Evaluation of the Environmental Compatibility of the Use of Waste to Energy Bottom Ash in Porcelain Stoneware Tile Manufacturing through Leaching Tests and Risk Assessment

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In recent years, the search for sustainable solutions to manage waste and reduce landfill dependency has led to the increased utilization of various industrial by-products and waste treatment residues. A type of waste material that is currently being increasingly used outside of landfills is the mineral fraction of waste incineration bottom ash (Blasenbauer et al., 2020). This material is employed as aggregates or sand substitutes in concrete or asphalt mixtures, as aggregates in unbound applications, or as raw material in cement or recently also in ceramics manufacturing (Silva et al., 2019; Verbinnen et al., 2017). In any case, the bottom ash is first treated to recover ferrous and non-ferrous metals (Šyc et al., 2020) and may undergo different treatments such as particle size separation, crushing, washing, natural weathering and/or binder addition, in view of the intended application (Astrup et al., 2016; Meima & Comans, 1997). This management strategy presents significant advantages compared to landfilling in terms of the avoided environmental impacts and costs of landfill disposal and of the replaced virgin raw materials (Allegrini et al., 2015; Costa et al., 2022). However, it is fundamental to assess whether the utilization of these materials would be acceptable in terms of risks to the environment and human health.

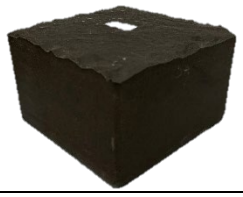
We have been hence developing a methodology to assess if the use of mineral fractions from bottom ash treatment may pose potential risks to the environment and human health that makes use of the results of leaching tests and evaluates them through a risk assessment procedure, assuming worst reasonable scenarios. By incorporating conservative assumptions, this methodology aims to ensure a high level of environmental and human safety in the decision-making process regarding BA-derived materials.

In this study, the procedure was applied to porcelain stoneware tiles produced by incorporating Waste to Energy (WtE) bottom ash as a partial replacement of feldspar sands. For comparative purposes, tests were conducted on porcelain stoneware tiles made with traditional materials and containing WtE bottom ash after milling and the removal of ferrous and non-ferrous metals. The following terminology is used throughout the discussion:

Sample SP: refers to porcelain stoneware tiles made with traditional formulations.

Sample SP-BA: refers to porcelain stoneware tiles containing WtE bottom ash

Table 1. Analyzed samples.

SP: traditional formulation	**SP-BA**: containing WtE bottom ash
	

Both types of samples underwent two types of leaching tests: the monolithic leaching test (UNI EN 15863:2015) and the compliance leaching test (EN 12457-2).

The monolithic test involves suspending the sample in a tank filled with deionized water at an 8:1 ratio, calculated on the basis of the surface area in cm² of the monolithic sample, for a predetermined period. The leaching solution is periodically renewed to maintain a concentration gradient between the material's surface and its internal pore structure. The renewal follows a semi-dynamic schedule consisting of eight intervals over a total duration of 64 days. The test was performed in triplicate (A, B, C).

The compliance leaching test was conducted at the native pH of the samples following the EN 12457-2 standard. Crushed samples from both traditionally formulated tiles and those containing bottom ash were tested. Crushed samples with a grain size below 4 mm were used (coarser material was crushed if more than 20% exceeded this size). Each test employed an L/S ratio of 10 L/kg, with deionized water contact for 24 hours. Tests were performed

in triplicate (D, E, F). This test was carried out to assess the end-of-life characteristics of the materials, as the results were compared with the limits set by Italy's End of Waste decree (152/2022) for construction and demolition materials. This evaluation was crucial to determine the compliance with recovery criteria. For both tests, the eluates collected were analyzed to determine their content of major and trace constituents, including anions such as chlorides, fluorides and sulfates.
The results of the monolith test were integrated into a risk assessment procedure based on conservative utilization conditions. Two scenarios were considered (see Figure 1):

- Scenario 0 represents a "no restrictions" case, where direct contact between the material and groundwater is assumed. This scenario does not account for attenuation in the unsaturated zone or dilution in the groundwater.
- Scenario 1 assumes the use of porcelain stoneware tiles for the external paving of a large area corresponding to that of St. Peter's Square, Vatican City. Here, the effects of attenuation in the unsaturated zone and dilution in the groundwater are considered.

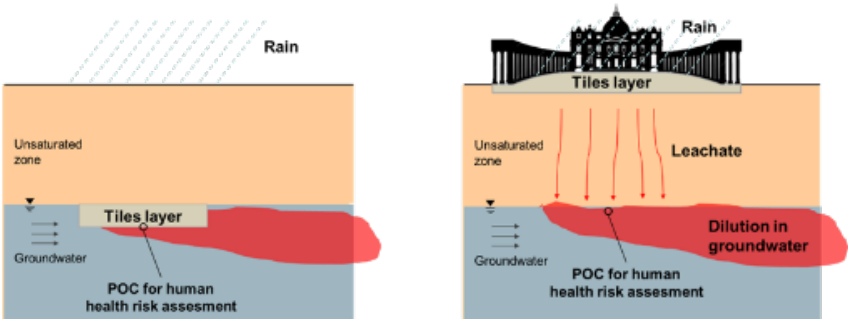


Figure 1. Scheme of the proposed scenarios for porcelain stoneware tiles.
Scenario 0 on the left and Scenario 1 on the right; POC stands for Point Of Compliance.

Given the nature of the contaminants (metals, metalloids, and salts), but also of the material and its utilization scenario, leaching to groundwater was the only migration pathway considered. Direct exposure (ingestion, dermal contact, or dust inhalation) was in fact excluded, as the bottom ashes are incorporated in the samples of porcelain stoneware tiles. Vapor inhalation was also deemed irrelevant, as the detected contaminants are non-volatile.
To assess risks to groundwater, a direct approach was used. The concentration in the groundwater (PEC) was calculated using maximum concentrations obtained from the monolith tests and standardized transport models as follows:

$$PEC = \frac{C_{max\ leachate}}{LF}$$

where $C_{max\_leachate}$ is the maximum concentration resulting from the monolith test for all the analyzed constituents, and LF is the Leaching Factor, which considers the dilution in the groundwater and attenuation in the unsaturated zone. The PEC was then compared to the Predicted No-Effect Concentration (PNEC), derived using risk-based criteria for water ingestion by a child receptor. The assessment was conducted with Risk-net 3.1.1 software, developed by the University of Rome "Tor Vergata".
The results of the monolithic tests showed that most of the constituents analyzed, particularly metals, presented concentrations below the instrument's limit of quantification (LOQ). Even in cases where measurable concentrations were found, particularly for macroconstituents like Ca, Mg (Figure 2), Na, and K, the release was very limited.

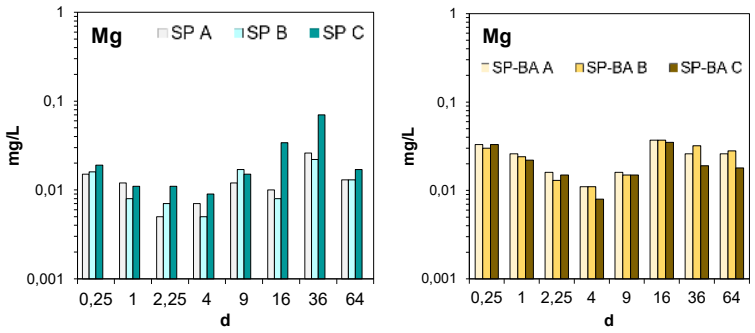


Figure 2. Results of the monolithic test for magnesium: SP on the left, and SP-BA on the right.

The results of the risk analysis showed that, for both scenarios and for both SP and SP-BA samples, the calculated risks were below the regulatory acceptability threshold (PEC/PNEC < 1), as the release of contaminants was very limited for all constituents. Notably, in Scenario 0, which was expected to present higher risks due to direct contact and the absence of attenuation effects, the risk for all contaminants was found to be significantly lower than the acceptable threshold, with differences of several orders of magnitude for Al, Cr, Ni, Zn, chlorides, and sulphates. Further supporting these findings, the compliance leaching tests confirmed the analogous environmental behavior of the two types of samples even after crushing. When comparing the results to Italy's End of Waste decree (152/2022) for construction and demolition materials, no exceedances of the regulatory limits were observed for both materials tested. This result indicates that also the recycled aggregates obtained at the end of life of the tiles, with or without BA addition, would be compatible for use as unbound aggregates from an environmental perspective.

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