AMERICAN UNIVERSITY OF BEIRUT

INCORPORATION OF BOTTOM ASH FROM MUNICIPAL SOLID WASTE INCINERATOR INTO PERVIOUS CONCRETE: A SUSTAINABLE APPROACH

by
GHIDA KAMEL GHOSSON

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GHIDA KAMEL GHOSSON

Approved by:

Rana A. Bilbeisi

Dr. Rana Bilbeisi, Assistant Professor　　Advisor
Civil and Environmental Engineering

Dr. Ghassan Chehab, Associate Professor　　Member of Committee
Civil and Environmental Engineering

Darine Salam

Dr. Darine Salam, Assistant Professor　　Member of Committee
Civil and Environmental Engineering

Date of thesis defense: [January 28, 2021]

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ABSTRACT
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Title: Incorporation of Bottom Ash from Municipal Solid Waste Incinerator into Pervious Concrete: A Sustainable Approach

Amounts of generated municipal solid wastes (MSW) are augmented by the fast population growth and development, making MSW management a great challenge for countries worldwide. Although landfilling is a convenient waste disposal approach, it has hazardous environmental, health, social, and economic effects directing countries to shift towards other waste management approaches. With the advantage of reducing the volume of waste and recovering energy, MSW incineration process is being adopted by various countries. Given that Lebanon is a small country, experiencing waste management challenges, incineration of MSW might offer a solution. Incineration of MSW is the conversion of wastes into flue gas, ash, and heat. Environmental concerns of the incineration process can be addressed by controlling the emissions of hazardous flue gases, and managing the residues (fly and bottom ash). Among the incineration byproducts, bottom ash (BA) constitutes 80-90% of the total ash content. Thus, sustainably dealing with the produced bottom ash is a priority.

The construction industry is facing challenges stemming from overexploitation and, hence, depletion of natural materials. Therefore current global trends are focused on exploring new sustainable recycled materials as alternatives for construction raw materials. This is applicable for all types of concrete structures (conventional concrete, pervious concrete, etc.) in various applications (buildings, bridges, roads, etc.).

Pervious concretes containing 5%, 10%, 20%, and 30% replacement of aggregates with bottom ash were prepared and tested for their air voids content and compressive strength. After validating the viability of bottom ash incorporation into pervious concrete, possible leachability of selected heavy metals from bottom ash - under neutral and acidic water - was investigated.

Results showed that pervious concrete containing 5 up to 20% bottom ash replacement achieved a relatively adequate compressive strength for pervious concrete exceeding 14 MPa. However, the compressive strength dropped when bottom ash content surpassed 20%. As for the leachability of heavy metals, results indicated that the concentrations of heavy metals in all tested water samples are below the allowable limit in waste as set by the Environmental Protection Agency (EPA). The obtained results suggest that bottom ash, as a substitute of aggregate, is environmentally safe.

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CHAPTER 1

INTRODUCTION

1.1 Waste Management

The growing population and fast development have led to the increase in the disposal of municipal solid wastes (MSW) in landfills imposing serious environmental concerns (Luo, Ying, He, & Yang, 2019). Landfilling is one of the frequently adopted waste disposal method being an inexpensive and economical technique for waste management, yet many limitations arise in terms of pollution as well as lands availability. Landfills result in groundwater pollution, soil contamination, rotten smells, and methane emissions that might put both the environmental and public health at risk. Accordingly, landfilling is considered as the least favorable solution for waste disposal (Luo, Ying, He, & Yang, 2019) (Joseph, Snellings, Heede, Matthys, & Belie, 2018) (Dou, et al., 2017) (Bakkali, et al., 2013). To limit the continuous growth of landfills, incineration of municipal solid wastes becomes a more desirable approach. Waste is converted into ash, flue gas and heat after the incineration process (Huber, Blasenbauer, Aschenbrenner, & Fellner, 2019) . Incineration contributes to volume reduction by around 90% and mass reduction by approximately 70% which is a significant decrease requiring less space if the alternative is landfilling (Vaitkus, Gražulytė, Šernas, Vorobjovas, & Kleizienė, 2019) (Luo, Ying, He, & Yang, 2019) (ISWE, 2015). In addition to volume and mass reduction, incinerating wastes generates considerable energy recovery that is either utilized as heat energy or converted into electrical energy (Joseph, Snellings, Heede, Matthys, & Belie, 2018) (Dou, et al., 2017).

The two types of solid byproducts from the MSW incinerators are bottom ash and fly ash. Bottom ash (BA) is the main byproduct of the incineration process constituting approximately 80-90% of the total ash content, which makes its utilization very important in the circular economy (Vaitkus, Gražulytė, Šernas, Vorobjovas, & Kleizienė, 2019) (Chen, et al., 2008). The utilization of bottom ash in construction materials as replacement of natural aggregates has become an attractive alternative to their disposal as it reduces the environmental impacts due to landfilling and conserves natural aggregates from dwindling by providing an ecofriendly sustainable solution to the shortage of natural aggregates. (Vaitkus, Gražulytė, Šernas, Vorobjovas, & Kleizienė, 2019) (Loginiva, Volkov, Van De Wouw, & Florea, 2019) (Valle-Zermeño, Gómez-Manrique, Giro-Paloma, Formosa, & Chimenos, 2017) (ISWE, 2015).

1.2 Waste Management in Lebanon

The waste generation in Lebanon is growing significantly due to the continuous increase in population counts, rapid urbanization and the rise in living standards (Abbas, Chaaban, Al-Rabaa, & Shaar, 2017) (El Fadel & Maalouf, 2019). Lebanon is witnessing a waste management crisis since years due to the closure of the main landfill “Naameh” which was the primary largest sanitary landfill serving more than half the total population of Lebanon. This crisis imposed serious environmental, health, social and economic concerns (El Fadel & Maalouf, 2019).

Approximately 7,500 tons of MSW are generated in Lebanon by which 50% of this amount is dumped in uncontrolled dumpsites, 35% is disposed in sanitary landfills and 15% is converted into organic soil fertilizers or recovered for recycling (El Fadel & Maalouf, 2019).

Lebanon is a relatively small country where the disposal of MSW has always been a challenge due to the scarcity of lands, the dense population, and the lack of awareness on the threats of unsustainable waste management practices. Accordingly, incineration of municipal solid waste is considered a solution that can limit the waste crisis in Lebanon knowing that incineration contributes to a volume reduction by 90%. However, the resulting gaseous emissions (flue gasses) should be captured before being released into the atmosphere and controlled using proper filters and the ash residue should be used rather than being dumped in landfills.

Currently, there is only one working municipal solid waste incinerator in Lebanon called “Sicomo” and located in the Bekaa Valley. Sicomo is a paper and cardboard recycling enterprise. It built its own incinerator years ago to treat the non-recyclable plastic and paper that accumulate in the company. Nowadays, it is also used to burn garbage sent to the incinerator by different Lebanese Municipalities. Sicomo’s incinerator consists of two chambers and a heat recovery system. The wastes are fed into the **primary chamber** and burned at a temperature of 850ºC where incomplete combustion takes place due to the low air-to-fuel ratios. Bottom ash residue settles down from the primary chamber whereas the volatile and gasified residues are burned in the **secondary chamber** at a temperature of 1100ºC in the presence of excess O_2 allowing complete combustion to take place. The short retention time (2.5 seconds) in the secondary chamber, the excess O_2 quantities and the relatively high temperature ensure that all gaseous products are entirely oxidized. In the **heat recovery system**, the temperature of the flue gas from the secondary chamber is immediately reduced to 270ºC thus stabilizing the remaining toxic particles. Granular Activated Carbon and Sodium Bicarbonate are then added to adsorb the remaining particles and heavy metals from the flue gas and to reduce excess hydrogen chloride (HCl) levels resulting in a neutralized flue gas.

Incineration converts the waste material into flue gas, ash, and heat. The ash that rises up with the flue gases is the fly ash while the heavier ash that settles down is the bottom ash. The bottom ash used in this research is the residue that comes out from the primary chamber noting that bottom ash constitutes 80-90% of the total ash content. Sicomo incinerator produces about 8,000 kilos per day of bottom ash.

1.3 Bottom Ash: Definition, Properties & Applications

Bottom ash is defined as a grey porous light weight material which is made up of ash, molten particles, ferrous and non-ferrous metals, potsherds and glass fragments (Wu, Lin, Huang, & Chen, 2016) (ISWE, 2015). Its particles size varies from 0.01 mm up to 100 mm (Loginiva, Volkov, Van De Wouw, & Florea, 2019). Bottom ash particles consist mainly from rocks, slag, glass and fine gravel, which are non-combustible materials in addition to threads & films that are unburnt organic matter and from metallic items and scraps (Loginiva, Volkov, Van De Wouw, & Florea, 2019) (ISWE, 2015). It is considered a granular material (Valle-Zermeño, Gómez-Manrique, Giro-Paloma, Formosa, & Chimenos, 2017). A common type of bottom ash is the coal bottom ash (CBA) generated during the coal combustion in thermal power plants. Another important source of bottom ash is that coming from waste incineration. The waste incinerated can be municipal waste, medical waste, biomedical waste, industrial waste, etc.

Bottom ash properties vary depending on the type and composition of the input waste and the parameters of the incinerator (Vaitkus, Gražulytė, Šernas, Vorobjovas, &

Kleizienė, 2019) (Joseph, Snellings, Heede, Matthys, & Belie, 2018). The primary constituents of bottom ash are silicon oxide, calcium oxide, ferric oxide, aluminum oxide, sodium oxide, magnesium oxide and other traces of metal oxides. These constituents make it similar to crushed stone and soil in composition (Luo, Ying, He, & Yang, 2019) (ISWE, 2015) (Kuo, C.C., & Su, 2013). Besides, some quantities of heavy metals such as chromium, nickel, lead, mercury, cadmium and zinc that are also commonly present in bottom ash (Luo, Ying, He, & Yang, 2019).

One of the common practices to dispose of bottom ash is dumping it in landfills. However, if the entire bottom ash residue resulting from the incineration process were to be buried, there would be no enough landfills to accommodate it (Kuo, C.C., & Su, 2013). Here arises the importance of utilizing bottom ash. Nowadays, different applications involve the integration of bottom ash. The main applications of bottom ash include: (1) in road construction as aggregate in foundation layers, sub-base layers and embankment (Joseph, Snellings, Heede, Matthys, & Belie, 2018) (Lynn, Ghataora, & Dhir, 2017), (2) in the production of cement and concrete (Luo, Ying, He, & Yang, 2019), (3) in controlled low-strength materials (Kuo, C.C., & Su, 2013) (ISWE, 2015), (4) in concrete blocks and concrete tiles (ISWE, 2015), (5) as aggregates in concrete (Dou, et al., 2017) (Kuo, C.C., & Su, 2013) (Chen, et al., 2008), (6) in glass and ceramic (Luo, Ying, He, & Yang, 2019), (7) as adsorbents (Luo, Ying, He, & Yang, 2019) and (8) as highway embankments/noise barriers (ISWE, 2015).

1.4 Pervious Concrete

Urbanization increased the construction of conventional impermeable pavements, which drastically influence the environment by changing the natural pervious ground into an impervious surface (Chandrappa & Biligiri, 2016). Here comes the importance of permeable pavements as an environmentally friendly pavement material substituting conventional pavements and thus minimizing the negative impacts on the environment (heat island effect, polluted runoff, etc.). Permeable pavements can be pervious concrete, porous asphalt, plastic grid systems or concrete interlocking blocks (Kassem, Al Hassanieh, Mrad, Chehab, & Abou Najm, 2016) .The use of pervious concrete is gaining research interest due to the legislations imposed by the Federal Water Pollution Control Act and the Environmental Protection Agency (EPA) for the quality and quantity of storm water runoff (Zhong, Leng, & Poon, 2018) and the environmentally friendly characteristics in reducing the heat island effect (Kuo, C.C., & Su, 2013). Pervious concrete is known as a sustainable building material (ACI, 2010). It has many environmental, economic, and structural advantages. Some advantages are controlling storm water runoff, reducing pollution of runoff water, reducing heat island effect, recharging groundwater, increasing road traffic safety, and enhancing skid resistance. Disadvantages of pervious concrete however, comprise limitations in strength and durability and the risk of clogging if not properly designed and maintained (Zhong, Leng, & Poon, 2018) (Zaetang, Wongsa, Sata, & Chindaprasirt, 2013) (Kuo, C.C., & Su, 2013) (Welker, Barbis, & Jeffers, 2012).

Pervious concrete (PC) is defined by the American Concrete Institute (ACI) as an open-graded and zero slump material (ACI, 2010). It is a concrete mixture consisting of Portland cement, coarse aggregate, water and a little to no fine aggregates. (Tijani, Ajagbe, Ganiyu, & Agbede, 2019) (Tripathi, Hussain, & Madhav, 2017; Kassem, Al Hassanieh, Mrad, Chehab, & Abou Najm, 2016). The porosity of pervious concrete typically varies from 15 to 35%, the permeability is usually between 1.4 and 12.3 mm/s and the compressive strength ranges from 2.8 to 28 MPa (ACI, 2010). Since pervious concrete is characterized by its high porosity, then the resulting compressive strength is less than that of conventional impervious concrete. (Tijani, Ajagbe, Ganiyu, & Agbede, 2019) (Wu, Lin, Huang, & Chen, 2016) (Kuo, C.C., & Su, 2013). Pervious concrete is used in numerous applications mainly in permeable pavements (for parking lots, sidewalks, pathways and local roads with minimal heavy truck traffic) and as water purification and noise absorbing materials (Zhong, Leng, & Poon, 2018) (Kim, Jang, Khalid, & Lee, 2017) (ACI, 2010).

CHAPTER 2

RESEARCH OBJECTIVES AND SIGNIFICANCE

2.1 Research Objectives

Deviating the effect of waste into various useful applications is a crucial aspect of sustainability. Accordingly, exploiting waste material and using it in construction applications as a sustainable alternative for natural aggregates provide a green and environmentally friendly solution for managing MSW residues. This solution protects the public health and environment, reduces the amount of wastes in landfills and consequently ground water contamination, and it saves resources used in construction from dwindling. Therefore, utilizing bottom ash by incorporating it into pervious concrete, as a partial replacement of aggregate, is considered a sustainable alternative for the disposal of bottom ash in landfills.

The first objective of this research is to investigate the physical and chemical properties of bottom ash collected from a local municipal solid waste incinerator, and its compatibility as partial replacement of aggregates in pervious concrete. Physical and chemical properties of bottom ash will be compared to those of natural aggregates to verify the suitability of using bottom ash in pervious concrete applications without significantly sacrificing the mechanical properties. Therefore, the compressive strength of the pervious concretes will be evaluated to determine the optimum percentage replacement of natural coarse aggregates without compromising its compressive strength.

The second objective of the study is to address the leachability of metals from the utilized bottom ash. Bottom ash samples will be digested to determine their heavy metal content (using representative metals) before testing the leachability of metals from bottom ash incorporated into pervious concrete specimens.

2.2 Research Significance

The increase in the municipal solid wastes and the dwindling of natural resources used in construction triggered us to account for both phenomena by finding a sustainable construction material alternative. This research focuses on utilizing bottom ash, as a sustainable alternative, replacing classically used natural aggregates in pervious concrete. After determining the physiochemical characteristics of BA, various pervious concrete cylindrical specimens were developed with different BA percentage replacement to check the compatibility of BA as a construction material without significantly sacrificing the compressive strength of the pervious concrete. This incorporation is considered a green and promising solution for waste disposal in landfills, as it decreases harmful effects on the environment. It also reduces the overall amounts of natural aggregates extracted from quarries and used in the continuously growing construction industry in Lebanon thus saving natural resources.

The outcome of this research offers a sustainable solution exploiting BA residue from the incineration of municipal solid wastes in pervious concrete while getting adequate compressive strength and showing that heavy metals content in the leachate are less than the allowable limits in waste as stated by the EPA. It is to be mentioned here that using pervious concrete also has its own significance and advantages in controlling storm water runoff and preventing flooding, recharging ground water, reducing pollution of runoff water, reducing the heat island effect, etc.

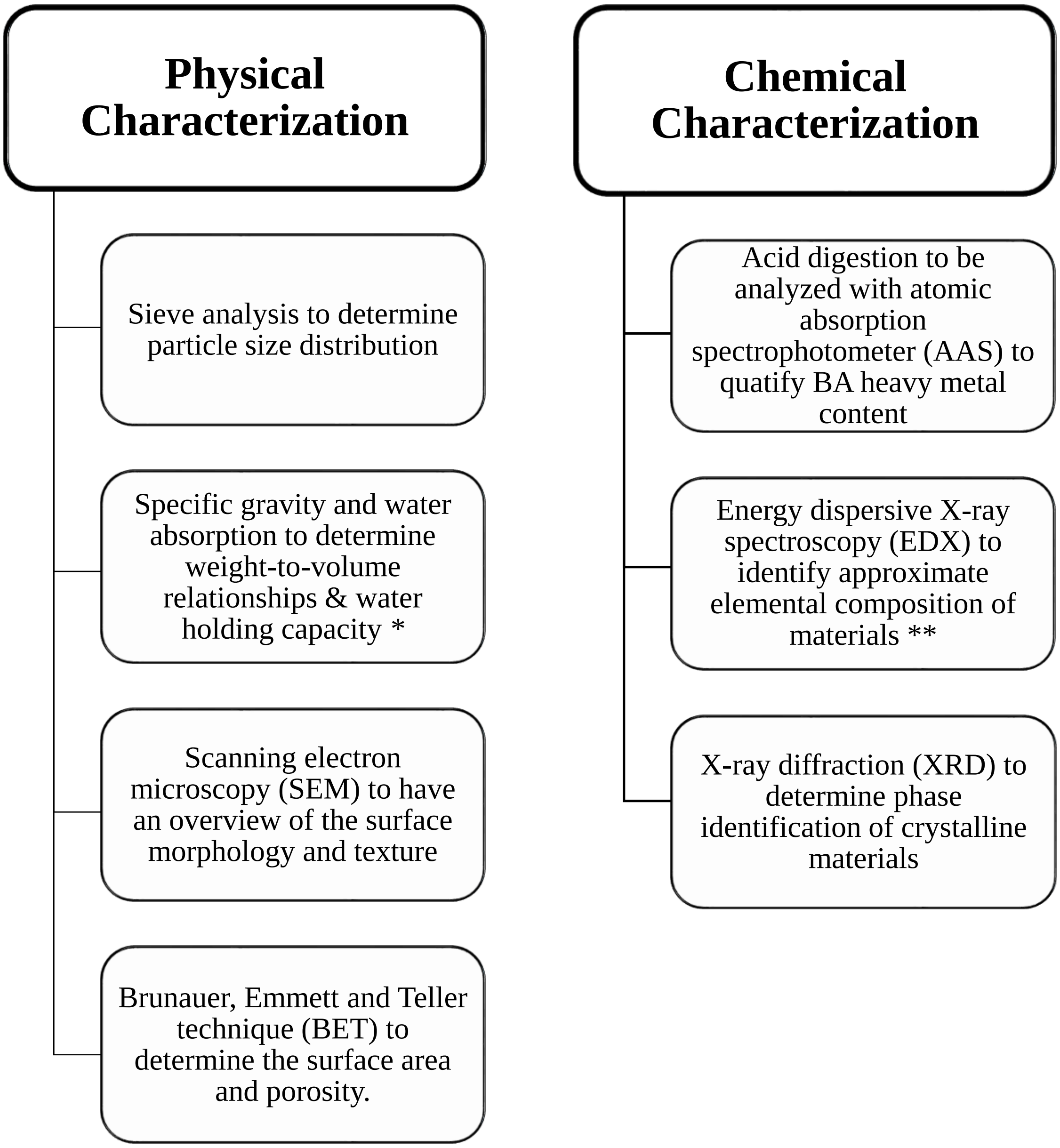
CHAPTER 3

METHODOLOGY

The properties of aggregate such as size, shape and distribution affect the mechanical properties of pervious concrete pavements (Tijani, Ajagbe, Ganiyu, & Agbede, 2019); so it is very crucial to understand the physical and chemical properties of bottom ash prior to its incorporation in pervious concrete. To achieve the objectives of this research, bottom ash physiochemical properties were investigated before incorporating different proportionality of BA in pervious concrete and testing its leachability. Therefore, in this research the experimental work was divided into three phases: (1) the experimental analysis to determine the physical and chemical properties of bottom ash particles, (2) the experimental procedure to determine the effect of incorporating bottom ash into pervious concrete on the compressive strength of the concrete samples and (3) the experimental investigations to assess the metal leachability of the BA incorporated samples.

3.1 Bottom Ash Characterization

The utilization of BA is highly dependent on their physiochemical properties (Dou, et al., 2017). This section provides the experimental methodology followed for the detailed characterization of bottom ash particles to assess and better understand their potential as partial replacement of aggregates. Bottom ash characterization was performed to determine the particle size distribution, surface morphology, approximate elemental composition, surface area, pore size, pore volumes, specific gravity and water absorption of the bottom ash samples. The experimental procedure adopted for the characterization of bottom ash is shown in the figure hereafter.



*A control is also tested based on the aggregates used in the study
**EDX does not necessarily represent the elemental composition of the bulk sample.

Figure 1: Experimental procedure for BA characterization

3.1.1 Physical Characterization

a. Particle size distribution

Particle size distribution plays a crucial role in utilizing bottom ash. It is crucial to the way a material performs in use. Studies have proved that utilizing bottom ash is correlated to its particle size distribution (ISWE, 2015).

Sieve analysis was done to determine the particle size distribution i.e. gradation of the bottom ash samples. Prior to sieving, the sample was oven-dried for 24 hours to help remove the moisture and prevent lump formation. Particle size distribution was determined in accordance with ASTM C136.

b. Specific gravity and water absorption

The specific gravity of both aggregate and bottom ash was used in mixture proportioning calculations by finding the absolute volume that a given material will occupy in a mixture. Specific gravity was defined as the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water. It is the measure of strength or quality of a material by which aggregates having low specific gravity are weaker than those with higher specific gravity. As for the water absorption test, it determines the water holding capacity of the aggregates and bottom ash. Water absorption was determined after 24 hours soaking time of bottom ash and aggregates.

The specific gravity and water absorption of the bottom ash and control aggregate used in the study are determined according to the test method of ASTM C128. The following equations are used for the calculation of specific gravity and water absorption:

- Specific Gravity (SSD Basis) = $W_{SSD}/ W_{SSD} - W_{Submerged}$
- Specific Gravity (OD Basis) = $W_{OD} / W_{SSD} - W_{Submerged}$
- Absorption (%) = $100*(W_{SSD}- W_{OD})/ W_{OD}$

Where, W_{SSD} is the weight of the sample at saturated surface dry conditions after being soaked in water for the specified period of time (24 hours); and W_{OD} is the weight of the sample after drying in oven for 24 hours.

c. Scanning electron microscopy (SEM)

The morphological study of the bottom ash samples was performed using Scanning Electron Microscopy (SEM). SEM analysis was conducted to analyze the shape, surface and structure of the MSWI-BA. SEM images provide a better analysis for the morphology as well as the porosity and identify the core-shell structure of the samples. The instrument used for SEM analysis was the TESCAN, VEGA 3 LMU, Scanning Electron Microscope. Prior to analysis, a sputter coater was used to coat the samples with a 20 nm platinum layer. The purpose of sputtering is to try to overcome charging effects and thus have high-resolution images. For the SEM, a voltage of 5 kV was used at different magnifications and scales ranging from a minimum of 50 µm to a maximum of 200 µm.

d. Brunauer, Emmett and Teller Technique (BET)

Brunauer, Emmett and Teller (BET) test was performed to measure the specific surface area in addition to the pore size and pore volume of bottom ash. The bottom ash samples were degassed in the vacuum degassing oven at 70ºC for 24 hours and then degassed again at 90ºC in the BET degassing system for about 3 hours prior to BET test. The degassing is mainly done to remove the adsorbed species from the samples ensuring that no moisture is present and thus having accurate results. The volume of gas adsorbed to the surface of the particles is measured at the boiling point of nitrogen (-196°C).

The BET instrument MICROMERITICS GEMINI VII Version 3.04 was used for the analysis, the evacuation rate was 30 kPa/min, the equilibration time was 5 seconds, and the saturation pressure was around 101.3 kPa.

3.1.2 Chemical Characterization

a. Acid digestion

The acid digestion of the bottom ash was performed by adding 60 ml of 65% Nitric acid to 4g of the bottom ash sample placed over a 90 ºC water bath for 2 hours until total digestion of the bottom ash sample. The sample was then filtered using a 2.5 µm filter. Afterwards, distilled water was added to reach a final volume of 200 ml. This diluted sample was tested for metals using Atomic Absorption Spectrophotometer.

b. Atomic Absorption Spectrophotometer

Atomic Absorption Spectrophotometer (AAS) is a spectrophotometry method that is used to identify the chemical composition of a sample based on the absorption of specific frequencies of light by atoms.

Heavy metals are commonly present in bottom ash samples. Accordingly, the concentrations of likely existing heavy metals in bottom ash (i.e. Pb, Cd and Cr) were investigated to make sure that concentrations do not exceed regulatory standards for hazardous substances and therefore its use as partial replacement of coarse aggregate in pervious concrete would not cause threats to the surrounding.

Atomic Absorption Spectrophotometer was used for two different purposes: 1) calculating the metal content of bottom ash and 2) testing for the leachability of bottom ash.

To analyze the trace elements and identify selected metal content of bottom ash, the bottom ash was acid digested using Nitric Acid (HNO_3) and the quantification and analysis of the heavy metals were done using the flame method of AAS analysis. As for the leachability of metals, it was tested after incorporating bottom ash into pervious concrete.

c. Energy Dispersive X-Ray Spectroscopy (EDX)

Energy Dispersive X-Ray (EDX) experiment was performed to determine the chemical composition of the control aggregates and bottom ash samples. EDX provides an approximate elemental analysis of the sample. However, this elemental analysis does not specify the chemical form in which each element occurs. EDX identifies the elemental composition of a specific part of the sample.

EDX analysis was carried out while performing the Scanning Electron Microscopy where laser beams are concentrated on either a point or a surface area of the sample until it is burned out thus estimating the chemical composition of the burned point/area of the sample.

Approximate elemental composition of the control aggregates and bottom ash was determined by selecting random spectrum points on SEM images. The average weight percentage for each element was determined as the average of the measured and selected spectrums. It is to be noted that EDX results do not necessarily represent the chemical composition of the bulk sample.

d. X-Ray Diffraction (XRD)

X-Ray Diffraction (XRD) was performed for phase identification of crystalline materials present in the bottom ash samples. Burker X-ray D8 advance was used to perform the XRD analysis. XRD patterns were recorded with radiation at 40 kV and 40 mA, a scan type of coupled 2θ and within a scanning range of 5 to 80 degrees.

3.2 Incorporation of Bottom Ash in Pervious Concrete

The figure below summarizes the experimental procedure followed to incorporate bottom ash into pervious concrete.

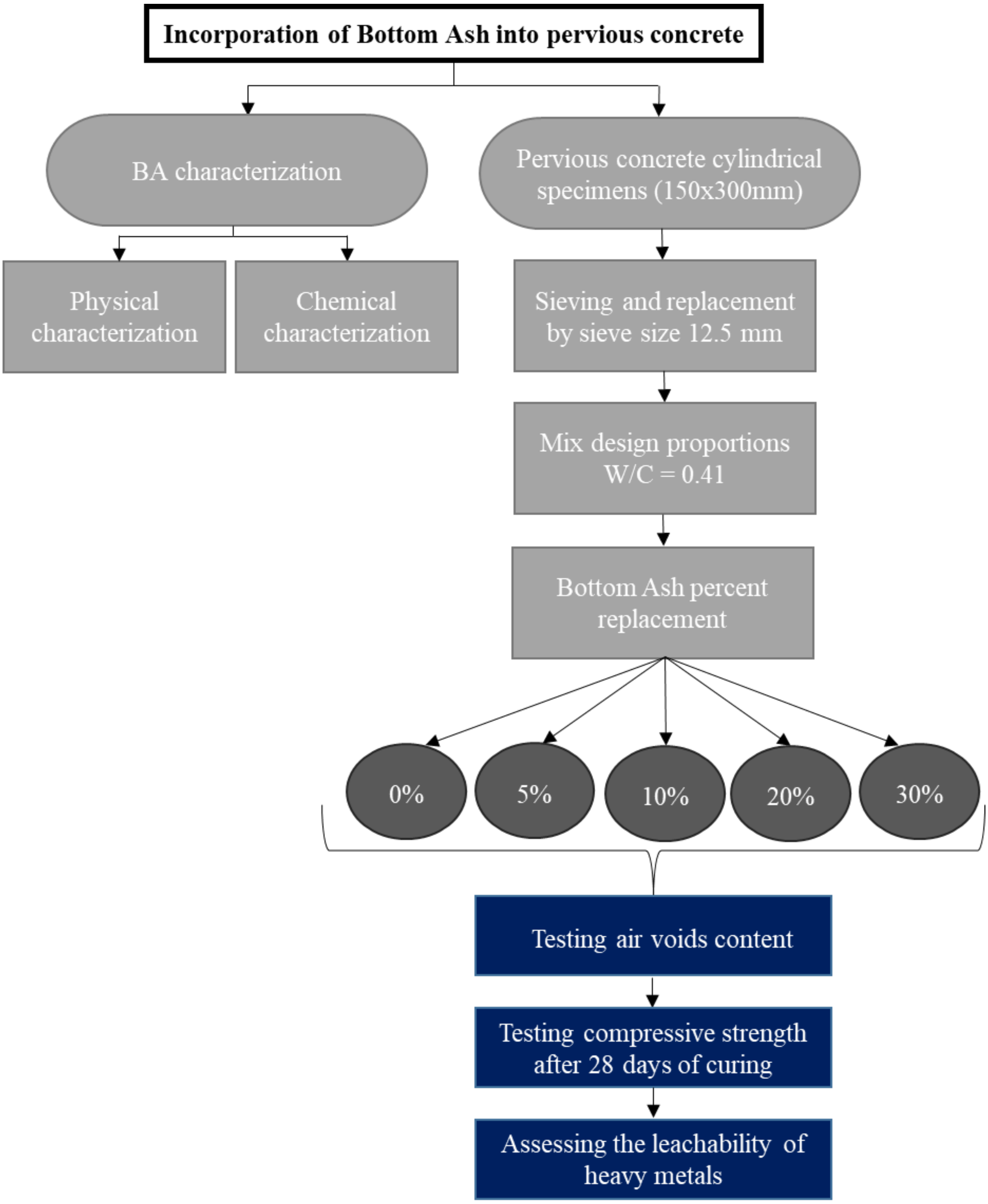


Figure 2: Methodology of incorporating BA into pervious concrete with different percent replacement

3.2.1 Materials

a. Cement

Type I Portland Cement obtained from Holcim local distributor in Chekka, Lebanon was used throughout this research.

b. Aggregate

12.5 mm single-sized limestone aggregates obtained from local quarries in Lebanon were used in all the pervious concrete mixes.

c. Bottom Ash

12.5 mm single-sized bottom ash particles obtained from a municipal solid waste incinerator located in Beqaa, Lebanon were used in the pervious concrete mixes.

d. Water

Tap water obtained from the materials laboratory was used throughout the research to prepare the pervious concrete specimens with a fixed water to cement ratio of 0.41 (Kassem, Al Hassanieh, Mrad, Chehab, & Abou Najm, 2016) as clearly illustrated in section 3.2.3 and then distilled water was used for curing the prepared cylindrical specimens.

3.2.2 Sample preparation

The bottom ash samples were dried for 24 hours at 100ºC, in an oven, and then cooled to room temperature. Bottom ash, being a waste material, was not sorted nor processed at the plant. Miscellaneous undesirable wastes (ceramic, glass, papers, etc.) were found. Accordingly, the bottom ash was sorted manually to remove the unwanted waste particles and attain a homogeneous mix and then sieved to get the desired 12.5 mm (1/2”) particle size.

3.2.3 Mix design proportions

Mix designs were adopted from the paper “Method to Investigate Mix Design Parameters of Pervious Concrete Mixtures” with water to cement ratio (w/c) of 0.41 and volume of binding mortar (Vmb) of 20% as recommended by the authors for pervious concrete mixes with single-sized aggregates of 12.5 mm. This recommendation is to have better air voids content and compressive strength (Kassem, Al Hassanieh, Mrad, Chehab, & Abou Najm, 2016) .

Ten different pervious concrete specimens were prepared with an effective w/c of 0.41. Duplicate specimens were developed using blended aggregate samples containing 0%, 5%, 10%, 20% and 30% BA replacement. The specimens were water cured for 28 days then tested for compressive strength to determine to what extent BA can be incorporated in pervious concrete.

3.2.4 Mixing procedure

The mixing of pervious concrete was carried out by hand in a pan following the below mixing procedure:

1. The limestone aggregates and bottom ash were mixed together to ensure homogeneity.
2. The required quantity of cement was spread all over the aggregates and bottom ash.
3. The cement, aggregates and bottom ash were mixed intimately.
4. A hollow was made in the middle of the mixed pile and then the required quantity of water was added.
5. The mixing continued until a uniform, homogeneous and consistent mix was obtained.

After mixing, the concrete samples were cast in the cylindrical metal molds and placed in a closed room to set and harden for 24 hours. After 24 hours, the specimens were demolded from the forms and placed in distilled water to be cured for 28 days. The top and bottom edges were sawed to remove irregularities within the specimens and ensure parallelism before conducting the compressive strength test.

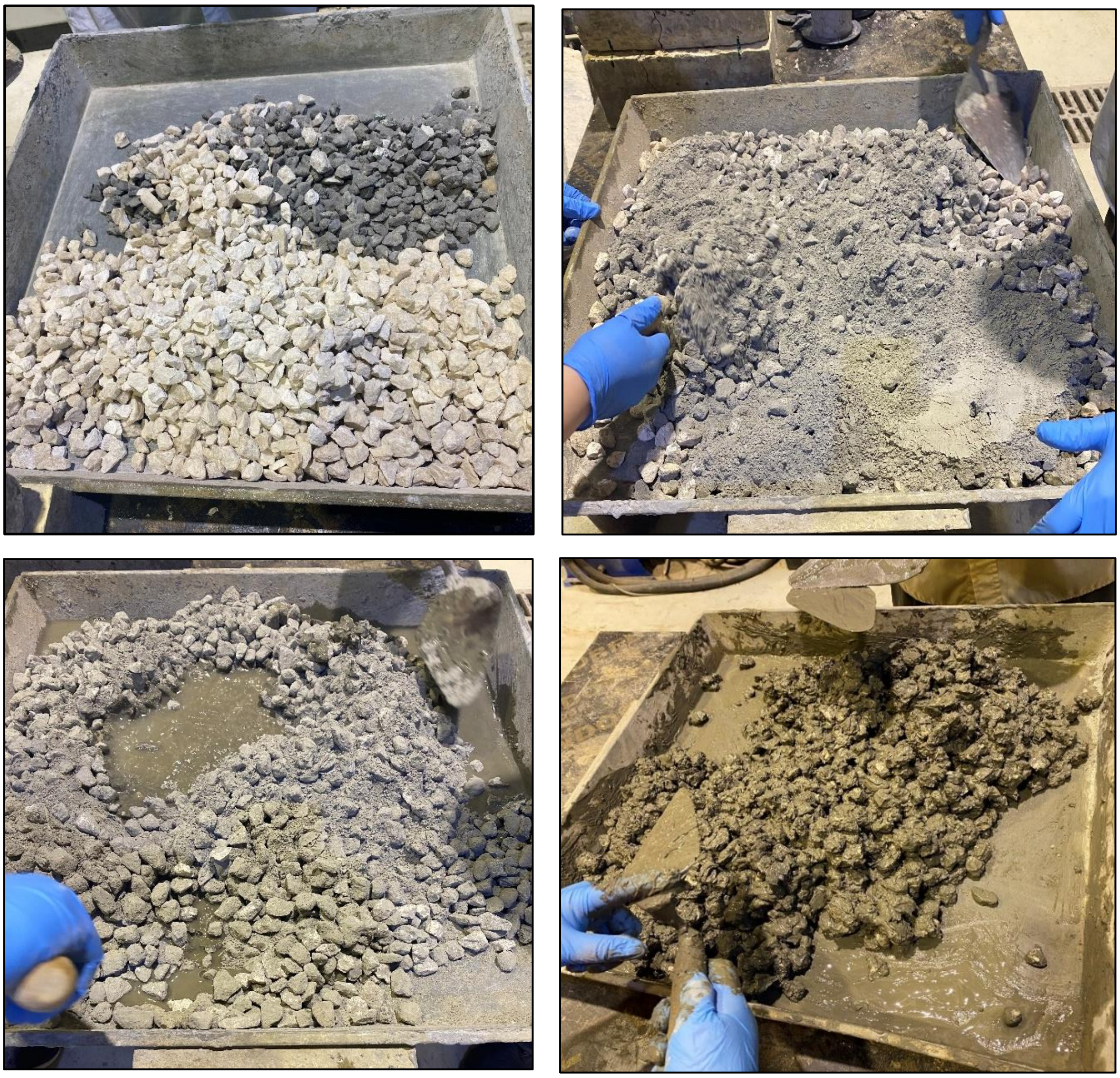


Figure 3: Hand mixing of 30% BA-based pervious concrete in a pan using limestone aggregates, bottom ash, cement and water

3.2.5 Air voids content and compressive strength testing

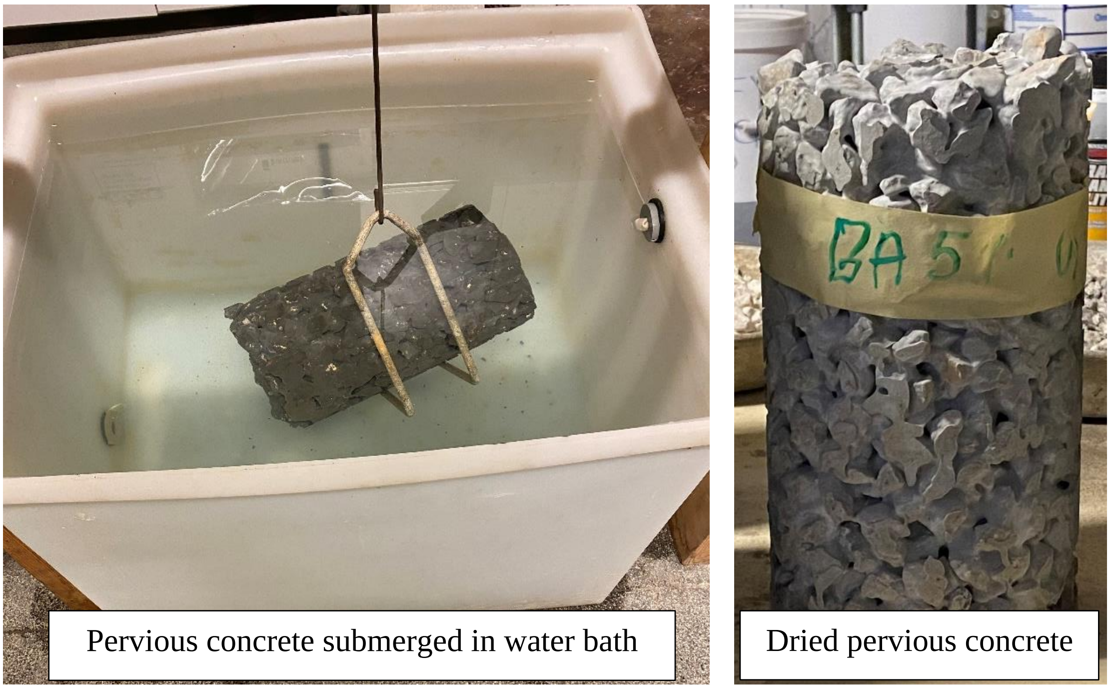
After preparing the cylindrical specimens with standard dimensions of 150 mm diameter and 300 mm height, the air voids content and compressive strength of the cylinders were tested. A total of 10 pervious concrete specimens were casted for all mixes of 0, 5, 10, 20 and 30% bottom ash replacement. Measurements of the cylinder dimensions (diameter and height) were recorded before the air voids and compressive strength test to correct for any size differences. The specimens were cured for 24 hours in the laboratory directly after being casted and then removed and cured in distilled water for 28 days. The compressive strength of the cylindrical specimens is reported as the average of two replicates for each mix design.

a. Air voids content

The volumetric method was adopted to determine the air void content of the pervious concrete specimens in accordance with ASTM C1754. The specimens were submerged in a water bath for 30 minutes and then the submerged masses were measured. Afterwards, the specimens were dried and the dry masses were recorded. The air voids content was calculated as follows:

$$\text{Air void content} = \left[1 - \left(\frac{K\ x\ (A-B)}{\rho\mathrm{w}\ x\ \mathrm{D2}\ x\ L}\right)\right] x\ 100$$

Where, A is the dry mass of the specimen (g), B is the submerged mass of the specimen (g), D is the specimen average diameter (mm), L is the specimen average length (mm), ρ_w is the density of water at the temperature of the water bath (kg/m^3), and K is a constant equal to 1,273,240 in SI units.



Pervious concrete submerged in water bath

Dried pervious concrete

Figure 4: Pervious concrete containing 5% BA submerged in a water bath for 30 minutes and then dried in an oven for the air voids content test

b. Compressive strength

The compressive strength was tested according to ASTM C39 after 28 days of curing. Since the pervious concretes have irregular surface due to aggregate overhang, the top and bottom edges were sawed to remove irregularities within the specimens and ensure parallelism before conducting the compressive strength test. The pervious concrete specimens were also capped prior to the compressive strength test to provide a better distribution of the compression force. The specimens were pressured until the point of fracture, then the maximum load was measured and the compressive strength was calculated as follows:

Compressive strength = F/A

Where, F is the maximum load in Newton and A is the area of the cylindrical specimen in cm^2.

0% Bottom Ash

5% Bottom Ash

Figure 5: 150 mm x 300 mm capped pervious concretes containing 0% and 5% BA respectively

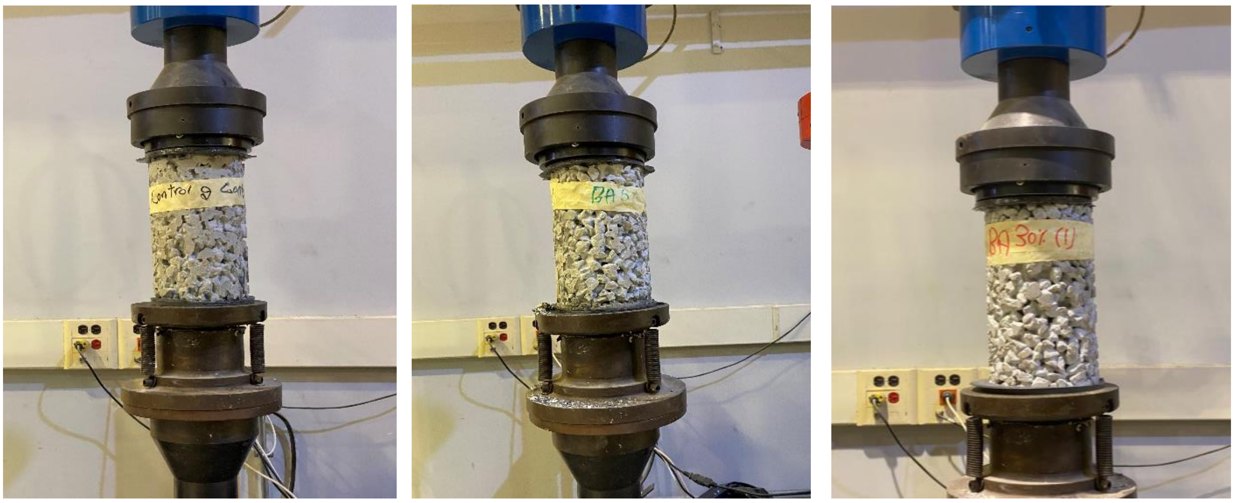


Figure 6: Compressive strength testing of pervious concrete with 0, 5% and 30% BA replacement respectively

3.3 Leachability of Heavy Metals

The most important issue, when using bottom ash from a municipal solid waste incineration, is the leaching of harmful elements. Through the leaching process, various types of pollutants are produced in which heavy metals are the most toxic and concerned (Luo, Ying, He, & Yang, 2019).

The Environmental Protection Agency (EPA) defines a toxic chemical as any substance that can be considered harmful to the environment or health if inhaled, ingested, or absorbed through the skin. Lead, cadmium, chromium, arsenic and mercury are rank among the priority heavy metals that are of public health significance since they are extremely toxic and can induce organ damage even at low levels of exposure (Tchounwou, Yedjou, Patlolla, & Sutton, 2012). Cr, Cd, Cu, Zn, Hg, Ni and Pb are the common existing heavy metals in municipal solid waste incineration bottom ash. These heavy metals may lead to serious environmental concerns if leached out (Luo, Ying, He, & Yang, 2019). As reported by Luo et al, heavy metals account for 0.5% by weight of municipal solid waste incinerator bottom ash (Luo, Ying, He, & Yang, 2019).

In this research, three heavy metals which are lead, cadmium and chromium, will be examined to check if they could leach out from the bottom ash based pervious concrete specimens. The leachability of heavy metals was tested using the AAS - Flame method at different stages of the project as follow: (1) testing the curing water of the pervious concrete specimens after 28 days of curing, (2) passing water into the pervious concrete cylinders and testing the infiltrated water, and (3) demolishing the pervious concrete specimens then immersing the rubble in water, of neutral and acidic pH, and testing the water for heavy metals content.

It is important to check that the bottom ash, which was collected from Sicomo’s municipal solid waste incinerator, is not harmful to the environment. If the concentration of leached heavy metals exceeds the regulatory limits in waste, then the bottom ash is considered as hazardous waste and should be treated before being used in concrete or dumped in landfills. The concentrations of heavy metals in water were compared to the allowable limits in waste as declared by the Environmental Protection Agency (EPA).

Table 1: EPA allowable limits of heavy metals in waste (EPA, Environmental Protection Agency, 2015)

Element	EPA allowable limits (mg/L)	AAS detection limit (mg/L)
Pb	5	17.5
Cr	5	12.5
Cd	1	3.75

Figure 7: Pervious concrete cured in 11.85 liters of distilled water for 28 days

Figure 8: 50 ml of water infiltrated into 30% pervious concrete and collected after 1 minute

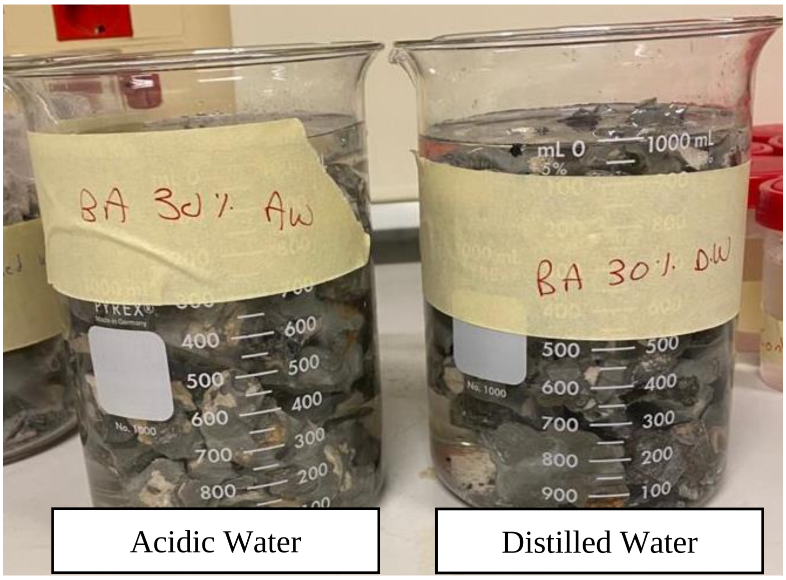


Figure 9: Rubble from pervious concrete containing 30% bottom ash immersed for 24 hours in 1000 ml acidic water and 1000 ml distilled water

CHAPTER 4

RESULTS AND DISCUSSIONS

Results and discussions of the conducted studies to investigate the metal composition; properties of BA samples and their incorporation in pervious concrete, as partial replacement of natural aggregates, are described in this section.

4.1 Bottom Ash Characterization

4.1.1 Physical Characterization

a. Particle size distribution

Particle size distribution of BA bulk samples was determined by performing progressive dry sieving of 2 kg of the sample as received from Sicomo. The particle size distribution of bottom ash is presented in Figure 10. It is revealed that particle size varies in the range from 0.074 mm to 25.4 mm. This is comparable to the natural aggregate size and distribution. Results indicate that about 75% of the bottom ash particles were found in the typical range of fine particles (0.074 to 2.38 mm), whereas the remaining represent the coarse particles (4.75 to 19 mm).

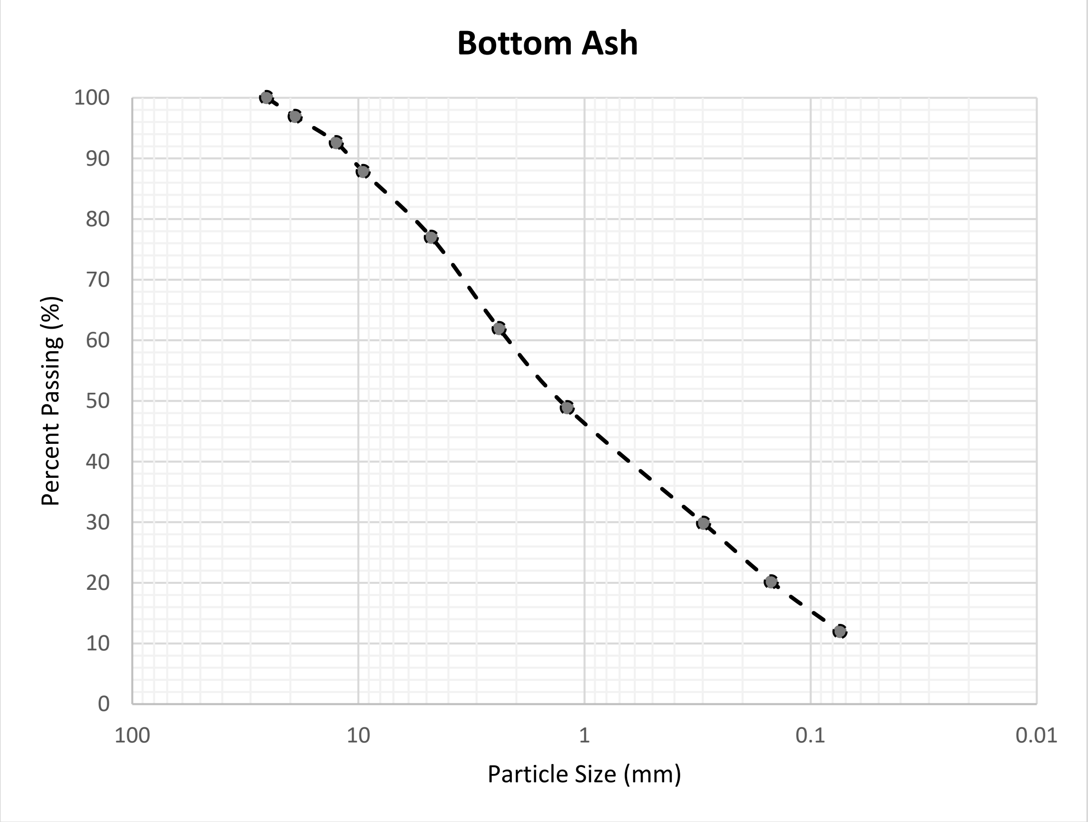


Figure 10: Particle size distribution of Bottom Ash

b. <u>Specific gravity and water absorption</u>

Specific gravity was done to determine the strength of the aggregate by which aggregates with a low specific gravity are weaker than those with a higher specific gravity. As for the water absorption, it determines the water holding capacity of the aggregates. Results indicated that BA exhibited a lower specific gravity and higher water absorption than conventional aggregates, as expected, since BA is a light weight and porous material that is known for its water absorption capacity (Wu, Lin, Huang, & Chen, 2016) (Kuo, C.C., & Su, 2013).

From the specific gravity test, it was found that the specific gravity of the bottom ash is 2.24, less than that of control aggregates which is 2.65 indicating that BA had less strength compared to conventional aggregate. This would definitely decrease the compressive strength when using bottom ash as a substitute of aggregates. The water absorption results, however, demonstrated that BA is a highly absorptive material characterized with a porous structure. The water absorption of the BA is around 12 times greater than the water absorption of control aggregates. Since BA are more porous than control aggregates, and thus will absorb more water to provide workability, then it is crucial to calculate the additional amount of water that should be added to the mix to maintain the desired water for the workability of the mix.

Table 2: Specific gravity and water absorption of bottom ash and natural aggregate

Parameter	Bottom Ash	Control Aggregate
Specific Gravity	2.24	2.65
Water Absorption (%)	6.82	0.59

Figure 11: Specific gravity and water absorption for 12.5 mm control aggregates and 12.5 mm bottom ash

c. Scanning electron microscopy (SEM)

SEM analysis was performed to analyze the shape, surface, structure, and porosity of the BA particles. The figure below shows the SEM images for the BA under different scales. It was revealed that BA particles are of irregular shapes, with no particular pattern, and with a rough texture. Moreover, the SEM images showed the availability of pores indicating that BA is porous, supporting the water absorption results. According to Chen *et al.*, SEM images for natural aggregates illustrate that aggregates consist of solid particles with a relatively dense packing structure (Chen, et al., 2008).

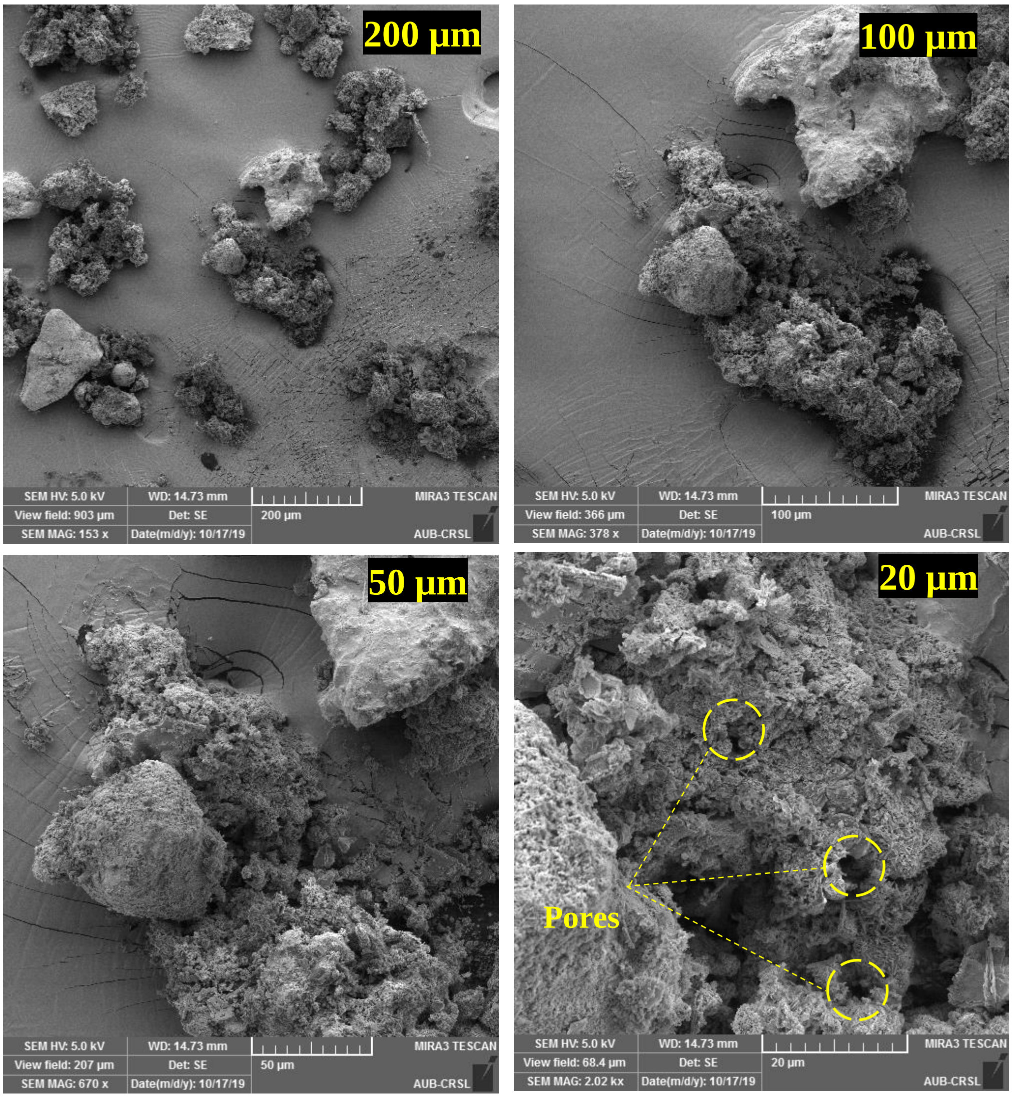


Figure 12: SEM images for the MSWI-BA (bulk sample)

4.1.2 Chemical Characterization

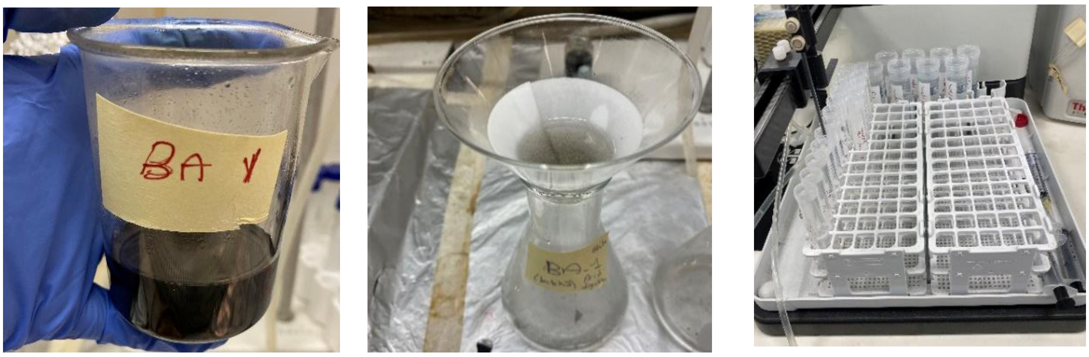
a. Atomic Absorption Spectrophotometer (AAS)

Bottom ash metal content varies depending on the type and composition of the incinerated waste material and the incineration process. Bottom ash, from a municipal solid waste incinerator, is produced from the burning of wastes at temperatures up to 950°C. The main constituents of BA are in the form of oxides, which are similar to the basic constituents of aggregates. However, BA contains some heavy metals such as lead, cadmium, chromium, mercury and zinc that are environmentally hazardous. The different particle sizes, the relatively large surface area, and the high porosity of the BA allow heavy metals to be adsorbed on the surface of ash residue during the burning of wastes (Chen, et al., 2008) (Gorme, et al., 2010). Particle size highly affects heavy metals content in the BA particle. As indicated by Luo et al., MSWI-BA with particle sizes less than 4 mm contain more heavy metals such as cupper, chromium, mercury and lead (Luo, Ying, He, & Yang, 2019). Similarly, Valle-Zermeño et al. determined that fine BA particles possess higher heavy metals content, mainly for lead, Zinc, Copper, Manganese and Titanium (Valle-Zermeño, Gómez-Manrique, Giro-Paloma, Formosa, & Chimenos, 2017).

In this study, metal content of MSWI-BA samples, collected from Sicomo, was analyzed for selected heavy metals using AAS analyses. AAS analyses were performed on the acid digested BA samples to quantify metal content per BA particle size before incorporating it in concrete mixes. Separated BA particles were digested by treating them with 65% Nitric Acid over a water bath for 2 hours at 90^{o}C. Five different particle sizes (<0.074 mm, 0.149 – 0.297 mm, 1.19 – 2.38 mm, 4.75 – 9.5 mm and 12.5 – 19 mm) of the bottom ash samples were tested for lead (Pb), cadmium (Cd) and chromium

(Cr). The calibration curves for the aforementioned metals are included in the appendix. As expected, results show that there is an inverse correlation between the metal content of tested bottom ash samples and their particle size distribution; in other words, it was found out that large particle sizes have less significant heavy metal content. Therefore, as indicated the particles size of bottom ash is an important factor that affects the concentration of heavy metals in the BA particle itself because the small particle size increases the available surface area exposed to adsorption process. Accordingly, heavy metals composition is higher in fine particles, that's why heavy metals were largely present in the smallest particle size (<0.074 mm) and the lowest heavy metals concentrations were in the largest particle size range (12.5 –19 mm).

12.5 mm BA | 65% nitric acid | Placed over a water



Digested BA | Filtered BA | Testing heavy metal content

Figure 13: Acid digestion of 12.5 mm BA particle using 65% nitric acid followed by metal analysis using AAS

Table 3: Distribution of selected metal content in BA samples of different particle sizes

Bottom Ash Particles	**Particle Size (mm)**	**Concentration (mg/kg ash)**		
		Pb	**Cd**	**Cr**
Filler	< 0.074 mm	2931	226	99
Fine Particles	0.149 – 0.297 mm	294	19	37
	1.19 – 2.38 mm	281	Not Detected	34
Coarse Particles	4.75 – 9.5 mm	65	Not Detected	30
	12.5 –19 mm	Not Detected	Not Detected	22

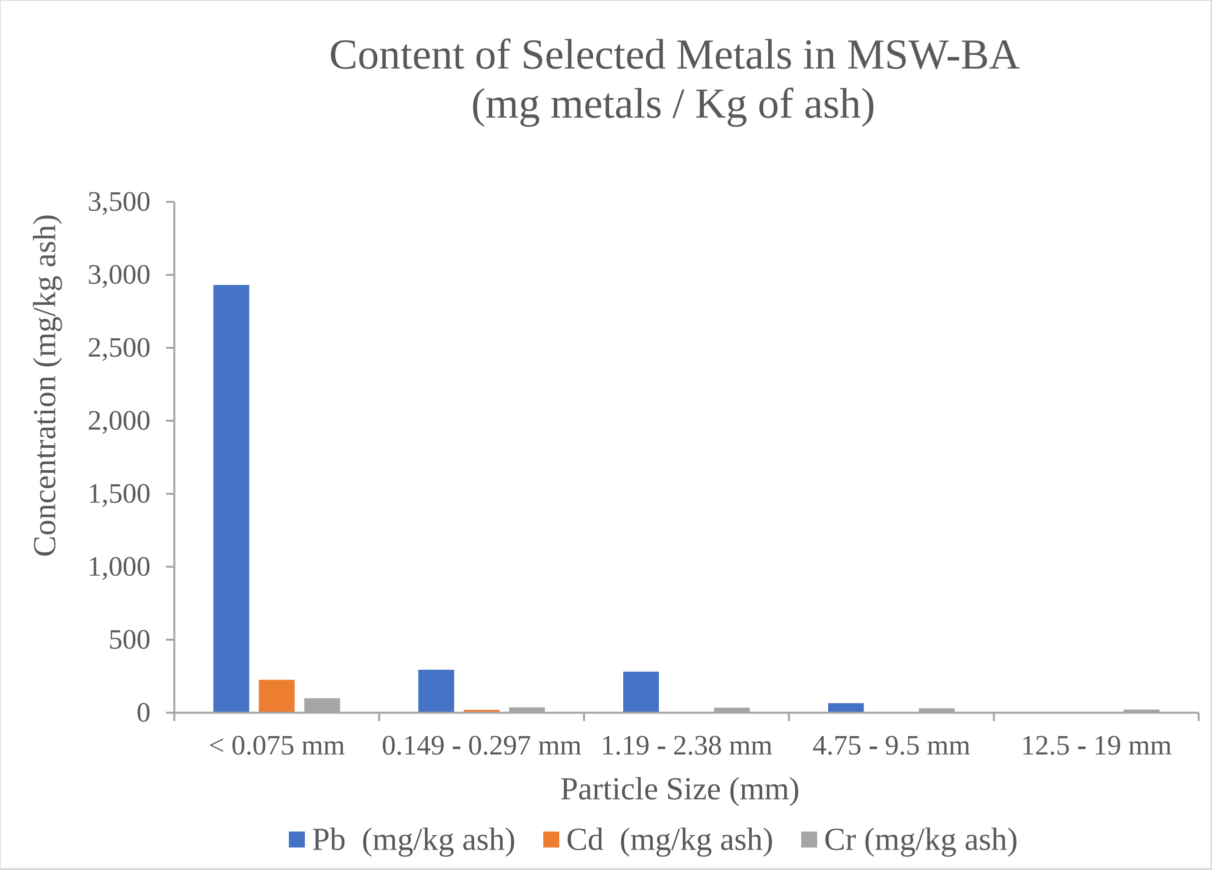


Figure 14: Bar chart showing the concentration of selected metal content (mg/kg) as a function of different MSWI-BA particle sizes

b. Energy Dispersive X-Ray Spectroscopy (EDX)

EDX was performed to determine approximate elemental composition of the 12.5 mm control limestone aggregates and the 12.5 mm bottom ash particles, to ensure that BA has a similar composition as control aggregates and thus can be a potential substitute for aggregates. The results presented in the tables below represent the average weight percentage for each element, which is estimated as the average of the randomly selected spectrums.

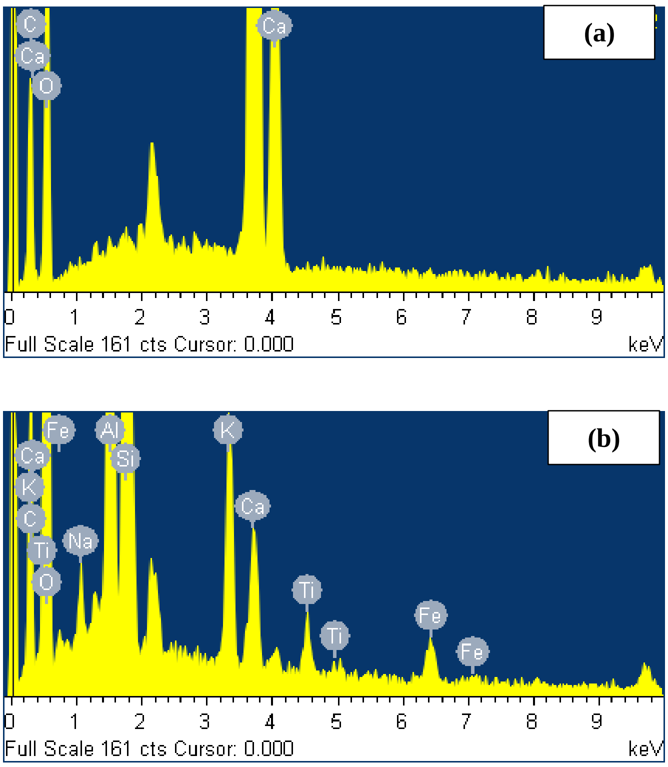


Figure 15: EDX spectra of: (a) control aggregate and (b) bottom ash sample

Table 4: Approximate elemental composition of 12.5 mm bottom ash

Element	**% by Weight**
Carbon	24.88
Oxygen	49.74
Sodium	0.13
Aluminium	5.38
Silicon	5.27
Potassium	0.74
Calcium	7.78
Titanium	1.47
Iron	4.61
Total	100

As indicated in the above figure, the major elements are Oxygen, Carbon and Calcium in the control aggregates which is expected since it is a limestone aggregate composed of calcium carbonate. As for the bottom ash sample, the major components are also Oxygen, Carbon and Calcium in addition to traces of Aluminum, Silicon, Potassium, Titanium, Iron and other metals are also scattered randomly. EDX results showed that traces of heavy metals were not detected, supporting the acid digestion and atomic absorption spectrophotometry analyses.

c. <u>X-Ray Diffraction (XRD)</u>

The sharp diffraction peaks of the XRD patterns for the BA correspond to quartz. It was found that quartz is predominant in all the BA particle sizes. There are also two other main components, which are feldspar and magnesium ferrite present in all the sizes of BA (Loginiva, Volkov, Van De Wouw, & Florea, 2019). The prevalent phases in the MSWI-BA are quartz and various aluminosilicates (Loginiva, Volkov, Van De Wouw, & Florea, 2019). This makes BA potential candidate for construction materials.

4.2 Incorporation of Bottom Ash in Pervious Concrete

4.2.1 Mix design proportions

Adopted mix design proportions for the pervious concrete specimens using single-sized aggregates of 12.5 mm and a fixed water to cement ratio of 0.41 are presented in Table 7. Mix designs are modified as per the percentage of bottom ash substituting natural aggregate in pervious concrete mix. Additional water is added to saturate the bottom ash and aggregates and for the workability of the mix based on the water absorption results (Table 2).

Figure 16: Pervious concrete cylinders with different BA percent replacement

Table 5: Mix design proportions

ID	**CA* %**	**BA %**	**CA (Kg)**	**BA (Kg)**	**Sand (Kg)**	**Water (Kg)**	**Cement (Kg)**	**Additional water to saturate CA (g)**	**Additional water to saturate BA (g)**
C0	100	0	7.1	0.0	0.0	0.9	2.1	41.9	0
BA05	95	5	6.7	0.4	0.0	0.9	2.1	39.8	24.2
BA10	90	10	6.4	0.7	0.0	0.9	2.1	37.7	48.4
BA20	80	20	5.7	1.4	0.0	0.9	2.1	33.5	96.8
BA30	70	30	5.0	2.1	0.0	0.9	2.1	29.3	145.1

*Control Aggregate

4.2.2 Air voids content and compressive strength results

Ten pervious concrete cylindrical specimens were prepared (duplicates of all the percentage replacements) comprising two control specimens without bottom ash and the remaining eight specimens include bottom ash as partial replacement of coarse aggregates with 5%, 10%, 20% and 30% bottom ash replacement. After curing the pervious concrete specimens in distilled water for 28 days, the air voids content and compressive strength of each cylinder were evaluated.

Mixes containing 5 up to 30% BA were developed, water cured and tested for their compressive strength, to determine to what extent considerably bottom ash can be incorporated in pervious concrete and the effect of the replacement on the compressive strength.

a. Air voids content

The air void content test (porosity test) is a key property of pervious concrete. It is the main factor that affects the permeability of the pervious concrete (Kuo, C.C., & Su, 2013). The air void content of pervious concrete typically ranges from 15 to 35% (ACI, 2010). Measured average air void content of the developed pervious concrete specimens are presented in Figure 17. The average air void content for the control specimens was 14%, whereas the 5%, 10%, 20% and 30% bottom ash replacement contained average air voids of16%, 16%, 13% and 22% respectively. The average air void content of the mixes with 5%, 10% and 30% BA replacement ranged between 16% and 22% thus meeting the specifications set by the ACI. However, that of the control specimens and the 20% BA replacement was slightly less than the lower limit of the air void content range, which is 15%; nonetheless, some references specify the lower limit for the porosity to be 11% (Wu, Lin, Huang, & Chen, 2016).

Air void content is dependent on several factors: aggregate gradation, cementitious material content and water to cement ratio. Moreover, as the density of the pervious concrete drops, the air void content increases (Tijani, Ajagbe, Ganiyu, & Agbede, 2019); this is also indicated in Table 6. The higher porosity noticed in the BA based pervious concrete might be due to the porous structure of the bottom ash itself and the influence of the rounded shape of the bottom ash particles (Tijani, Ajagbe, Ganiyu, & Agbede, 2019).

Table 6: Air void content and density of specimens with different BA percent replacement

BA Percent Replacement (%)	**Average Air Void Content (%)**	**Average Density (Kg/m^3)**	**Standard Deviation (±)**
0	14	2,022	0.54
5	16	1,966	3.81
10	16	1,954	0.19
20	13	2,013	0.04
30	22	1,829	1.10

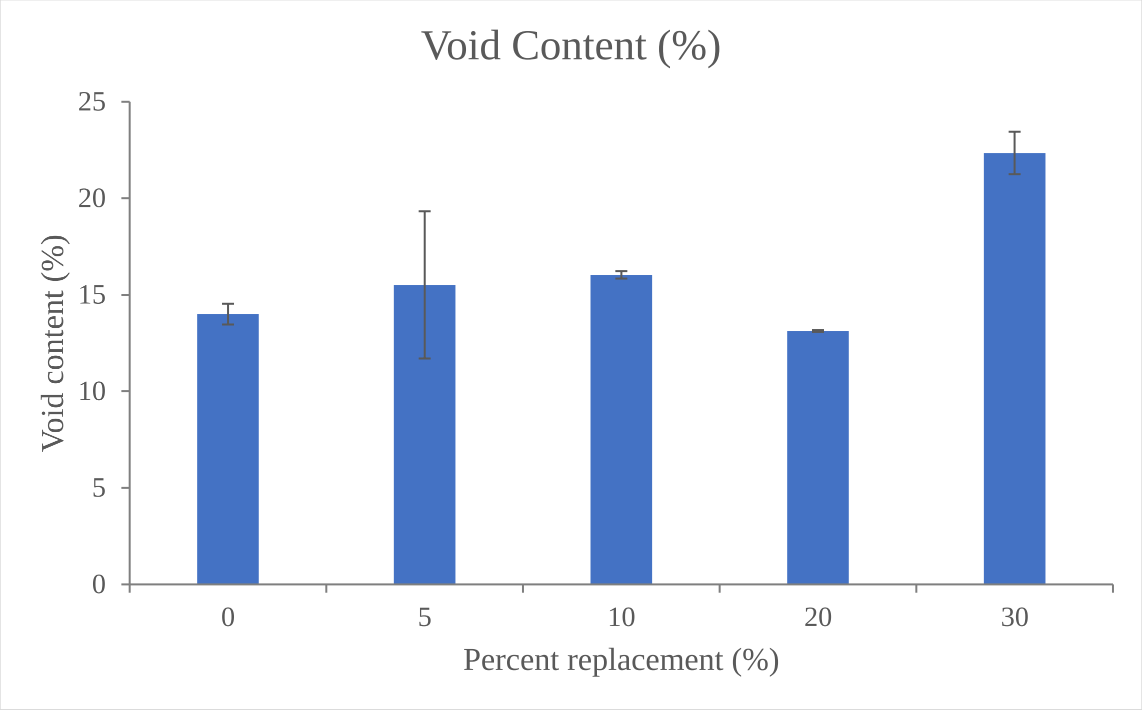


Figure 17: Air voids content of pervious concrete for mixes with 0, 5, 10, 20 and 30% bottom ash replacement. The error bars attached to each column represent the standard deviations

b. Compressive strength

The compressive strength results for the pervious concrete with 0 to 30% bottom ash replacement at 28 days of curing are presented in Figure 19. The average compressive strength of the control specimens was 21.72 MPa. As expected, the compressive strength decreased when incorporating bottom ash into the pervious concrete mixes. The 10% BA based pervious concrete specimens recorded the highest strength of 15.95 MPa. The specimens containing 5% and 20% BA recorded a compressive strength of 14 and 13.7 MPa respectively. However, the mixes with 30% replacement showed the lowest strength of 8.69 MPa compared to the control mix, which had the highest compressive strength. The mixes containing 5%, 10% and 20%

BA exhibited a decrease in the compressive strength relative to the control mix by 35%, 27% and 37% respectively, while the mix containing 30% BA exhibited a huge drop in the compressive strength, which was calculated to be around 60%. There is almost a plateau in the decrease of compressive strength representing the 5 to 20% replacement. However, after increasing the percent replacement up to 30% BA, the compressive strength dropped immediately by 60% relative to the control mix and by 37% relative to the specimen with 20% bottom ash.

Several studies showed the relation between the air void content and the compressive strength (Wu, Lin, Huang, & Chen, 2016) (Kassem, Al Hassanieh, Mrad, Chehab, & Abou Najm, 2016). There is an inverse relationship between the air voids content and the compressive strength, so the greater the air void content of a pervious concrete the lesser is its compressive strength. The mix with 30% bottom ash replacement recorded the highest air void content, that’s partially why it had a significantly reduced compressive strength compared to the other specimens that had relatively lower air void content values.

The higher compressive strength of the control mixes might be due to the angular shape of the limestone aggregates, which would allow a stronger bond between the aggregates and the cement (Tijani, Ajagbe, Ganiyu, & Agbede, 2019). However, the rounded shape of the bottom ash might affect the proper interlock between aggregates and thus a lower compressive strength is produced. This is illustrated in Figure 18. It is worth mentioning here that the rounded bottom ash particles shape can be changed into angular shape by crushing the bottom ash particles, doing this allows a better interlock between the aggregates therefore increasing the compressive strength.

As reported by Tijani et al, the aggregate strength highly affect the compressive strength, meaning that stronger aggregates produce higher compressive strength (Tijani, Ajagbe, Ganiyu, & Agbede, 2019). Since bottom ash had a relatively smaller strength relative to the limestone aggregates, as indicated from the specific gravity test in Table 2, then the compressive strength of BA based pervious concrete specimens would be lower than that of the control specimens.

Briefly, the results show that the strength of the pervious concretes prepared with the incorporation of BA (up to 30%) is adequate, exceeding 14 MPa for pervious concrete containing 5 to 20% BA replacement and approximately 9 MPa for the mixes containing 30% BA thus meeting the strength requirements for the pervious concrete as set by the ACI (2.8 to 28 MPa). Due to the limited compressive strength, which is less than 20 MPa, it cannot be used for busy roads and high traffic. Accordingly, these mixes can be used for sidewalks, pathways and walkways, general bicycle ways, landscaping, pavement curbs and patios (Engineers, 2018) (Wu, Lin, Huang, & Chen, 2016).

It is worth mentioning that the strength of the pervious concrete can be improved by using fibers or by replacing some of the cement with supplementary cementitious materials or pozzolanic materials (Tang, C.K., & Tsai, 2019).

Figure 18: Shape of bottom ash and control limestone aggregates

Table 7: Compressive strength results with different BA percent replacement

BA Percent Replacement (%)	**Average Compressive Strength (MPa)**	**Standard Deviation (±)**
0	21.72	2.31
5	14.06	0.4
10	15.95	0.12
20	13.72	0.16
30	8.69	0.05

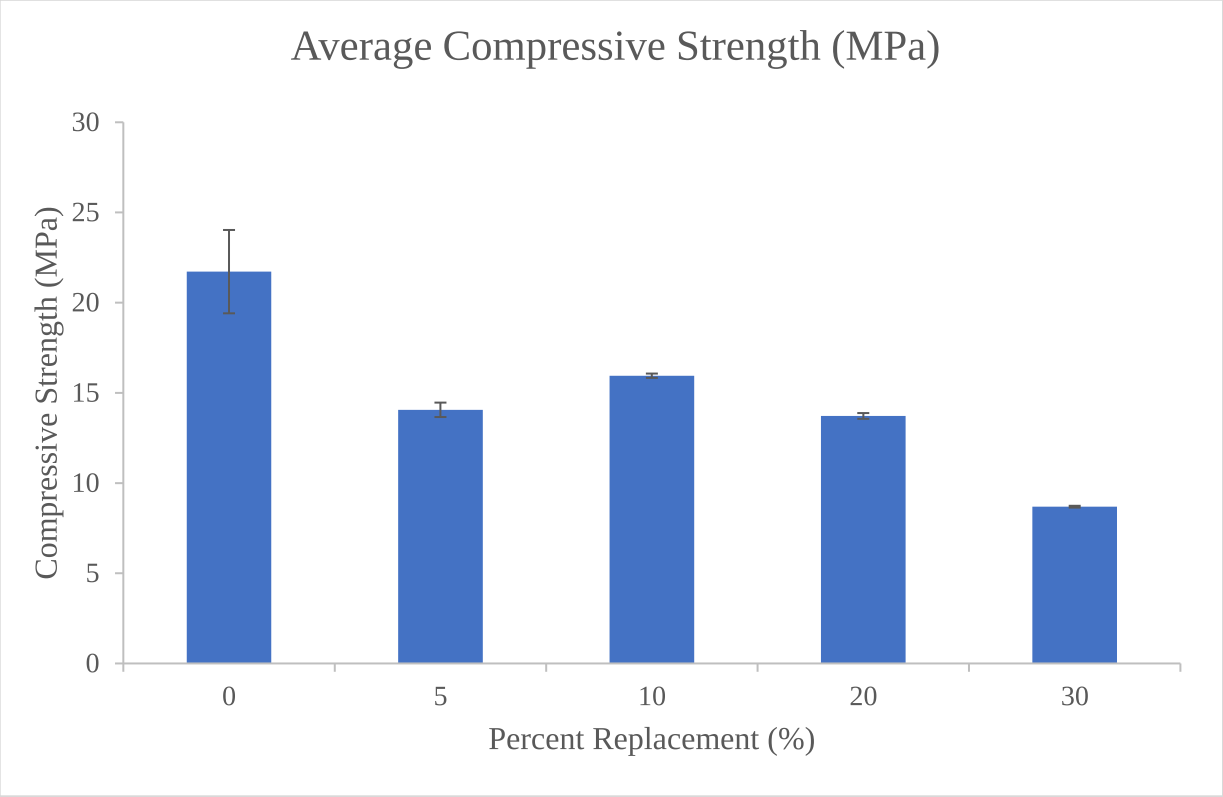


Figure 19: Compressive strength of pervious concrete for mixes with 0, 5, 10, 20 and 30% bottom ash replacement under water curing conditions of 28 days. The error bars attached to each column represent the standard deviations

4.3 Leachability of Heavy Metals

After assessing the suitability of using BA as a partial replacement (5 up to 30%) of coarse aggregates in pervious concrete mechanically, it is important to check that this incorporation is environmentally safe. The major issue, when using bottom ash from a municipal solid waste incineration, is the leaching of heavy metals. Accordingly, leachability of metals is tested to check if heavy metals would leach out of the prepared BA-containing - pervious concretes cylinders.

Leachability of metals was investigated at different stages of the project. First, each of the prepared cylinders were cured separately in 11.85 liters of distilled water and covered at room temperature for 28 days. The curing water was then collected and its heavy metals content was analyzed using AAS. Afterwards, distilled water (DW) was infiltrated into the pervious concrete cylinders (control specimens, 5% BA, 10% BA, 20% BA and 30% BA) and the collected water was also analyzed. Acidic water (AW) was infiltrated through the 30% BA containing pervious concrete specimen. In each case, the collected water was tested for Pb, Cd and Cr. Finally, after crushing the pervious concrete specimens, rubble from the demolished pervious concretes were immersed in distilled and acidic water (pH of 5.5) and similarly tested for heavy metals content. As mentioned earlier, heavy metals were evaluated using the flame method of the atomic absorption spectrophotometer and the results are compared with the allowable limits of heavy metals in waste as stated by the Environmental Protection Agency (EPA, Environmental Protection Agency, 2015).

4.3.1 Curing Water

The leaching results of selected metal contents (Pb, Cd and Cr) from the curing water of the pervious concretes, after 28 days of curing, are presented in Figure 20. It was found that neither lead nor cadmium was detected in the curing water, which was expected since these two heavy metals were not detected in the 12.5 mm bottom ash particle itself when digesting the sample as presented in Table 3. Chromium, on the other hand, was detected in all the curing water samples, including the control sample. Chromium results fluctuated between 0.103 mg/l to 0.13 mg/l in an almost increasing trend from specimens with 0% BA (control) to specimen with 30% BA, this is predictable due to the increase in BA content. Leachability of chromium from the control specimens is due to the chromium leaching from cement used in preparing the pervious concrete specimens (Estokova, Palascakova, & Kanuchova, 2018). It was found that the concentration of leached chromium from the control pervious concrete specimens is equal to that incorporating 5 and 10% BA, demonstrating that chromium is leaching from the cement. However, after incorporating 20 and 30% BA, the concentration of leached chromium started to slightly increase indicating that after 20% BA incorporation, chromium starts leaching from the BA – incorporated into pervious concrete specimens. However, all the concentrations of the leached chromium from all pervious concrete cylinders are below the EPA limitations for chromium in waste, which is 5 mg/l (EPA, Environmental Protection Agency, 2015).

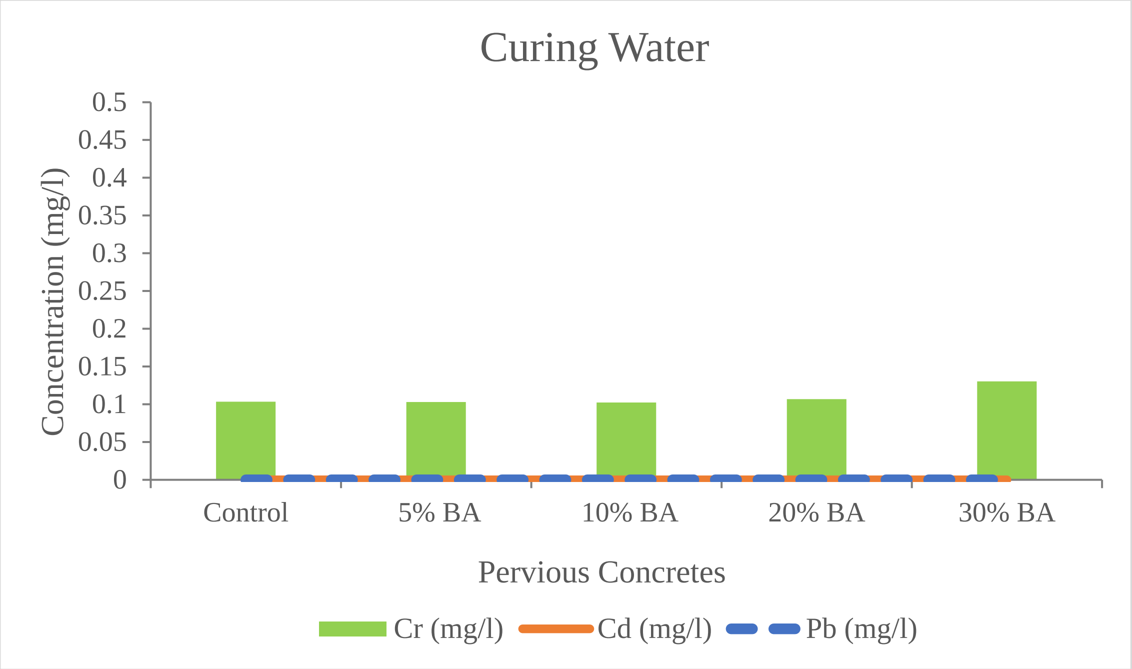


Figure 20: Concentrations of Cr, Cd, and Pb in curing water after 28 days of curing of all specimens

4.3.2 Infiltrated Water

The second stage of assessing the leachability of heavy metals is by infiltrating water through different casted pervious concrete cylinders, including control specimens and specimens with BA (5 up to 30%). Testing of infiltrated water is of great importance to make sure that water percolating through the pervious concrete into the groundwater will not result in groundwater and the soil contamination. In this stage, distilled water was infiltrated through all pervious concrete specimens and acidic water (pH of 5.5) was infiltrated only through the specimen with the highest percentage of BA which is 30%, being the most critical as it includes more BA.

The results of the leaching of Pb, Cd and Cr in infiltrated water through all pervious concrete cylinders are presented in Figure 21. Pb and Cd were not detected in the all infiltrated water indicating that their concentrations are below the concentrations allowed in waste for Pb and Cd as set by the EPA which are 5 mg/l and 1 mg/l, respectively. Again, this is justifiable since neither Pb nor Cd was detected in the used 12.5 mm BA (Table 3). Chromium, however, was detected in all the specimens, ranging from 0.073 mg/l to 0.094 mg/l. The highest chromium concentration (0.094 mg/l) was detected in the distilled water infiltrated through the 30% BA pervious concrete, this is expected as it contains more bottom ash than other specimens. There is a direct correlation between the percentage of BA and the metal content, by which the concentration of leached chromium increases as the percentage of BA increases (5 to 30%). However, control specimens were found to leach Cr of 0.085 mg/l, which is due to chromium leaching from cement used in the pervious concretes (Estokova, Palascakova, & Kanuchova, 2018). As indicated earlier, in the 5 and 10% BA-based pervious concrete cylinders, the concentration of leaching chromium is almost the same which is due to chromium leaching from cement; however, after 20 and 30% BA replacement, leaching chromium concentration increased indicating that it is leached due to the presence of BA. Regarding the AW infiltrating the 30% BA - containing - pervious concrete, it was expected that more chromium will be leached when infiltrating acidic water into the pervious concrete however this was not the case by which 0.079 mg/l of chromium leached from the 30% BA based pervious concrete. This might be due to the short contact time between the acid percolating through the pervious concrete and the BA used in the pervious concrete cylinders.

All results of leaching chromium from infiltrated water are less than that from curing water, this might be due to the washing of the heavy metals during the curing process of 28 days.

Most importantly, the concentrations of leached chromium from all infiltrated water through pervious concrete specimens are below the limits for chromium in waste as declared by the EPA, which is 5 mg/l (EPA, Environmental Protection Agency, 2015) and also below the EPA limits for drinking water, which is 0.1 mg/l (EPA, Environemntal Protection Agency, 2018). Since water percolates through the pervious concrete to the ground water, the leaching concentrations of chromium were also compared to the drinking water limits as per the EPA.

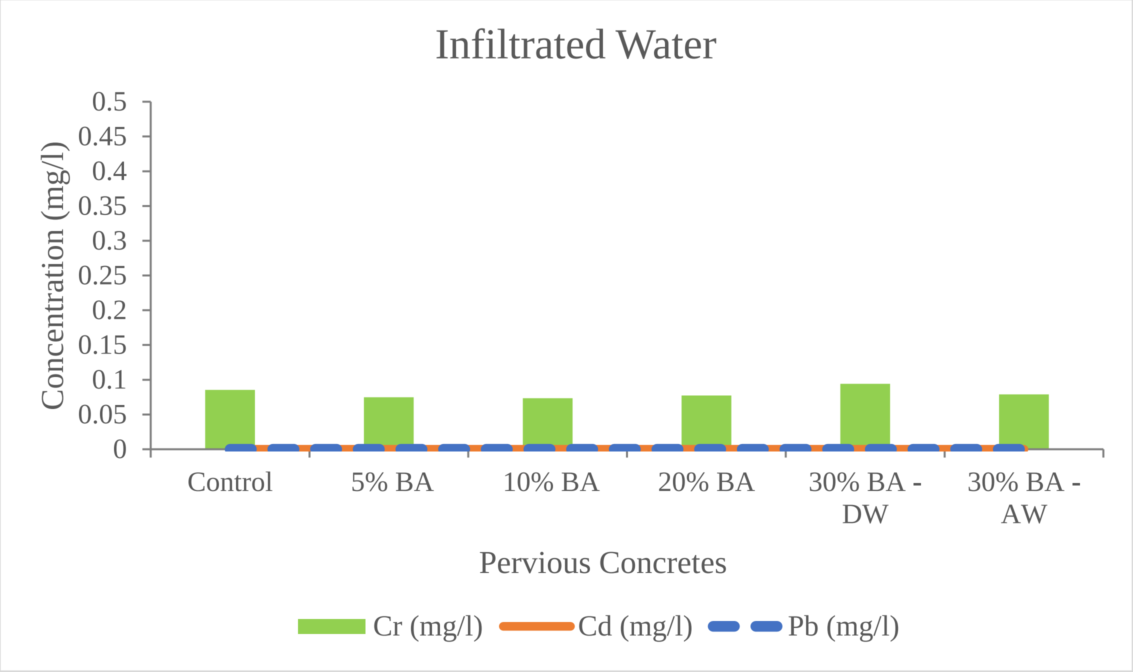


Figure 21: Concentrations of Cr, Cd, and Pb in infiltrated water through pervious concrete cylinders

4.3.3 Rubble Immersed in Distilled and Acidic Water

After performing the compressive strength test on the different casted pervious concrete cylindrical specimens and after demolishing the specimens. A constant weight of 800g was taken from each demolished pervious concrete cylinder and immersed in distilled water and acidic water (pH of 5.5). Results of Pb, Cd and Cr leaching from the demolished specimens are listed in Figure 22 and Figure 23. It was found that demolishing the cylinders before immersing them in water increases the leachability of leaching of chromium in some specimens, which is expected due to the increased surface area when demolishing the pervious concrete cylinders.

Pb and Cd were not detected in all demolished specimens, similarly this is because both heavy metals were not detected in the 12.5 mm BA used. Chromium, however, was detected in the all the water samples. Chromium readings fluctuated between 0.08 mg/l and 0.17 mg/l when immersing the demolished specimens in distilled water and between 0.07 mg/l to 0.18 mg/l when immersing the demolished cylinders in acidic water. No clear trend was found and with the highest chromium concentration leaching from the control specimens which is due to the leaching of chromium from the cement (Estokova, Palascakova, & Kanuchova, 2018). This might be due to the immersion of only part of the specimen in water (800 grams) rather than immersing the whole specimen (10 kilograms). Therefore, leaching of chromium might be affected by the distribution of bottom ash within the pervious concrete specimen itself. Briefly, no correlation between the bottom ash percent replacement and the leachate contents could be observed. Despite the fluctuation in chromium concentration, all the resulting concentrations are below the EPA allowable limits for chromium in waste, which is 5.0 mg/l.

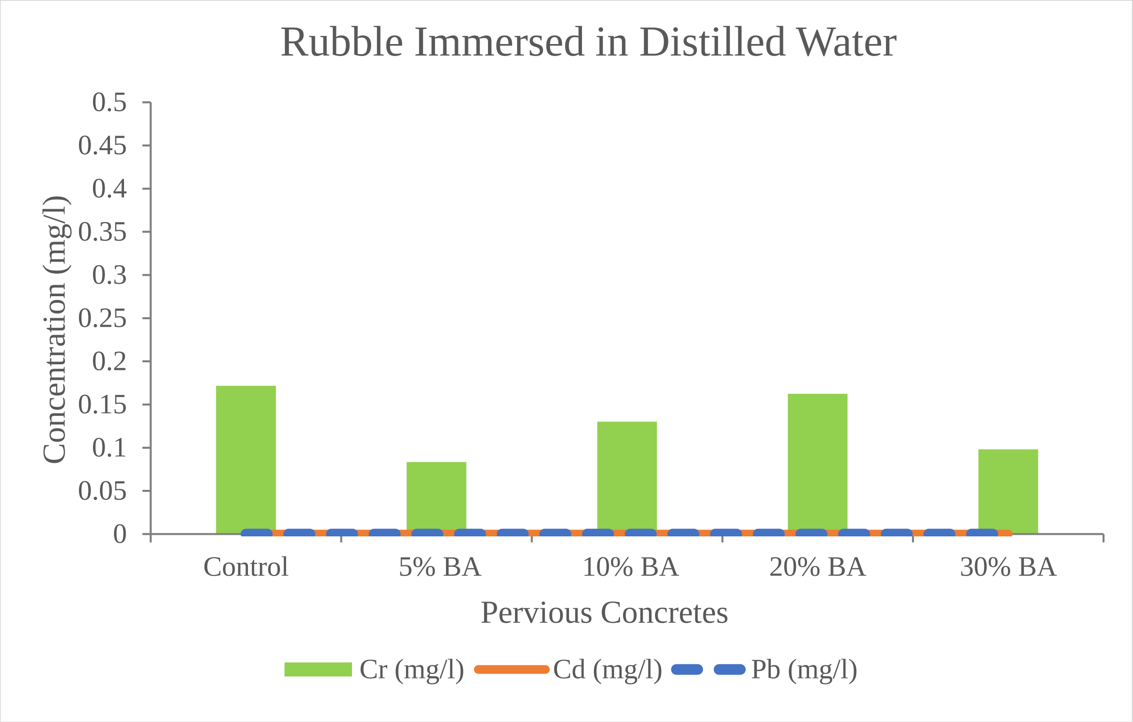


Figure 22: Concentrations of Cr, Cd, and Pb after immersing each demolished cylinder in distilled water

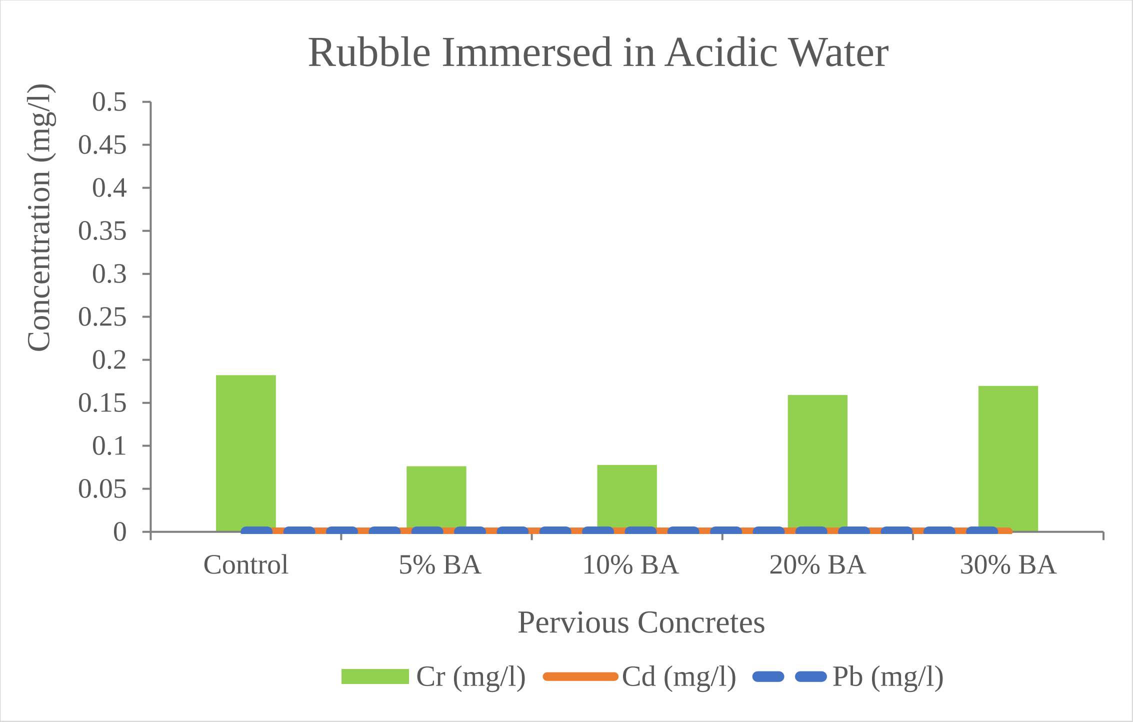


Figure 23: Concentrations of Cr, Cd, and Pb after immersing each demolished cylinder in acidic water

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

Increase in the formation and release of municipal solid wastes combined with the depletion of natural construction materials call for a sustainable alternative of replacing natural construction materials with municipal solid waste incinerator residue. These sustainable alternatives provide solutions to manage ash residue from municipal solid waste incinerator without being dumped in landfills while addressing the over exploitation of natural aggregates in the construction industry.

Use of bottom ash (BA), collected from a local municipal solid waste incinerator, as a partial replacement of coarse aggregates in pervious concrete is reported in this thesis. Size and composition of bottom ash particles make them potential substituents for natural aggregates. However, this replacement requires a deep understanding of the material's properties before its incorporation into pervious concrete. Once BA properties are investigated, it becomes easier to understand the performance and mechanical properties of pervious concrete upon incorporating bottom ash. Accordingly, physical and chemical characterization of BA including particle size distribution, specific gravity, water absorption, SEM, BET, EDX, XRD and quantification of selected heavy metals content were performed. After characterizing BA particles, pervious concrete cylindrical specimens were developed with 12.5 mm BA particles replacing 12.5 mm coarse aggregates by 5, 10, 20 and 30% to check the viability of using BA as a construction material. After incorporating 12.5 mm BA particles into pervious concretes, air voids content and compressive strength tests were performed to determine the optimum amount of bottom ash incorporated into pervious concrete without compromising its mechanical properties. Furthermore, a detailed investigation of the leachability for three heavy metals; Pb, Cd, and Cr from the prepared 5 - 30% BA mixes were performed to ensure that the samples are environmentally safe.

Porosity and compressive strength of the prepared pervious concrete cylinders met the engineering requirements for pervious concrete as set by the ACI. Additionally, the leachability tests of the selected heavy metals from the prepared specimens met the EPA standards for waste. Thus, we conclude that 12.5 mm BA particle, obtained from Sicomo, is a suitable substitute for coarse aggregate in pervious concrete.

5.1 Conclusions

In this study, 12.5 mm MSWI-BA was incorporated into pervious concrete cylindrical specimens replacing different percentages (5%, 10%, 20% and 30%) of coarse aggregates in the mixes. Results obtained from the characterization of bottom ash, air void contents and compressive strength of the pervious concretes and heavy metals contents in the leachate, are as follows:

1- Physical and chemical characterization investigating the properties of BA confirmed that the BA samples are porous, absorptive, and have disordered shape structures. Testing metal content of different BA particles indicated that there is an inverse correlation between the heavy metal content and particle size – the smaller the particles size the larger the metal content – because the small particle size increases the available surface area available for metals. Therefore, adsorbed heavy metals are concentrated at the surface of the smallest particles, that’s why heavy metals were largely present in the smallest particle size

(<0.074 mm) whereas the lowest concentrations were in the largest particle size range (12.5 –19 mm).

2- Bottom ash is a highly absorptive material that absorbs a substantial amount of water. That was taken into account during the mix design calculations to reach optimum water to cement ratio. As indicated in the water absorption test, the 12.5 mm BA has a water absorption of 6.82% which is around 12 times greater than that of control aggregates estimated to be 0.59%.

3- The air voids content of different casted pervious concretes (5%, 10%, 20% and 30% BA replacement) ranged from 13 to 22% almost meeting the limits stated by the ACI (15 to 35%). The higher air voids content upon incorporating bottom ash into the pervious concrete might be due to the porous structure of the bottom ash itself and the influence of the rounded shape of the bottom ash particles.

4- The incorporation of bottom ash, from 5 to 30%, as partial replacement of coarse aggregates in pervious concrete decreased the compressive strength at 28 days of curing. Nevertheless, compressive strength results of the pervious concretes with 12.5 mm BA satisfy the engineering requirements for pervious concrete as declared by the ACI, which ranges from 2.8 to 28 MPa.

    A. The use of bottom ash particles with 5 to 20% replacement of coarse aggregate decreased the compressive strength by 27% to 37%.
    B. Bottom ash content beyond 20% significantly decreased the compressive strength of the pervious concrete by 60%.

5- Due to the relatively limited compressive strength which is less than 20 MPa, BA-based pervious concretes (containing % BA replacement) can be used for sidewalks, pathways and walkways, general bicycle ways, landscaping, pavement curbs, and patios.

6- Heavy metals in leachate are important for assessing the safety of using BA in pervious concretes.
    A. Lead and cadmium were not detected in the leachate from BA-pervious concrete cylinders since these two heavy metals were not detected in the 12.5 mm BA particles itself during the digestion process.
    B. Chromium was detected in all water samples (curing water, infiltrated water, water after immersing the rubble of pervious concretes).However the resulting concentrations of chromium (ranging from 0.07 to 0.18 mg/l) are below the limit stated by the EPA for waste, which is 5 mg/l. Thus, BA used in this study is considered relatively safe to be used as substitute for coarse aggregates.

5.2 Recommendations

This research had some limitations which can be addressed in future research and accordingly the following recommendations are listed herein:

1- **Mix design and water content:** The total water to cement ratio, in the mix, was kept constant for all mixes while adding extra water to saturate bottom ash by accounting for the absorptive property of bottom ash. However, the effective w/c ratio depends greatly on the amount of water released from the bottom ash particles and could influence the mechanical properties of pervious concrete incorporating bottom ash. This is a function of the absorption-desorption behavior of bottom ash which is a complex phenomenon. Thus, future work can be directed towards understanding such kinetics before bottom ash incorporation into pervious concrete. Further studies on the effect of w/c ratio and water saturation of bottom ash particles before incorporating them into pervious concrete is necessary to determine the optimum mix design.

2- **Bottom ash particle size:** Bottom ash's physical and chemical properties and consequently the compressive strength and the leaching behavior of heavy metals are highly affected by the particle size of the BA. Therefore, particle size other than the 12.5 mm can be further investigated as replacement of either fine aggregates (sand) or coarse aggregates as to explore the incorporation of a wider range of BA particle in pervious concrete and

3- **Metal content:** Since Pb and Cd were not detected in the AAS - flame method. Other analysis methods like Inductively Coupled Plasma (ICP) can be further used to quantify the presence of lower concentrations of Pb and Cd, especially in coarse bottom ash particles.

4- **Testing for other heavy metals:** Heavy metals other than Pb, Cd, and Cr can also be further explored in the BA particles and in the leachate content.

5- **Assessing the application of the investigated pervious concrete mixes:** Water purification potential and efficiency of the pervious concretes incorporating BA can be investigated.

APPENDIX I

ATOMIC ABSORPTION SPECTROSCOPY CALIBRATION CURVES

This appendix presents the calibration curves for lead, cadmium, and chromium metals prepared and used to quantify the metal content through AAS analysis:

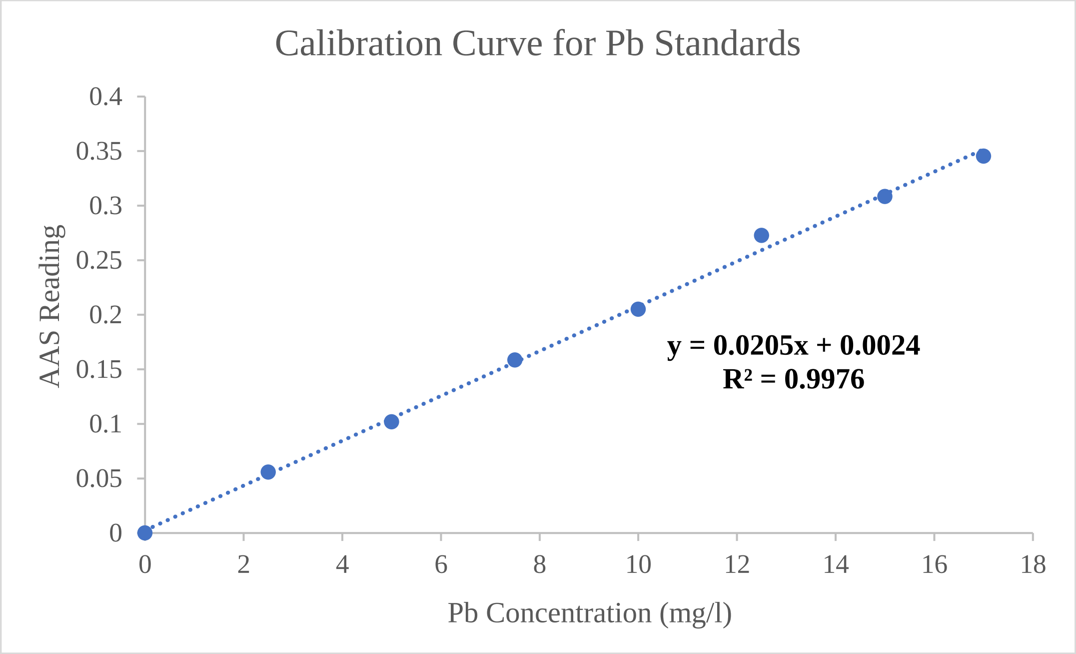


Figure 24: Lead calibration curve

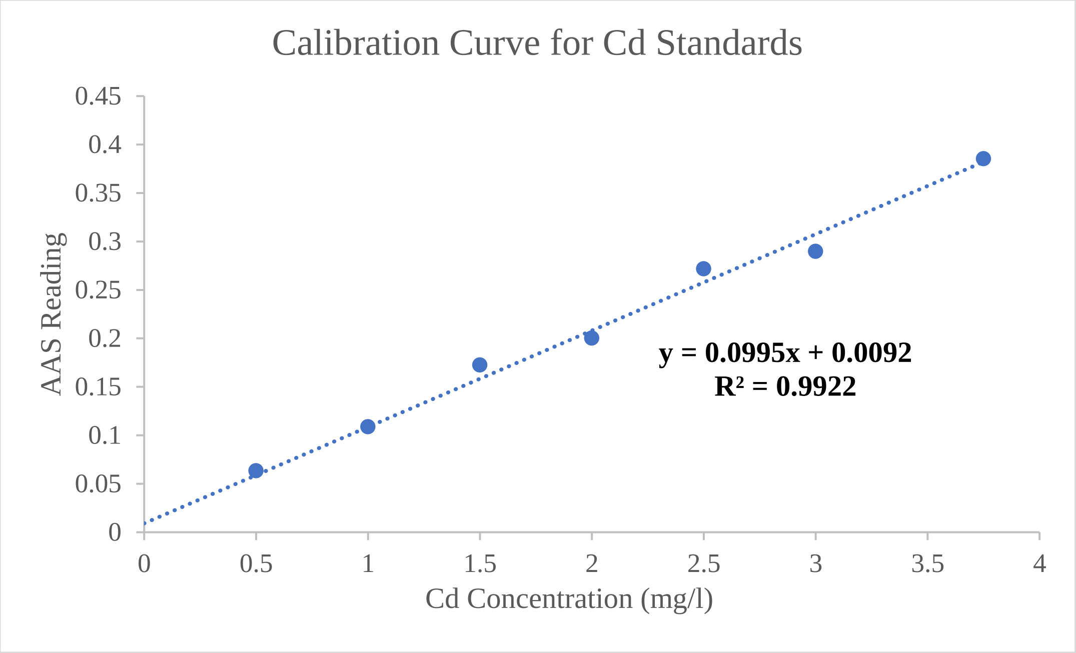


Figure 25: Cadmium calibration curve

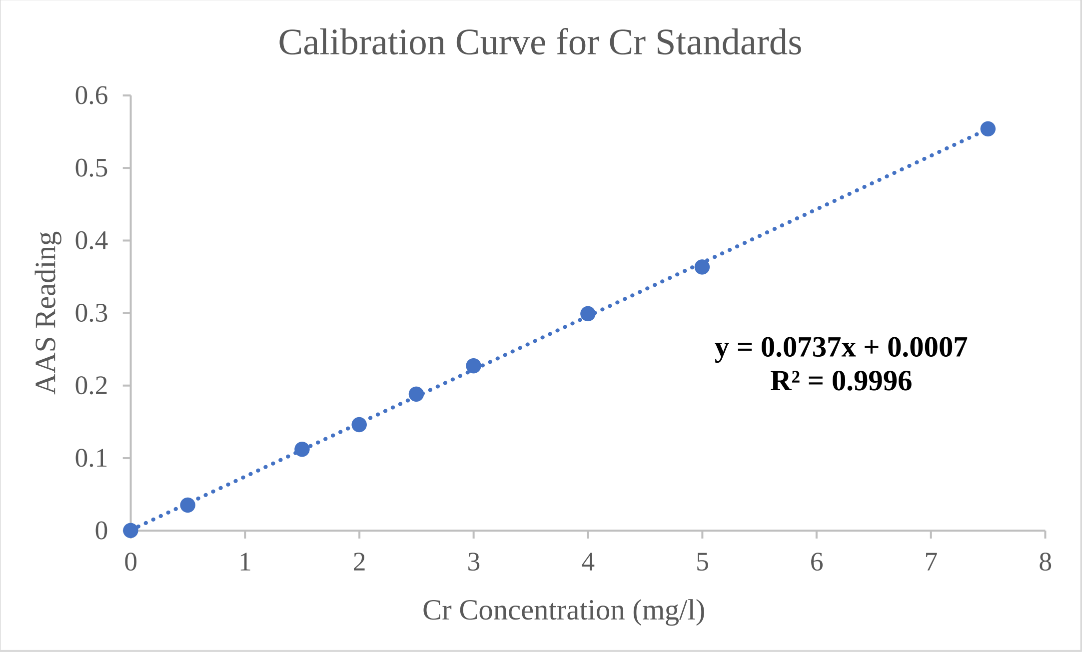


Figure 26: Chromium calibration curve

APPENDIX II

X-RAY DIFFRACTION PATTERNS

This appendix presents the XRD patterns for the bottom ash bulk sample after drying the sample.

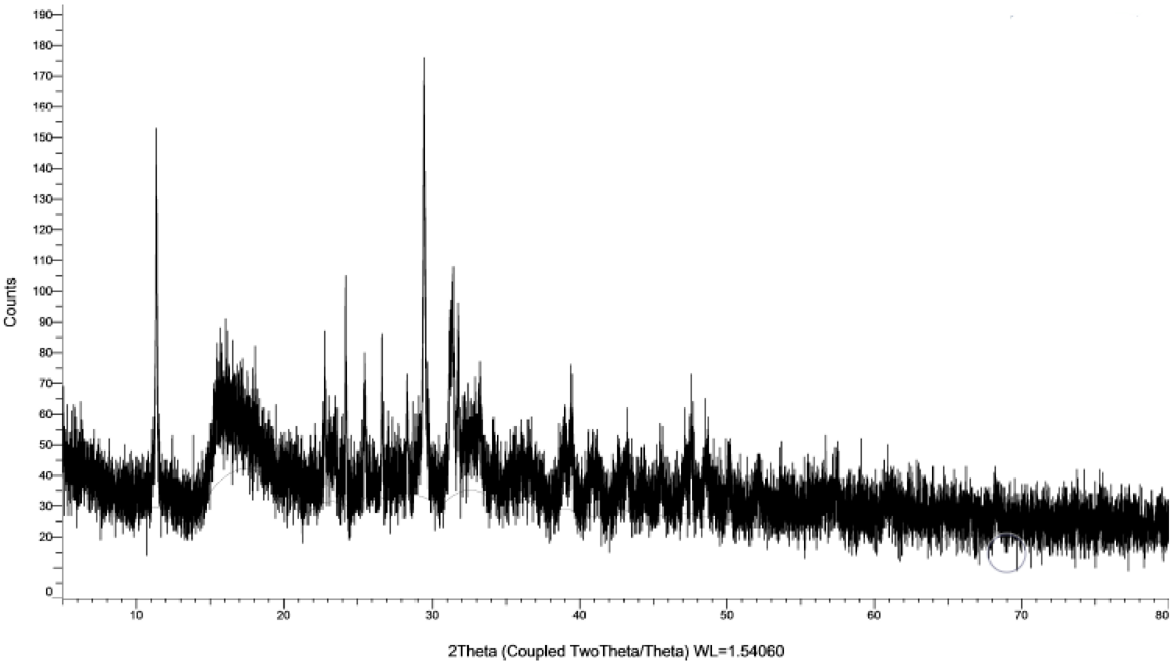


Figure 27: XRD patterns for the MSWI-BA sample analyzed after drying the received sample

APPENDIX III

BRUNAUER, EMMETT AND TELLER TECHNIQUE (BET)

This appendix contains the results of the BET test. BET was performed to determine the specific surface area, pore size and pore volume of bottom ash. The porosity, as indicated in the water absorption test and SEM images, was further investigated using BET. BET adsorption studies were performed on the powder BA samples (0.074 mm) after degassing the powder to ensure that the pores are not occupied. The BET analysis data, presented in Table 3, indicate that the measured specific surface area of the MSWI-BA sample is 8.7734 m^2/g. Regarding the pore width, the bottom ash samples are classified as mesoporous since the pore width falls into the mesoporous category, which ranges between 2 nm and 50 nm.

Table 8: BET test results for MSW Bottom Ash

Parameter	**Results**
Specific Surface Area (m^2/g)	8.7735
Pore Width (nm)	13.9649
Pore Volume (cm^3/g)	0.038588

APPENDIX IV

ENERGY DISPERSIVE X-RAY SPECTROSCOPY

This appendix shows the major elements in the 12.5 mm lime stone aggregate which is composed of calcium carbonate.

Table 9: Approximate elemental composition of 12.5 mm control aggregates

Element	**% by Weight**
Carbon	11.80
Oxygen	46.49
Calcium	41.72
Total	100

APPENDIX V

METAL CONTENT

This appendix presents a graph that shows the inverse correlation of selected metal content concentration (mg/kg) and the different bottom ash particle sizes

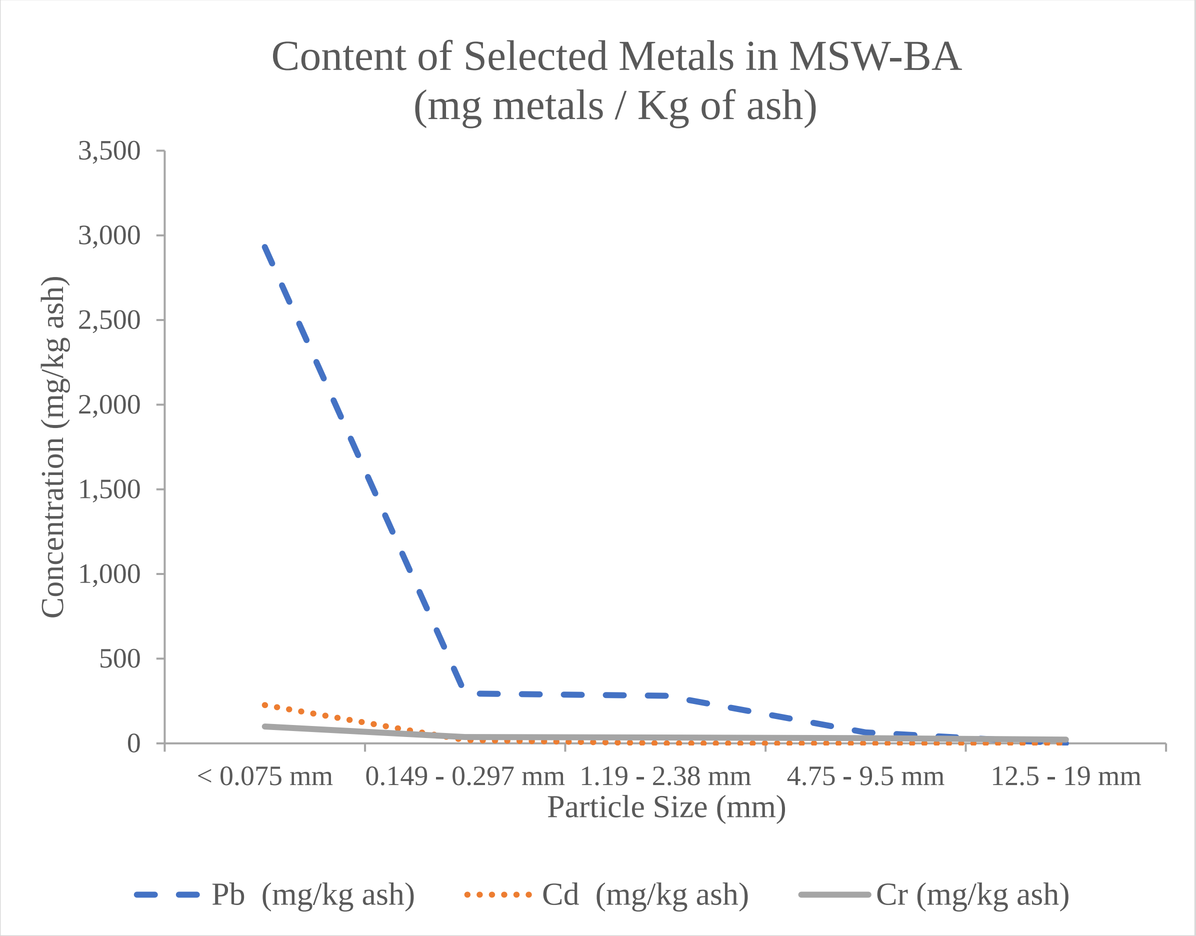


Figure 28: Line graph showing the selected metal content (mg/kg) as a function of different MSWI-BA particle sizes

REFERENCES

Abbas, I., Chaaban, J., Al-Rabaa, A., & Shaar, A. (2017). Solid Waste Management in Lebanon: Challenges and Recommendations. *Journal of Environment and Waste Management*, 053-063.

ACI. (2010). Report on Pervious Concrete. Report ACI 522R-10. *American Concrete Institute*, 38.

Bakkali, M., Bahri, M., Gmouh, S., Jaddi, H., Bakkali, M., & Laglaoui, A. &. (2013). Characterization of Bottom Ash from Two Hospital Waste Incinerators in Rabat, Morocco. *Waste Management Resources*, 1228-36.

Chandrappa, A. K., & Biligiri, K. (2016). Pervious Concrete as a Sustainable Pavement Material – Research Findings and Future Prospects: A State-of-the-Art Review. *Construction and Building Materials*, 262–274.

Chen, J.-S., Chu, P.-Y., Chang, J.-E., Lu, H.-C., Wu, Z.-H., & Lin, K.-Y. (2008). Engineering and Environmental Characterization of Municipal Solid Waste Bottom Ash as an Aggregate Substitute Utilized for Asphalt Concrete. *Journal of Materials in Civil Engineering*, 432-439.

Dou, X., Ren, F., Nguyen, M., Ahamed, A., Yin, K., & Chan, W. &. (2017). Review of MSWI Bottom Ash Utilization from Prespectives of Collective Characterization, Treatment and Existing Application. *Renewable and Sustainable Energy Reviews*, 24-38.

El Fadel, M., & Maalouf, M. (2019). *Challenges of Waste Management in a Developing Context: Lessons From Lebanon.*

Engineers, W. C. (2018). *Different Grades of Concrete and their Uses/Applications*. Retrieved from https://wecivilengineers.wordpress.com/2018/09/10/different-grades-of-concrete-and-their-uses-applications/

EPA. (2015). *Environmental Protection Agency*. Retrieved from www.hazardouswasteexperts.com/heavy-metal-waste-regulation-which-substances-make-up-the-rcra-8-metals/

EPA. (2018). *Environemntal Protection Agency*. Retrieved from https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

Estokova, A., Palascakova, L., & Kanuchova, M. (2018). Study on Cr(VI) Leaching from Cement and Cement Composites. *International Journal of Environmental Research and Public Health*.

Gorme, J., Maniquiz, M., Kim, S., Son, Y., Kim, Y., & Kim, L. (2010). Characterization of Bottom Ash as an Adsorbent of Lead from Aqueous Solutions . *Environmental Engineering Research*, 207-213.

Huber, F., Blasenbauer, D., Aschenbrenner, P., & Fellner, J. (2019). Chemical Composition and Leachability of Differently Sized Material Fractions of Municipal Solid Waste Incineration Bottom Ash. *Waste Management*, 593–603.

ISWE. (2015). *Bottom Ash from WTE Plants – Metal Recovery and Utilization.* International Solid Waste Association.

Joseph, A., Snellings, R., Heede, P., Matthys, S., & Belie, N. (2018). The Use of Municipal Solid Waste Incineration Ash in Various Building Materials: A Belgian Point of View. *Materials*, 141.

Kassem, H., Al Hassanieh, D., Mrad, M., Chehab, G., & Abou Najm, M. (2016). Method to Investigate Mix Design Parameters of Pervious Concrete Mixtures. *Journal of the Transportation Research Board*, 43-52.

Kim, G., Jang, J., Khalid, H., & Lee, H. (2017). Water Purification Characteristics of Pervious Concrete Fabricated with CSA Cement and Bottom Ash Aggregates. *Construction and Building Materials*, 1-8.

Kuo, W., C.C., L., & Su, D. (2013). Use of Washed Municipal Solid Waste Incinerator Bottom Ash in Pervious Concrete. *Cement & Concrete Composites*, 328–335.

Loginiva, E., Volkov, D., Van De Wouw, P., & Florea, M. &. (2019). Detailed Characterization of Particle Size Fractions of Municipal Solid Waste Inciniration Bottom Ash. *Journal of Cleaner Production*, 866-874.

Luo, H., Ying, C., He, D., & Yang, E.-H. (2019). Review of Leaching Behavior of Municipal Solid Waste Incineration. *Science of the Total Environment*, 90-103.

Lynn, C., Ghataora, G., & Dhir, R. (2017). Municipal Incinerated Bottom Ash (MIBA) Characteristics and Potential for Use in Road Pavements. *International Journal of Pavement Research and Technology*, 185–201.

Tang, C., C.K., C., & Tsai, C. (2019). Mix Design and Mechanical Properties of High-Performance Pervious Concrete. *Materials*.

Tchounwou, P., Yedjou, C., Patlolla, A., & Sutton, D. (2012). Heavy Metals Toxicity and the Environment.

Tijani, M., Ajagbe, W., Ganiyu, A., & Agbede, O. (2019). Effect of Aggregate Type on Properties of Pervious Concrete. *Journal of Modern Technology and Engineering*, 37-46.

Tripathi, D., Hussain, S., & Madhav, P. (2017). An Experimental Study on Pervious Concrete (Mix-Ratio, Strength and Porous Properties). *International Journal of Engineering Research & Technology*.

Vaitkus, A., Gražulytė, J., Šernas, O., Vorobjovas, V., & Kleizienė, R. (2019). An Algorithm for the Use of MSWI Bottom Ash as a Building Material in Road Pavement Structural Layers. *Construction and Building Materials*, 456-466.

Valle-Zermeño, R. D., Gómez-Manrique, J., Giro-Paloma, J., Formosa, J., & Chimenos, J. (2017). Material Characterization of the MSWI Bottom Ash as a Function of Particle Size. *Science of the Total Environment*, 897–905.

Welker, A., Barbis, J., & Jeffers, P. (2012). A Side-by-Side Comparison of Pervious Concrete and Porous Asphalt. *Journal of the American Water Resources Association*.

Wu, M., Lin, C., Huang, W., & Chen, J. (2016). Characteristics of Pervious Concrete using Incineration Bottom Ash in place of Sandstone Graded Material. *Construction and Building Materials*, 618–624.

Zaetang, Y., Wongsa, A., Sata, V., & Chindaprasirt, P. (2013). Use of Lightweight Aggregates in Pervious Concrete. *Construction and Building Materials*, 585–591.

Zhong, R., Leng, Z., & Poon, C. (2018). Research and Application of Pervious Concrete as a Sustainable Pavement Material: A State-of-the-Art and State-of-the-Practice Review. *Construction and Building Materials*, 544-553.