100 % relative humidity is 46.4 $kg/m^3$. Those values are closely related to the obtained for test specimens 1-4 confirming the seamless integration of tailings in foamed concrete.

The water vapor permeance of materials is commonly reported in the construction trade with the unit “perm” rather than their SI equivalent (g/Pa s $m^2$). The values obtained for the LPPs (> 10 perm) indicate that panels are classified as vapor permeable. This characteristic is convenient for their use in certain hygrothermal conditions (Lstiburek 2002).

## CONCLUSIONS

Mine tailings obtained from a silver mine were mixed with Portland cement, water, and other additives to obtain foamed concrete, which is useful in the fabrication of LPPs. Their properties were similar to those reported for common foamed concrete, indicating that tailings are suitable as a replacement of aggregates in foamed concrete mixtures. Moreover, characterization indicates that LPPs have a net neutralization potential of 192, proving the stabilization of tailings and that there is no risk of AMD generation.

Lottermoser (2011) describes waste-management practices with a hierarchy in the following order: (*i*) prevention, (*ii*) reuse, (*iii*) recycling, (*iv*) energy recovery, and (*v*) treatment and disposal. As tailing´s generation is inevitable, their use as aggregates replacement in foamed concrete is a promising alternative for their handling. Other uses of foamed concrete include their use as backfill material for heat preservation pipes, foundation for the highway roads, fire insulation, trench reinstatement, etc. (Tan et al. 2014, Amran et al. 2015). This leaves us with plenty of opportunities remaining unexplored in the replacement of aggregates with mine tailings.

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