AMERICAN UNIVERSITY OF BEIRUT

THE EFFECT OF DIFFERENT PARTICLE SIZES OF BOTTOM ASH ON THE PROPERTIES OF PERVIOUS CONCRETE AND THE QUALITY OF INFILTRATED WATER

by
GHADI YASSER SAMIA

A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
to the Department of Civil and Environmental Engineering
of the Maroun Semaan Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
March 2022

AMERICAN UNIVERSITY OF BEIRUT

THE EFFECT OF DIFFERENT PARTICLE SIZES OF BOTTOM ASH ON THE PROPERTIES OF PERVIOUS CONCRETE AND THE QUALITY OF INFILTRATED WATER

by

GHADI YASSER SAMIA

Approved by:

Dr. Rana Bilbeisi, Assistant Professor Civil and Environmental Engineering	Advisor
Dr. Ghassan Chehab, Associate Professor Civil and Environmental Engineering	Member of Committee
Dr. Yousef Mubarak, Professor University of Jordan	Member of Committee

Date of thesis defense: March 7, 2022

AMERICAN UNIVERSITY OF BEIRUT

THESIS RELEASE FORM

Student Name:	Samia	Ghadi	Yasser
	Last	First	Middle

I authorize the American University of Beirut, to: (a) reproduce hard or electronic copies of my thesis; (b) include such copies in the archives and digital repositories of the University; and (c) make freely available such copies to third parties for research or educational purposes:

☒ As of the date of submission

☐ One year from the date of submission of my thesis.

☐ Two years from the date of submission of my thesis.

☐ Three years from the date of submission of my thesis.

Ghadi Samia

March 24th, 2022

Signature Date

ACKNOWLEDGEMENTS

First of all, I would like to thank Ms. Dima Hassanieh and Mr. Abed Sheikh for their insight and help in the materials lab.

I would also like to thank Dr. Amani Jaafar for her constant help and readiness to answer any of my questions.

Special thanks to Mr. Karim Haddad of SICOMO for providing the materials necessary to make this research possible.

Thanks to my thesis committee Dr. Ghassan Chehab and Dr. Yousef Mubarak for their constructive comments to help improve this research.

Also, a big thank you to my advisor, Dr. Rana Bilbeisi for her continuous and unrelenting support and guidance, and for constantly pushing me and motivating me through the ups and downs of this project.

Last but not least, I would like to extend my profound gratitude to my friends and family for their support throughout my years of undergraduate and graduate studies. I would not be where I am today without you.

ABSTRACT
OF THE THESIS OF

Ghadi Yasser Samia for Master of Engineering
Major: Civil and Environmental Engineering

Title: The Effect of Different Particle Sizes of Bottom Ash on the Properties of Pervious Concrete and the Quality of Infiltrated Water

Amounts of generated municipal solid wastes (MSW) are augmented by the fast population growth and development, making MSW management a global challenge. Although landfilling is a convenient waste disposal approach, it has hazardous environmental, health, social, and economic effects directing countries to shift towards more sustainable 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, a small country, is experiencing waste management challenges, municipal solid waste incineration (MSWI) might offer a practical solution, provided the byproducts of the process are controlled. Among the incineration byproducts, bottom ash (BA) constitutes 80-90% of the total ash content. Thus, sustainably dealing with the produced BA is a priority.

The construction industry is facing challenges stemming from overexploitation, hence, depletion of natural resources. Therefore, current global trends focus on exploring new sustainable recycled materials as alternatives for construction natural resources. This is applicable for all types of concrete structures (conventional concrete, pervious concrete, etc.) in various applications (buildings, bridges, roads, etc.). Therefore, incorporating MSWI BA into pervious concrete offers environmentally friendly solution for the disposal of BA and depletion for natural resources.

Pervious concrete samples containing 20% replacement of natural aggregates (NA) with BA, collected from a local incinerator in Lebanon, were prepared using different BA particles (4.75, 9.5 & 12.5 mm). Prepared samples were tested for their mechanical properties and metal leachability. The potential of using BA as heavy metal adsorbents was also investigated for a selection of heavy metals (Pb, Cd and Hg).

The physical and chemical characterization tests of BA concluded that BA were seven times more water absorptive and have around 15% lower specific gravities compared to natural aggregates. The surface of BA was found to be rougher, less uniform, and more porous than natural aggregates. BA and NA were found to have similar chemical compositions; both containing $CaCO_3$, SiO_2, MgO and FeO indicating that BA can be used to substitute natural aggregates.

Acid digestion, of different BA particle sizes, followed by ICP-MS analysis detected concentrations of heavy metals (Pb, Cd, Cr, Hg, Zn, Cu) ranging between 0.002 and

0.05 mg/g BA with the concentration of metal content increasing with decreasing BA particle size. Heavy metal adsorption tests, using 4.75 mm BA as a sorbent, resulted in adsorption percentages of 99% (Pb), 70% (Cd) and 48% (Hg) when exposed to contaminated water containing all three metals.

Three different BA particle sizes, 4.75, 9.5 & 12.5 mm, were used as 20% replacement to NA in pervious concrete samples. Four control samples were also prepared using NA with the same aggregate grading to assess the mechanical properties and metal leachability of the PC samples containing BA. Upon incorporating BA into PC, the decrease in compressive strength ranged between 15% to 33%, compared to the control samples. The highest compressive strength value being for the sample with 4.75 mm BA aggregate replacement, with only 15% decrease relative to the control sample. No drastic variation between the control and test samples in terms of air void contents was observed. The compressive strength and air void values were all found to be in the range set by the ACI for pervious concrete applications. When analyzing the leachability of heavy metals into curing water, distilled, and acidic infiltrated water, chromium was detected in all PC samples in concentrations ranging between 4 and 46 ppb. Traces of Hg, Zn, Cu and Pb (less than 38 ppb) in some samples. The leached heavy metals were all found to be below the acceptable limit set by the EPA for all water quality standards.

TABLE OF CONTENTS

ILLUSTRATIONS

Figure

TABLES

Table

CHAPTER 1

INTRODUCTION

1.1. Waste Management

The increasing rate of municipal solid waste generation has been directly influenced by the growing population worldwide [1]. As a result, solid waste disposal and treatment techniques are required to keep up with this increasing trend.

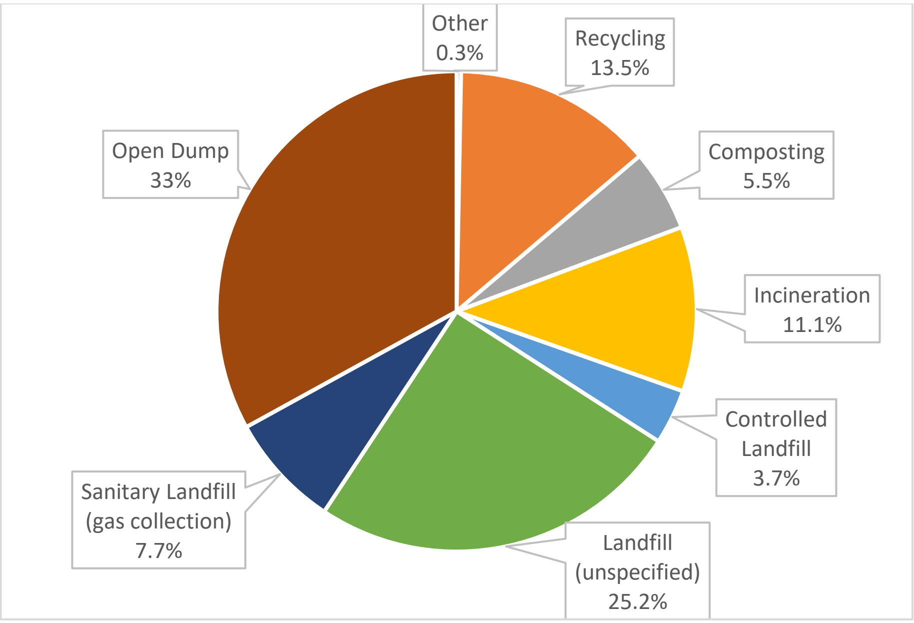


Figure 1: Global waste treatment and disposal techniques [2]

Some of the most widely used technologies are landfilling and incineration as they account for around 40% and 11% of the global treated/disposed waste, respectively [3]. Landfills are considered one of the most attractive techniques used in waste management due to its simplicity and low cost [4]. However, its many disadvantages include groundwater contamination, soil pollution, greenhouse gas emissions and large carbon footprint [5, 6]. As for incineration, it provides a feasible alternative to landfills in regions where large land areas are not available. It also results in the reduction in the volume of the waste by up to 90% with the potential for energy recovery [7]. There remains the issue of the flue gas emissions as well as the unwanted byproducts known as bottom and fly ash [8].

1.2. Waste Management in Lebanon

Around 7,500 tons of MSW were generated in Lebanon in 2019, of which, 50% were dumped in open dump sites, 35% in sanitary landfills and the remaining was converted into fertilizers or recovered for recycling. The lack of an integrated waste management plan has resulted in the majority of waste being openly dumped or disposed of in landfills [9].

Figure 2: Open dumpsites in Lebanon, 2015 [10]

These disposal methods result in water pollution, due to rainwater runoff getting polluted by the openly dumped waste as well as the spread of diseases in densely populated areas. This also results in soil pollution as well as groundwater pollution due to the infiltration of surface water polluted by the waste or by the leakage of landfill leachate [9]. In addition to waste management, Lebanon is also suffering from a major energy crisis resulting from years of mismanagement of the sector and the lack of alternative sources of energy. Therefore, the adoption of incinerators can mitigate the issue by providing factories with on-site electricity generation or provide energy to nearby residential areas by converting waste into energy. For a relatively small country such as Lebanon (10,452 km^2), the adoption of well-designed waste incinerators seems like a favorable choice. Incineration has been adopted in many countries where land scarcity is a main issue. For example, Japan which is a mostly rugged and a mountainous country, relies on incineration to dispose ~70% of the MSW generated annually. Of the 1000 incinerators present in Japan, 380 are waste-to-energy plants that generate around 1719 GWh from MSW as of 2018. In Singapore (729 km^2), around 40% of its MSW is burned through its 4 incineration plants that are capable of generating around 936 GWh of electricity per year [11, 12, 13, 14].

As landfills require large areas of land, the application of incinerators can vastly reduce the volume of the waste entering the landfills thus increasing their lifespan. The large quantity of heat produced in an incinerator creates another opportunity which is energy generation. Adopting these waste-to-energy techniques has the ability of easing the burden of the electricity crisis while providing a simple and cheap solution to the municipal solid waste (MSW) issue of open dumps and the pollution accompanied by it. However, several considerations should be taken into account prior to the implementation of such processes. Treatment systems should be installed in order to remove the harmful gases present in the flue gas, which is a major waste product of incineration, as to avoid air pollution. Incineration also has solid byproducts known as fly and bottom ash. These represent the unburnt residue of the solid MSW and should be treated effectively as they may contain several toxic compounds such as heavy metals [9].

1.3. Industrial Partner_Sicomo

Despite incineration being a favorable technique that can solve Lebanon's many issues, there are several hurdles facing the implementation of such a process. Chief among these hurdles are the social and political issues. Currently, only one operating incinerator is present in Lebanon called SICOMO. It is a paper and cardboard recycling enterprise in the Bekaa region which has built its own incinerator to treat the accumulating non-recyclable materials. It is currently also treating the MSW of several Lebanese municipalities. The plant is also capable of generating electricity for on-site uses. Each kg of MSW incinerated generates on average 2.2kW of heat (steam), 22% of which is used to generate electricity through a turbine, 60% is used for process heating, and the rest is exhausted.

The incinerator consists of 2 chambers and a heat recovery system. The MSW is fed into the primary chamber where incomplete combustion takes place at 850˚C. The bottom ash residues settle at the bottom of the 1st chamber whereas the rest of the volatile and gasified residues are sent to the secondary chamber where complete combustion takes place in the presence of excess O_2 at 1100˚C. After that, all the volatile substances are completely oxidized. In the heat recovery system, the temperature of the flue gas from the secondary chamber is 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 and to reduce excess hydrogen chloride (HCl) levels resulting in a neutralized flue gas. The flowchart of the process can be seen in Figure 3.

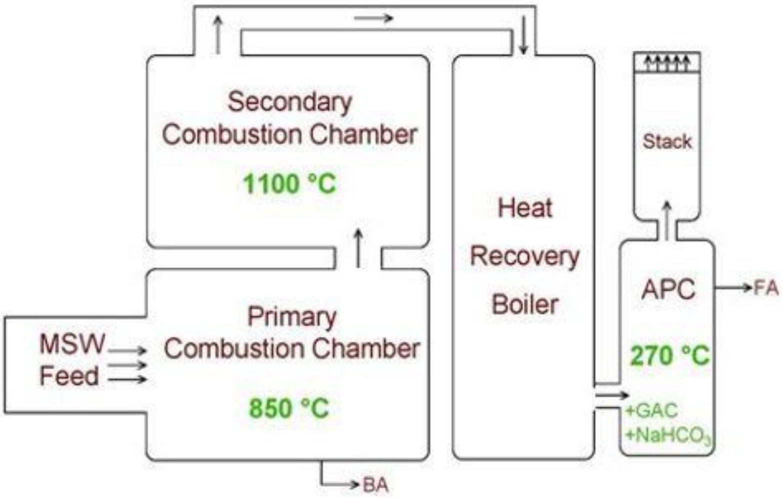


Figure 3: Double chambered combustion process (BA: bottom ash; FA: fly ash, APC: air pollution control, GAC: granulated activated carbon, $NaHCO_3$: Calcium Bicarbonate

SICOMO produces around 8 tons of bottom ash per day which accounts to nearly 80-90% of the total ash produced during incineration. Therefore, this research utilizes the BA generated from SICOMO as it consists the bulk of the waste generated from the process.

1.4. Bottom Ash: definition, properties & applications

Bottom ash is defined as a dark colored porous light material made up of unburnt materials, molten particles, ferrous and non-ferrous metals, potsherds, and glass fragments etc. Its particle size can range between 0.01 mm and 100 mm [15, 16, 17]. One of the main sources of BA is that resulting from burning coal in thermal power plant. Another common source of bottom ash is waste incineration. The incinerated waste could be medical, domestic, and industrial waste.

The properties of BA vary based on the incinerated waste and the incineration parameters [18, 19]. The main compounds present in these aggregates primarily include silicon oxides, calcium oxides, ferric oxides, aluminum oxides, sodium oxides, magnesium oxides and other metal oxides. As a result of this composition, it is highly similar to that of natural aggregates and soil [4, 20, 17]. However, additional materials can be present such as chromium, cadmium, lead mercury and other heavy metals that give BA its hazardous nature [4].

One common way to dispose of BA would be to dump it in landfills. However, this raises the issue heavy metals leaching into groundwater as well as reaching the maximum capacity of the landfill. Therefore, new applications for BA arose to reduce the quantities sent to landfills. These applications include: (1) in road construction as aggregate in foundation layers, sub-base layers and embankment [19, 21], (2) in the production of cement and concrete [4], (3) in controlled low-strength materials [20, 17], (4) in concrete blocks and concrete tiles [17], (5) as aggregates in concrete [20, 22], 2008), (6) in glass and ceramic [4], (7) as adsorbents [4, 23, 24] and (8) as highway embankments/noise barriers [17].

1.5. Pervious Concrete

Rapid urbanization has changed the nature of the surface to one that is impermeable. This has led to an increased stormwater runoff flow with high levels of pollution and unwarranted flash floods. Other issues with the increased use of impermeable surfaces include decreased groundwater recharge as well as urban heat island (UHI) effect. UHI is a phenomenon that results in increased temperatures in urban areas which lead to increased electricity consumption for cooling purposes and thus CO_2 emissions. Therefore, utilizing pervious or permeable surfaces is necessary to reverse the adverse environmental effects of concretization. Some of these permeable surfaces include pervious concrete, porous asphalt, plastic grid systems and interlocking blocks [25].

Pervious Concrete Porous Asphalt

Plastic Grid Systems Concrete Interlocking Blocks

Figure 4: Types of permeable pavements

These structures can serve to promote the infiltration of stormwater into the ground thus reducing runoff, recharging the groundwater, reducing risks of flash flooding, enhanced skid resistance by increasing friction, and reducing UHI effect as the presence of pores promotes heat loss [26].

The use of pervious concrete (PC) has been gaining research interest due to the legislations imposed by the Federal Water Pollution Control Act and the Environmental

Protection Agency (EPA) for its eco-friendly characteristics [20, 27]. PC is defined as an open graded and zero slump material which consists of interconnected, dead end and capillary pores [28, 26]. It consists of coarse aggregates, water, an optimal amount of cement to coat and bind the aggregates together and little to no fines [29, 30, 25]. The porosity of PC 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 [28]. The compressive strength of PC decreases with the increase in its porosity, this makes it weaker than conventional impermeable concrete [29, 15, 20]. PC serves 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 [27, 31, 28].

PC is considered a sustainable building material as it has many environmental, economic, and structural advantages. In addition to the previously mentioned advantages, PC is known to reduce the amount of pollution in surface runoff.

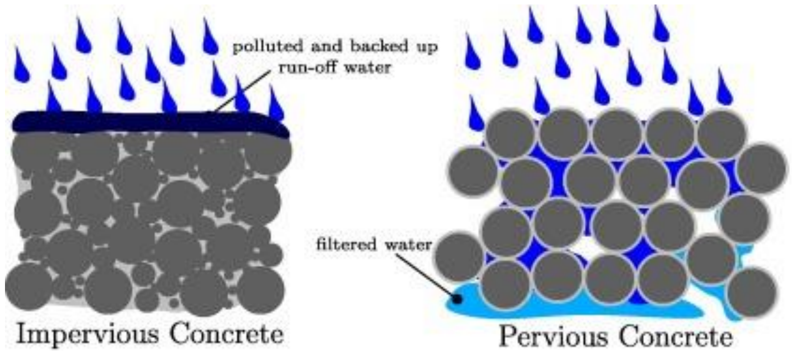


Figure 5: Pervious concrete vs conventional impermeable concrete [27]

Its pores can promote physical purification by allowing suspended solids in the water to precipitate onto the pore walls. In a study by Kim et al. [31], PC fabricated with incorporated BA aggregates was found to reduce the total phosphorous and nitrogen contents in polluted infiltrated water by around 70%. Also, the alkaline nature of pervious concrete releases hydroxide (OH^-) and carbonate (CO_3^{2-}) ions which react with the pollutants resulting in precipitating them and reduces the acidity of the water. Finally, the porous nature of PC provides a large surface area for microbial activity which consumes and dissolves certain pollutants [26]. However, this comes at the cost of compromising the strength and durability of the concrete, in addition to the risk of clogging if not maintained properly [27, 32, 33].

CHAPTER 2

RESEARCH OBJECTIVES & SIGNIFICANCE

2.1. Objectives

This research aims at finding a sustainable solution for exploiting ash residues from MSW incinerator in pervious concrete structures. Based on previous studies conducted by our group, the incorporation of 12.5 mm bottom ash (BA) particles, in pervious concrete was optimized without compromising the concrete structural properties. It was concluded by the study, that the optimum percentage for replacing natural limestone aggregates with BA aggregates was 20%, without compromising the strength and void content of the structure. The physical properties of the prepared pervious concrete were also assessed and the leachability of heavy metals from BA was studied to ensure that the leached metals are within allowable limits set by the EPA [4]. Building on that, we are proposing the incorporation of various particle sizes of BA into pervious concrete structures to assess the effect BA particle sizes on the properties of the resulting concrete structures as well as on the quality of water infiltrating through the structures. The proposed research project focuses on obtaining the optimum BA particle size that will leach minimal heavy metal concentrations without compromising the integrity of pervious concrete structures. The objectives of this study were satisfied through the following steps: (1) First, BA characterization (specific gravity, SEM, EDX acid digestion etc.) was conducted to compare the physical and chemical characteristics of BA to that of limestone and to study the adsorption of heavy metals onto BA to assess their water purification potential. (2) The BA particles were then incorporated into PC samples replacing 20% of the natural limestone aggregates. (3) Leachability of heavy metals from PC samples with BA into curing water and infiltrated distilled and acidic water was tested to ensure that adsorbed heavy metals do not leach out of BA upon exposure to different weather conditions as this could pose a hazard to the environment. (4) Finally, the air void content and compressive strength of the PC specimens were measured to assess the effect BA has on the properties of the PC samples.

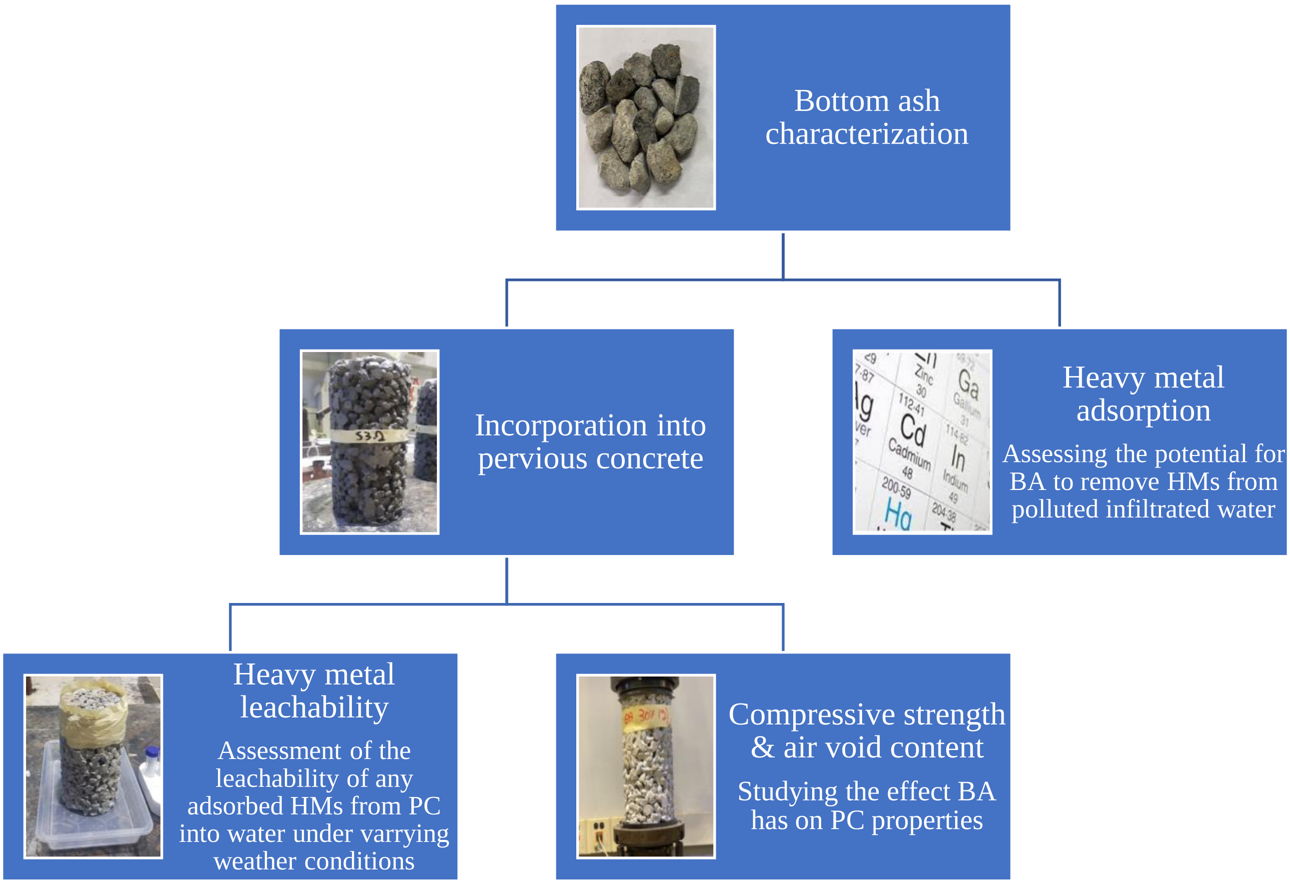


Figure 6: Schematic summarizing the objectives of this research

2.2. Significance

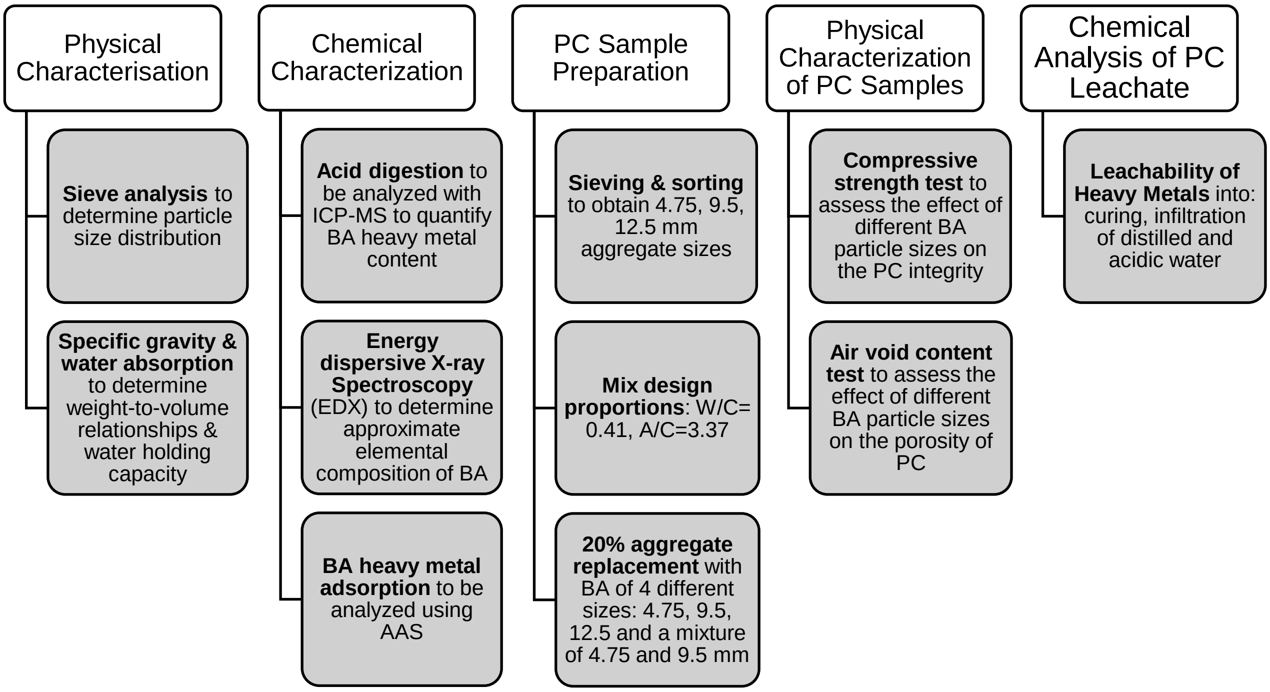
Deviating the effect of waste into various useful applications defines sustainability. Exploiting waste material and using it in construction applications as sustainable alternative for natural aggregates, cement, or sand provides an environmentally friendly solution for managing MSW residues. This solution protects the environment and public health, reduces the amount of wastes in landfills, which often leads to groundwater contamination, and saves resources used in construction from overexploitation.

Pervious concrete is a porous structure which allows water to percolate through its voids. Its significance lies in controlling storm water runoff and preventing flooding, recharging ground water, reducing pollution of runoff water, and reducing the heat island effect.

Bottom ash, which is collected from SICOMO (an incinerator in the Bekaa region) is a by-product of incineration which is made up of unburnt materials such as molten particles, metal oxides glass fragments, etc. It is known to have similar characteristics to natural limestone aggregates which makes it a suitable candidate for partial component replacement of limestone in pervious concrete. This is considered a sustainable alternative to their disposal in landfills. In addition to that, it is known for being a natural sorbent material with water purification potential. This study will address the issues of waste management, natural resource management, the collection of rainwater and the potential enhancement of its quality.

CHAPTER 3

METHODOLOGY



**PC: Pervious concrete; W/C: water-to-cement ratio; A/C: aggregate-to-cement ratio*

3.1. Physical Characterization

3.1.1. Sieve Analysis & Particle Size Distribution

Sieving was conducted in accordance with ASTM C135. The sieve analysis was performed in order to determine the particle size distribution of the bottom ash samples as it is important in determining the possible uses of the bottom ash aggregates. The BA samples were oven dried for 24 hours prior to sieving to remove the moisture and avoid lump formation. After collecting the desired particle sizes (4.75, 9.5 & 12.5 mm), the BA aggregates were sorted by hand to remove impurities such as glass, metals, textiles, and other light materials.

Figure 7: Difference between non-sorted (right), semi-sorted (top) and sorted (left) aggregates

3.1.2. Specific Gravity & Water Absorption

The specific gravity and water absorption tests were performed in accordance with ASTM 127. The specific gravity of an aggregate is the ratio of the density of the aggregate to the density of water. It is used to find the volume of aggregates occupying a certain space and can be used to assess the strength of the aggregates where higher specific gravity implies greater aggregate strength. Water absorption is used to determine the water holding capacity of an aggregate by calculating the change in the mass of a sample after being saturated with water. This information is required for the preparation of pervious concrete mixes accounting for the water that is absorbed by the aggregates.

The tests were conducted on the semi-sorted BA samples. First, 1 kg of the test sample was soaked in water for 24 hours in the case of limestone and 72 hours in the case of bottom ash in order to make sure that all the voids in the ash were saturated with water. After that, the samples were dried to SSD conditions to record their mass. While still saturated, the samples were then submerged under water in a bucket to record their apparent mass in water. Finally, the samples were placed in an oven for 24 hours (limestone) or 72 hours (BA) and to record their oven dry mass.

The specific gravity and water absorption were calculated on an oven dry basis using equations 2 & 3, respectively.

$$SP\ (OD) = \frac{A}{B-C} \qquad (2)$$

$$\%\ Absorption = \frac{B-A}{A} \times 100 \quad (3)$$

Where:

- A is the mass of oven dry test sample in air (kg)
- B is the mass of saturated surface dry sample in air (kg)
- C is the apparent mass of saturated test sample in water (kg)

3.2. Chemical Characterization

3.2.1. Atomic Absorption Spectroscopy (AAS)

AAS is a spectroscopy method used to identify the chemical composition of a sample based on its absorption of specific wavelengths of light. AAS requires standards with known analyte concentrations to establish a calibration curve for the analyte concentration and measured absorbance [34]. The flame method was used to determine the concentration of mercury, lead and cadmium in the heavy metal adsorption test using the 4.75 mm BA as the adsorbents. The 4.75 mm aggregates were chosen for this experiment since they have the largest surface area, and they are expected to have a higher capacity of metals ions.

Figure 8: AAS flame method

AAS was used to determine the concentration of these 3 heavy metals absorbed by BA from a solution. This was done by measuring the level of heavy metals remaining in this solution after incubation with BA for 24h.

3.2.2. Inductively Coupled Plasma Mass Spectroscopy (ICP-MS)

ICP is an elemental analysis technology which uses an induction coil to form plasma, that is coupled with argon gas in order to fully ionize a sample into its constituent elements in the form of ions. Unlike AAS, which can only detect the presence of individual elements in a specific concentration range, ICP-MS is capable of detecting a range of elements at milligrams to nanograms per liter [34]. ICP can also detect the presence of more than one heavy metal per test run, unlike AAS which can only detect one at a time.

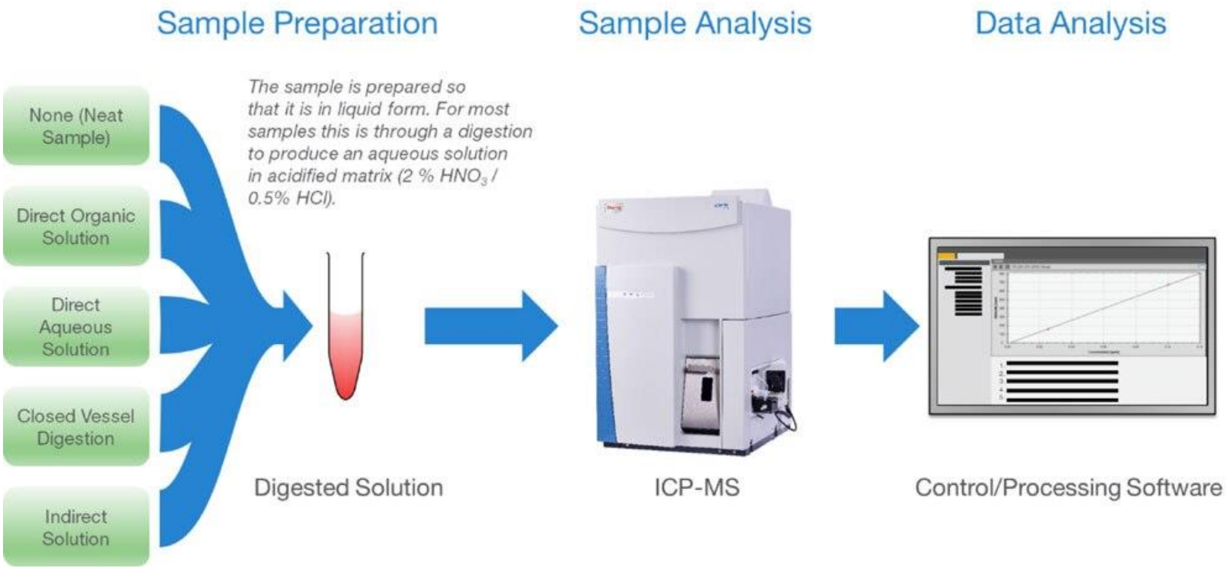


Figure 9: ICP-MS workflow [34]

The ICP-MS in LEAF Laboratories at AUB was used to determine (1) the heavy metal content of the BA samples and (2) the leachability of heavy metals from PC samples to curing water, infiltrated distilled water and infiltrated acidic water. These analyses were done for the 6 heavy metals lead, cadmium, chromium, mercury, copper, and zinc.

3.2.3. Acid Digestion

To calculate the heavy metals content of the BA, acid digestion was performed on triplicates of each bottom ash sample. The samples were separated based on their particle sizes (4.75mm, 9.5mm, 12.5mm) after the sieving process.

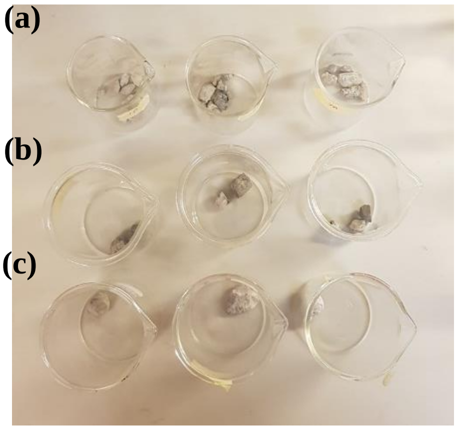


Figure 10: Bottom ash samples to be digested.(a: 4.75 mm, b: 9.5 mm, c: 12.5 mm)

A mass of 4 g of bottom ash was placed in each glass beaker to add 60 ml of 65% Nitric Acid to each. The beakers were then placed in a 90 ˚C water bath and left for 2 hours until complete digestion of the BA particles was achieved. After digestion, the content of the beakers was filtered using Whatman 42 (2.5 µm retention) and the filtrates were collected in Erlenmeyer flasks and diluted to a volume of 200 ml. The filtrates were then analyzed using ICP-MS to detect the quantity of each of lead, mercury, cadmium, chromium, zinc, and copper. This method is adopted from Uddin et al. [35]

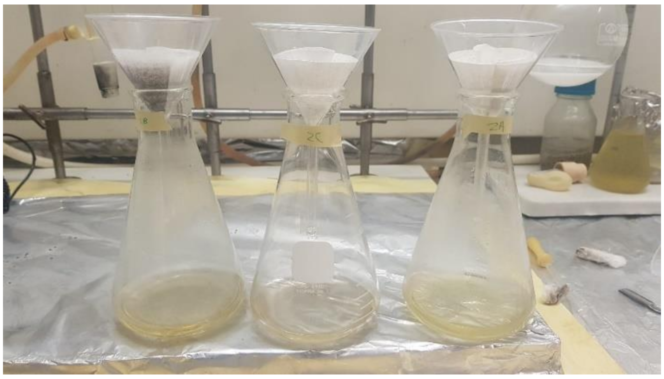


Figure 11: Digested bottom ash samples after filtration(left: 9.5 mm, center: 12.5 mm, right: 4.75 mm)

3.2.4. Heavy Metal Adsorption

This experiment took place in order to assess the adsorption capacity of heavy metals on the bottom ash samples. The experiment was carried using the 4.75 mm particle size with different concentration of Pb(II), Hg(II) and Cd(II) ranging from 100 ppm to 1000 ppm. These metals were chosen as they are considered the most toxic among the 6 metals studied in this project. This was to establish a trend between the initial concentration and the level of adsorption associated with that concentration. Thus, this determines the concentration at which optimal adsorption takes place for the metal under study. First of all, stock solutions of 1000 ppm were prepared for Pb, Cd and Hg. After that, the solutions were diluted to 100, 200, 500 and 700 ppm. A volume of 10 ml from the 5 solutions was placed in PET tubes containing around 3.4 g of BA each. The tubes were then placed in a shaker for 24 hours at 140 rpm. After 24 hours, the solutions were removed from the tubes and filtered using nylon 0.45 µm filter syringes to remove any residues. The filtered solutions were then diluted accordingly to the range of detection of heavy metals in the atomic adsorption spectrophotometer (0-17ppm for lead, 0-700 ppm for Hg and 0-3.5 ppm for Cd). The dilution was done assuming an adsorption of 60%.

3.2.5. SEM & EDX

Scanning Electron Microscopy was used to assess the morphology of the bottom ash samples. The analysis of the shape, surface, structure, and porosity of the BA samples was conducted.

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 15 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.

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, it provides the elemental composition at a certain point or in a specified area. Therefore, it is considered an approximation as it is not representative of the bulk sample as the BA sample is not uniform in composition.

EDX analysis was carried out while performing the Scanning Electron Microscopy where laser beams were concentrated on either a point or a surface area of the sample until it was 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 were 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.

3.3. Pervious Concrete Sample Preparation

The concrete specimens were prepared as to have 20% bottom ash aggregate replacement. The required bottom ash particle sizes obtained from sieving were 4.75, 9.5 and 12.5 mm. Four different mixes using these particle sizes were prepared, the 1st using 12.5 mm BA aggregates as replacement, the 2nd using 9.5 mm, the 3rd using 4.75 mm and the 4th using an equal mixture of both 4.75 and 9.5 mm. In the 4 mixes, limestone aggregates (12.5 mm) were used as the natural aggregate. Each of these 4 scenarios were prepared in replicas with a control specimen for each using completely natural aggregates of the same particle size.

The mix design proportions were adopted from the paper “Method to Investigate Mix design Parameters of Pervious Concrete Mixtures” [25] as the main particle size used was 12.5 mm. Based on that, the water to cement ratio and the aggregate to cement ratio were chosen to be 0.41 and 3.37, respectively. The quantities used in preparation of the concrete samples are summarized in Appendix E.

The mixing procedure was carried out by hand one mix at a time in a pan. Firstly, the limestone and bottom ash aggregate were mixed together to achieve homogeneity. After that, the required amount of cement was added to the aggregates and a hollow was made in the middle of the pile where the water was added. The materials were thoroughly mixed until a uniform and consistent mix was obtained. The mix was then cast into cylindrical metal molds with a diameter and height of 15 and 30 cm, respectively. The casts were placed in a closed room and left for 24 hours to harden. After 24 hours, the mold was removed and placed in distilled water for 28 days to be cured. Table 1 summarizes the labelling followed during PC sample preparation.

Table 1: PC cylinder labelling

Sample Label	*Sample Type*	*20% Aggregate Size*
C1	Control	12.5 mm
C2	Control	4.75 mm
C3	Control	9.5 mm
C4	Control	4.75 & 9.5 mm
S1	Test Sample	12.5 mm

S2	Test Sample	4.75 mm
S3	Test Sample	9.5 mm
S4	Test Sample	4.75 & 9.5 mm

Figure 12: Pervious concrete sample preparations from mixing materials to curing for specimen using 9.5 mm BA as 20% aggregate replacement

3.4. Air Void 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 their submerged masses were measured. Afterwards, the specimens were oven dried at 38 ˚C for 24 h and the dry masses were recorded. The air voids content was calculated as follows:

$$Air\ Void\ Content\ (\%) = \left[1 - \left(\frac{K \times (A - B)}{\rho_w \times D^2 \times L}\right)\right] \times 100 \quad (4)$$

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), ρw is the density of water at the temperature of the water bath (kg/m3), and K is a constant equal to 1,273,240 in SI units.

3.5. Compressive Strength

The compressive strength test was performed 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 to the point of fracture, then the maximum load was measured, and the compressive strength was calculated as follows:

$$Compressive\ Strength\ \left({}^{N}/_{cm^2}\right) = \frac{F}{A} \qquad (5)$$

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

3.6. Leachability of Heavy Metals

The most important aspect to address when reusing BA in building materials is the leachability of heavy metals during their lifetime [4]. The Environmental Protection Agency (EPA) defines toxic chemicals as those that can be considered harmful to the environment or health if inhaled, ingested, or absorbed through the skin. Metals including Cr, Cd, Cu, Zn, Hg, and Pb are some of the commonly existing heavy metals in municipal solid waste incineration bottom ash. These metals can be extremely toxic and may lead to serious environmental concerns if leached out. As reported by Luo et al, heavy metals account for 0.5% by weight of municipal solid waste incinerator bottom ash [4].

In this research, the six metals (zinc, copper, cadmium, chromium, lead and mercury) were examined for their possible leachability from BA based PC specimens. The presence of the metals was tested using ICP-MS for each of the following cases: (1) curing water of each prepared PC specimens after 28 days, (2) infiltrated distilled water through the PC specimens to simulate rain, and (3) infiltrated acidic water (pH of 5) to simulate acid rain. The concentration of heavy metals leaching out of the BA was compared to the allowable limits set by the EPA. The EPA standards and limits are shown in Table 16 in Appendix J.

CHAPTER 4

RESULTS & DISCUSSIONS

4.1. Physical Characterization

4.1.1. Particle Size Distribution

The particle size distribution of bottom ash presented in Figure 29 varies in the range from 0.1 to 10 on the log scale (i.e., 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 25% represent the coarse particles (4.75 to 19 mm), half of which are retained on the 4.25 mm sieve. The range of coarse aggregates are the targeted particle size in this project.

4.1.2. Specific Gravity & Water Absorption

The specific gravities of the aggregates were found as they are an estimate of their strength where lower specific gravity values indicate lower strength of aggregates. Also, the water absorption capacity of BA was determined as it is a direct indication of the porosity of the aggregates. High water absorption capacity of aggregates will affect the pervious concrete sample preparation as this will require the addition of water to the concrete mix to maintain workability of the mix.

The tests were performed for the 3 aggregate sizes, 4.75, 9.5 and 12.5 mm, both limestone (NA) and bottom ash (BA) aggregates. Bottom ash aggregates exhibited very high-water absorption capacities nearly 7 times those of the natural limestone aggregates with 7.48%, 7.06% and 6.82% for the 4.75 mm, 9.5 mm, and 12.5 mm aggregates, respectively. Similar results were obtained in a study by Wu et al. [15]. This indicates that bottom ash is porous and has high water adsorption capabilities whereas limestone aggregates are significantly less porous [20, 15]. Therefore, incorporating BA as a replacement to limestone in PC requires the addition of more water to the mix to account for that absorbed by BA. A trend was noticed in the obtained results, where the water absorption capabilities of the aggregates was found to decrease with the increase of aggregate size. The inversely proportional relationship between the particle size and water absorption was expected due to the higher surface area exhibited by the smaller aggregates. The results are illustrated in Figure 13.

In the case of the specific gravity test, the bottom ash aggregates' results were very close: 2.293, 2.28, 2.24 for the 4.75 mm, 9.5 mm, and 12.5 mm aggregates, respectively. These values, when compared to the natural aggregates, were found to be 12%, 14% and 15% less than the specific gravity of NA. The difference in specific gravity between BA and NA is comparable to the results found in the literature [15]. This indicates that bottom ash has lower strength and durability when compared to natural aggregates. This lower strength can be attributed to the hollow pores present within the BA aggregates which significantly decrease their strength [15]. A similar trend was also observed where the specific gravity marginally decreased with the increase in aggregate size; however, the variation is not prominent as the standard deviation of the values is only 0.02. Results are illustrated in Figure 14. Surface area and pore volume of BA and limestone were determined through BET testing and are in line with the results of the water absorption test as BA exhibited 80% and 90% more surface area and pore volume, respectively, compared to limestones. This can be seen in appendix D.

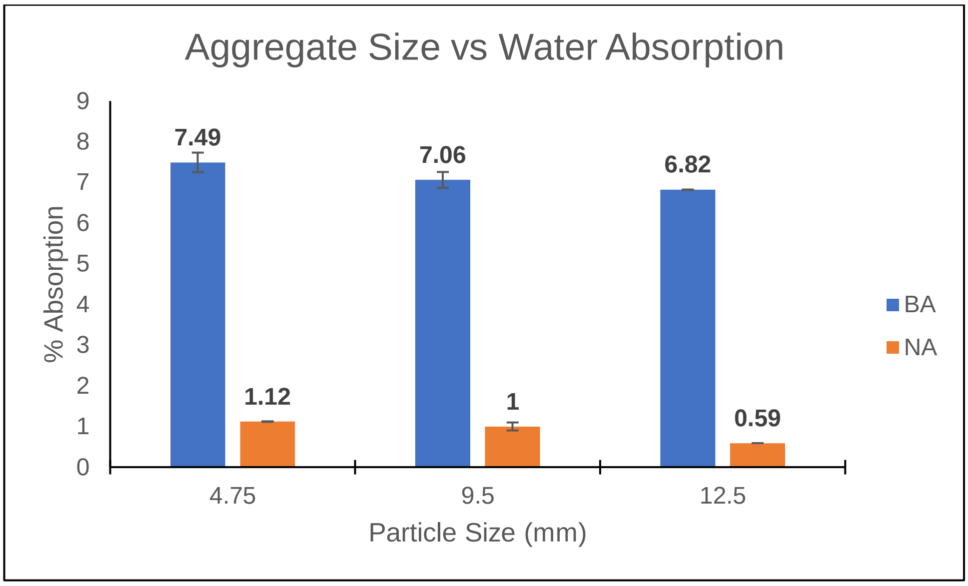


Figure 13: Variation of water absorption capacity of aggregates with different particle sizes

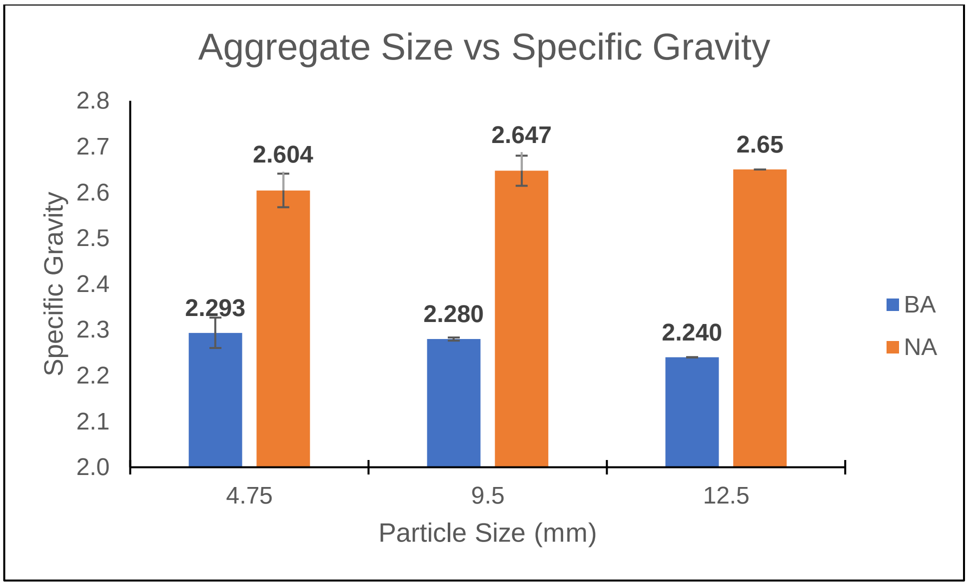
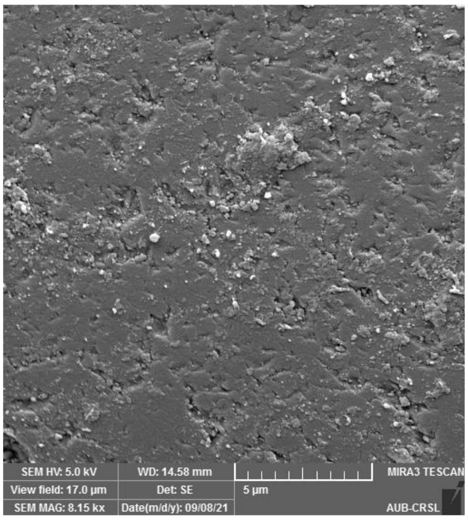


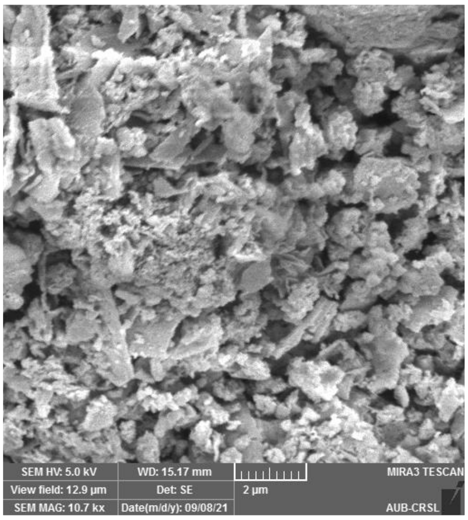
Figure 14: Variation of specific gravity of aggregates with different particle sizes

4.1.3. Scanning Electron Microscopy

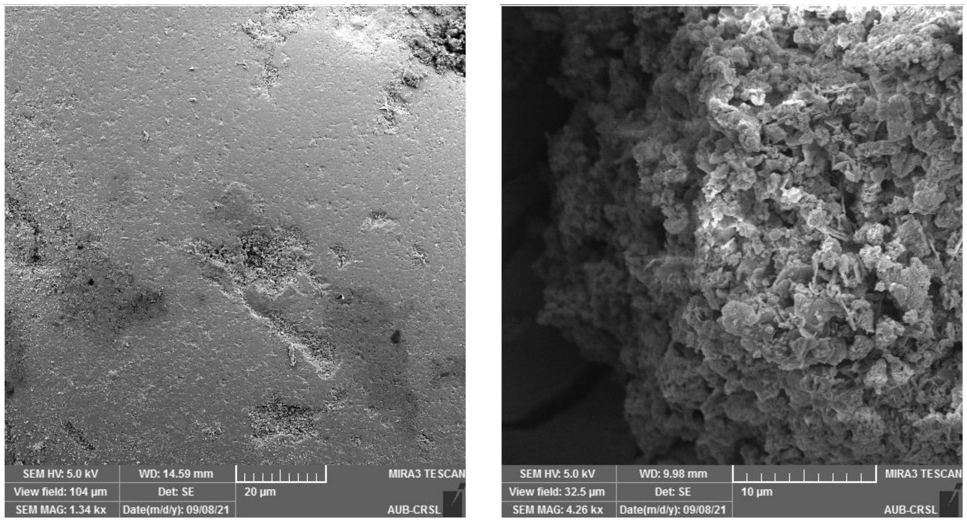
Scanning electron microscopy (SEM) was conducted to assess and compare the surface morphology and texture of the limestone and bottom ash aggregates. Obtained images are presented in Figure 15. It was observed that the surface of limestone aggregates was smoother compared to that of BA which was more jagged and rough. At lower magnifications (2µm), it can be seen that the surface of the BA sample lacked uniformity as a variety of shapes can be observed. This is a result of various types of wastes burned during the incineration process. In one study by Xie et al. [36], the lack of uniformity is attributed to the adhesion of smaller particles on the surface of larger ones creating crystalline structures of various shapes. Also, the images clearly show the presence of hollow pores, which are referred to as cenospheres in the literature [24], in the BA samples compared to the limestone ones which justifies the higher water absorption capacity of bottom ash stated previously. According to Shim et al. and Chen et al., SEM imagery for both limestone and BA observed similar results in terms of the uniformity of the limestone aggregates and the irregular and porous surface of BA [22, 24].



Limestone aggregate (5µm)



Bottom ash aggregate (2µm)



Limestone aggregate (20µm) **Bottom ash aggregate (10µm)**

Figure 15: SEM image comparison between limestone and bottom ash aggregates at different magnification levels

4.2. Chemical Characterization

4.2.1. Energy Dispersive X-Ray Spectroscopy

Energy dispersive X-ray spectroscopy (EDX) was conducted to assess the chemical composition of BA aggregates relative to natural aggregates to ensure that they can be suitable for incorporation in PC without compromising on the properties of PC. The test was run on 6 different spectra for each sample to minimize errors and the results are presented as averages of the 6 runs in Table 2 below. Typically, limestone aggregates are mainly composed of calcium carbonate, silica as well as magnesium and aluminum oxide [37, 38]. The results showed the presence of $CaCO_3$, SiO_2, MgO and iron in the limestone aggregates as well as in BA. Since around 80% (wt.) of the chemical composition of BA is identical to that of limestones, which is similar to other studies performed in the literature [39], then BA can be considered a suitable aggregate replacement in PC. The errors shown in the table are a result of the fluctuation in the

EDX readings due to the variation in the elemental analysis between the different spectra. This is why this analysis is considered an estimation and not an exact measure.

Table 2: Elemental analysis of bottom ash and limestone samples using EDX

Weight %	***C***	***O***	***Mg***	***Al***	***Si***	***S***	***Cl***	***K***	***Ca***	***Fe***	***Cu***
Bottom ash	23.4±3.44	47.5±11.6	2.1±2.05	0.8±0.34	2.8±3.84	0.2±0.05	1.5±1.25	0.2	21.0±9.51	0.6±0.4	0.2
Limestone	18.8±4.53	43.9±6.96	0.8±0.49	-	29.3±19.57	-	-	-	16.0±12	2.1±2.61	-

4.2.2. Acid Digestion

As indicated by the EDX results, BA is mainly comprised of metal oxides as well as calcium carbonate and silica similar to natural limestone aggregates. However, due to the fact that BA are products of MSW incineration, they are known to have high concentrations of heavy metals [40]. These heavy metals, such as lead, cadmium, chromium, mercury, zinc, and copper, are known to pose severe health and environmental hazards as they can be extremely carcinogenic and can bioaccumulate in the environment [41]. Therefore, since BA is being incorporated into PC, then this can lead to heavy metals leaching out as they would be exposed to different weather conditions.

In this experiment, different particle size ranges of BA were subjected to acid digestion to determine their metal content and assess its variation between the different particle sizes. A commonly used Nitric Acid-digestion procedure is used to digest the BA samples [35]. The digested samples were then diluted and analyzed using ICP-MS to determine the heavy metal content of selected metals in the digested particles. The 3 particle sizes studied in this experiment are 4.75 mm, 9.5 mm, and 12.5 mm and the metals tested are Pb, Cd, Cr, Cu, Hg and Zn since these are the most prominent heavy metals present in MSWBA [40, 42].

Obtained results show that the content of heavy metals decreases with increasing the aggregate's particle size as expected. This is mainly due to the increase in the surface area for adsorption as the particle size decreases [40, 24, 42]. During the combustion process of MSW, the evaporated heavy metals would adsorb to the surface of the ash particles. Therefore, as the contact surface increases (with decreasing particle size), more metals adsorb onto the surface of the BA particles [40]. This trend is presented in the case of Cu and Zn where their contents decreased from 0.0456 mg/gBA and 0.0522 mg/gBA in the 4.75 mm particle size to 0.0038 mg/gBA and 0.0047 mg/gBA in the 12.5 mm particle size, respectively. In the case of Pb and Cr, their overall quantities are significantly less than those for Cu and Zn, but the same trend applies. The contents of Pb and Cr decreased from 0.0092 mg/gBA and 0.0072 mg/gBA to 0.0016 mg/gBA and 0.0027 mg/gBA, respectively, as the particle size increased from 4.75 mm to 12.5 mm. As for Hg and Cd, the detected quantities were negligible as they were in the order of 10^{-4} mg/gBA. Overall, the concentrations of heavy metals obtained are low (in the order of 10^{-2} and 10^{-3} mg/g) compared to similar studies conducted in the literature [40, 24, 42, 15]. This might be an indication that the present heavy metals are within the safe limits set by the EPA.

The results show some variation in the values especially for Zn and Cu for the 4.75 mm BA aggregates. This could be attributed to the small size of the aggregates which made it difficult to sort them from the many impurities, such as metal fragments and other unburnt materials, present in the bulk sample. The results are summarized in the Figure 16 below.

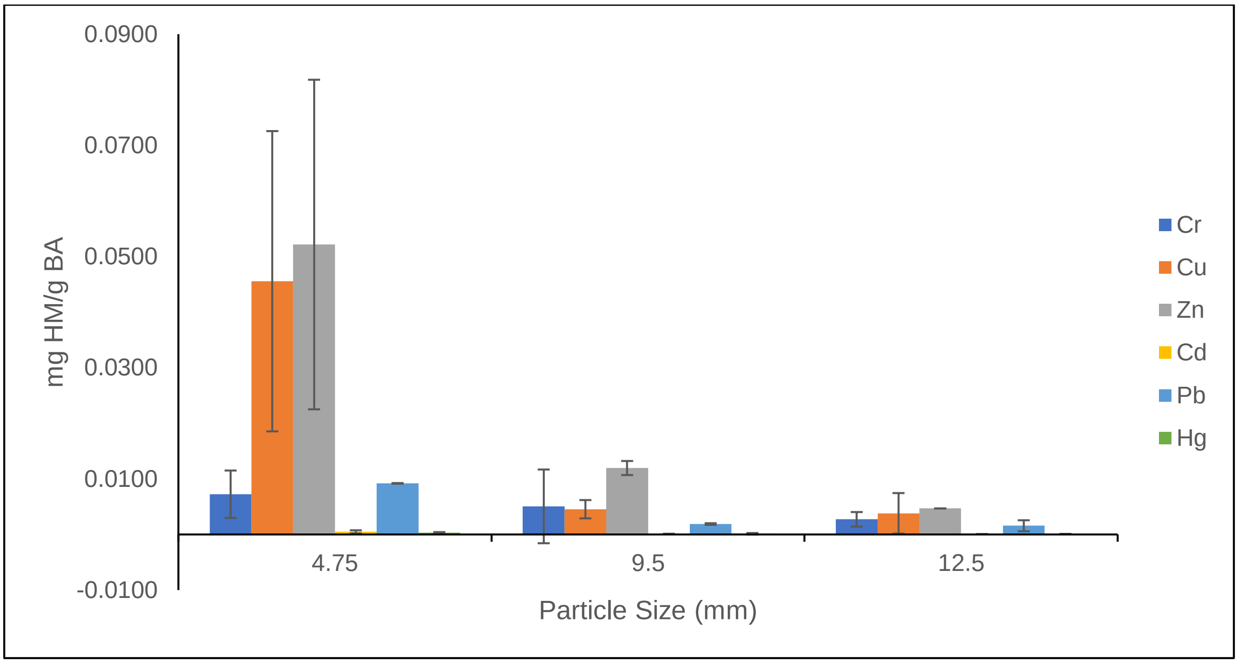


Figure 16: Acid digestion results showing the variation of heavy metal concentration with BA particle size

4.2.3. *Heavy Metal Adsorption*

The adsorption of lead, cadmium and mercury was assessed on the 4.75 mm BA aggregates. These 3 metals were chosen as they are considered the most toxic heavy metals in this study [41]. This experiment was carried out to assess the potential BA has in adsorbing heavy metals from polluted water. The 4.75 mm BA were chosen as they have the largest surface area of adsorption compared to the 9.5 mm and 12.5 mm.

All three heavy metals exhibited linear removal trends with more heavy metals being removed per gram of BA at higher initial concentrations. The percentage removal for lead was the highest with nearly 99% removal at all initial concentrations. For mercury, however, a maximum percentage removal of 48% was achieved at an initial concentration of 700 ppm, whereas for cadmium, the highest percentage removal was 70% at 1000 ppm. This shows that the BA has different affinities for different heavy metals and does not adsorb all heavy metals equally, which is in accordance with the literature. Similar studies on heavy metal adsorption onto BA were conducted in the literature [43, 44, 23]. One study by Cho et al. showed similar results were Pb adsorbed the most (99%) compared to Cd, Zn and Cu [44]. This shows that BA has great potential in its use as a heavy metal adsorbent.

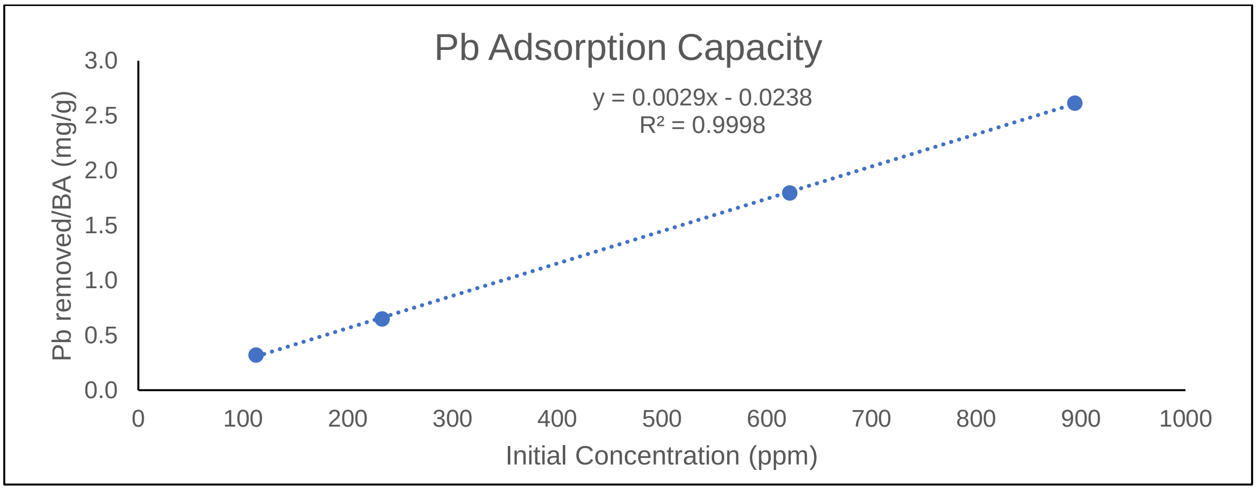


Figure 17: Adsorption of Pb onto 4.75 mm BA aggregates at different initial concentrations of Pb(II)

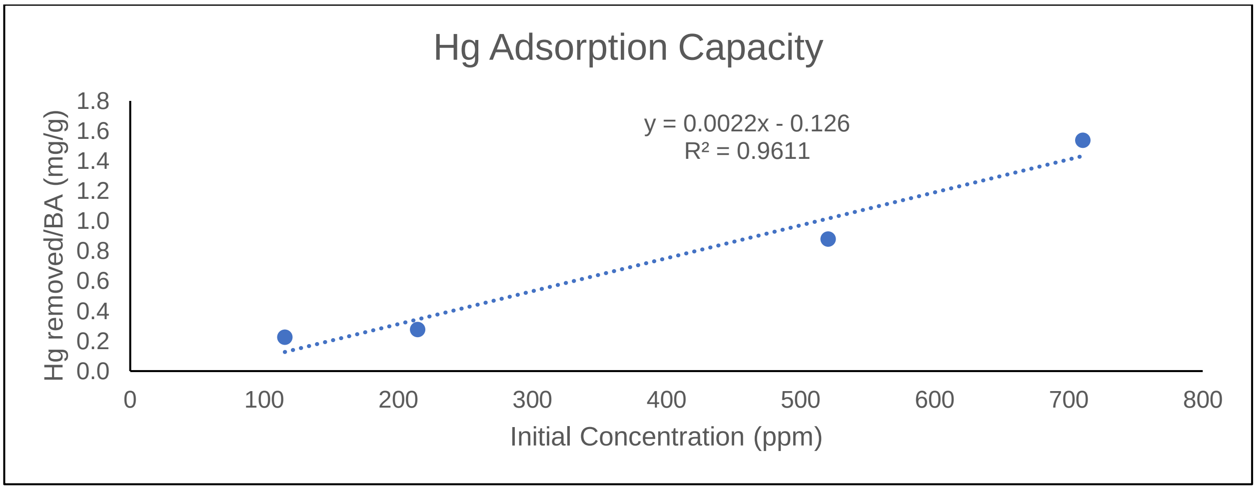


Figure 18: Adsorption of Hg onto 4.75 mm BA aggregates at different initial concentrations of Hg(II)

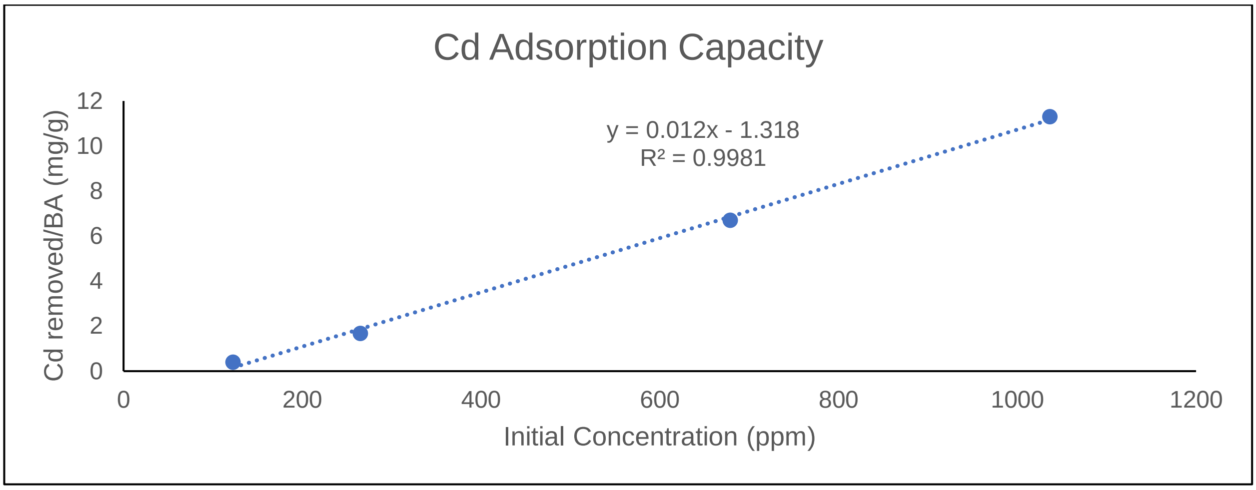


Figure 19: Adsorption of Cd onto 4.75 mm BA aggregates at different initial concentrations of Cd(II)

4.3. Physical Characterization of Pervious Concrete Samples

4.3.1. Compressive Strength & Air Void Content of Cylinders

After 28 days of curing, the PC specimens were prepared for testing their physical properties through compressive strength and air void content tests. Comparing each specimen to their control samples, it can be seen that an overall decrease (between 15 and 34 %) in compressive strength was observed upon incorporating different particle sizes of BA as 20% replacement in NA. This was expected as it was established that BA have a lower strength compared to limestones due to their higher porosity. Upon replacing 12.5 mm BA aggregates with 9.5 mm BA aggregates there is hardly any change in the compressive strength (8.6±0.16 to 8.5±0.64 MPa). Using 4.75 mm BA resulted in a more significant increase in the compressive strength to around 9.7±1.1 (more than 13% increase) MPa. However, using both 4.75 and 9.5 mm mix BA aggregates resulted in similar compressive strength to the 12.5 and 9.5 mm samples (8.3±0.26 MPa). That being said, all the samples meet the strength requirements for pervious concrete applications set by the ACI (2.8 to 28 MPa) [28].

When it comes to the void content of the cylinders, it can be said that no clear trend was observed between the specimens and their controls. For the 12.5 mm samples, the void content was almost the same as the control sample (24%±0.6 and 23%, respectively), whereas in the samples with 9.5 mm aggregates, the void content of the sample with BA (21%±1.8) was higher than that of the control sample (17%). However, for the 4.75 and mixture of 4.75 and 9.5 mm aggregates, the controls' void contents were around 16% and 34% higher compared to the samples with BA, respectively. This could be attributed to the fact that limestones retained on the 4.75 mm sieve tray were generally larger than those of the BA, meaning that aggregates in the 4.75-9.5 mm range were more on the upper end of the spectrum when it came to limestone compared to bottom ash. **Error! Reference source not found.** shows that the limestones retained on the 4.75 mm sieve were larger and more elongated compared to the BA aggregates which have a rounder shape and smaller size. This may have contributed to the control sample having a higher void content than the test sample which was more densely packed. These results also fall in the range set by the ACI for air void content in pervious concrete (15% to 35%) [28].

Previous results conducted by our group confirmed that the increase in the air void contents of pervious concrete result in a decrease in its compressive strength. In this study however, no clear cut relation between the air void content and the compressive strength is established. This might be attributed to the fact that varying the particle size of 20% of the aggregate is not enough to cause a drastic change on the physical properties of the PC specimen. If the controls and the test samples are each observed on their own it can be seen that the standard deviation between the results was 1.04 MPa and 0.63 MPa for the controls and test samples, respectively. Similarly, for the void content, the standard deviation for the controls and test samples was 4.2% and 1.6%, respectively.

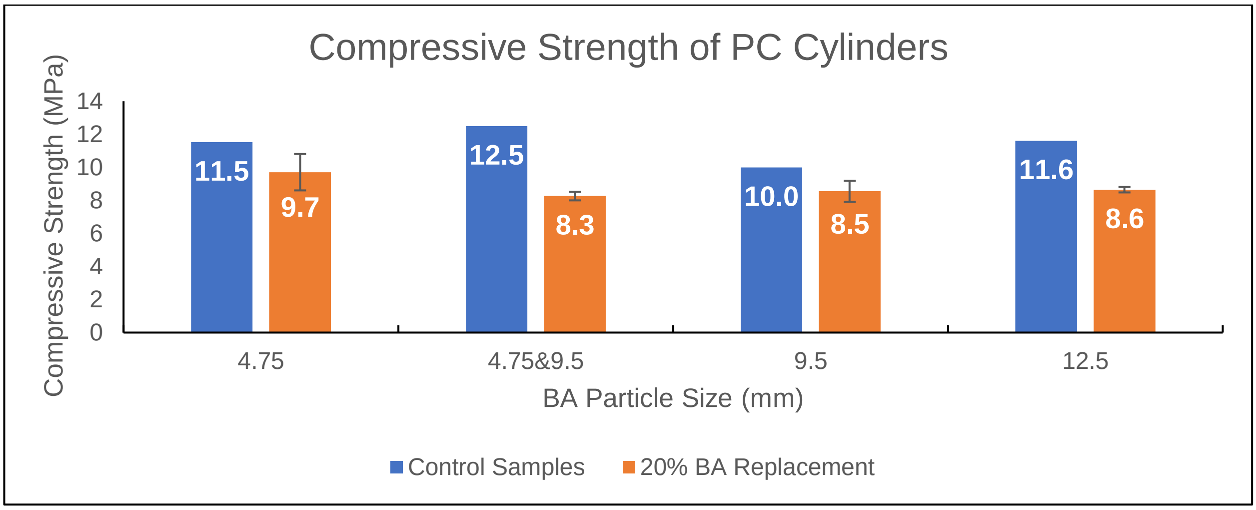


Figure 20: Compressive strength comparison between control and test samples using 4 different particle sizes of BA as aggregate replacement

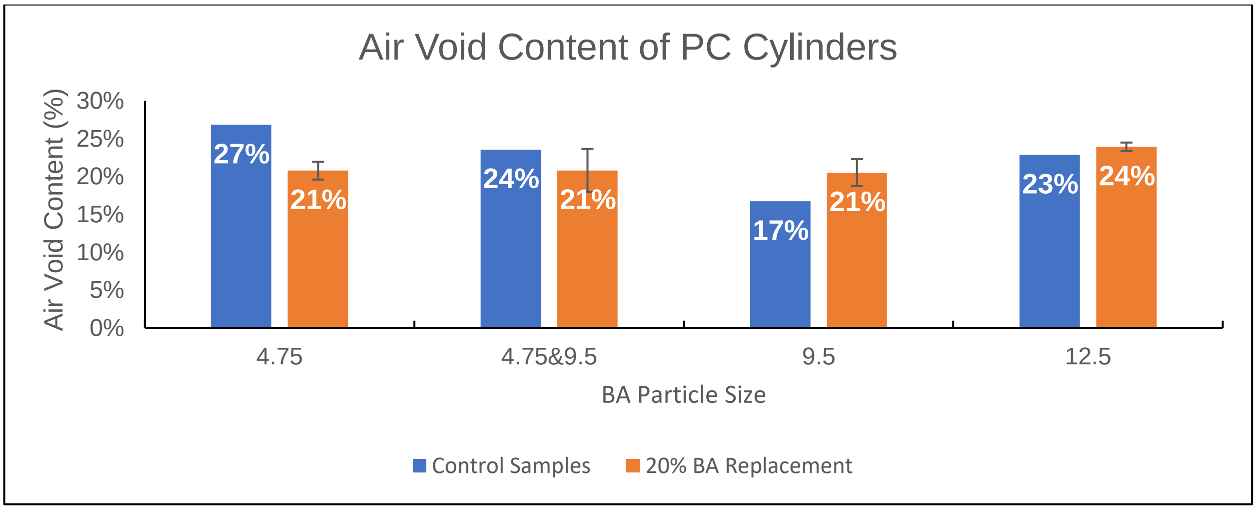


Figure 21: Air void content comparison between control and test samples using 4 different particle sizes of BA as aggregate replacement

4.3.2. Previous Results (Ghosson et al.)

Previous studies were conducted by our group on PC cylinders with varying the percentage of BA aggregate replacement (0-30%) using single sized 12.5 mm aggregates. A trend was observed showing a decrease in the compressive strength with the increased incorporation of BA into the specimens. The compressive strength decreased from 21.72 MPa at 0% replacement to 8.69 MPa at 30% indicating a 40% decrease in the compressive strength of the cylinders. Similar results were obtained in the air void content test were the voids increased with the increase in the percentage replacement in BA. Therefore, due to the porous nature of BA, incorporating them into pervious concrete samples would increase the air void content and as a result decrease the compressive strength. This study concluded that the optimal percentage of aggregate replacement would be the 20% replacement as it uses the most bottom ash without extremely compromising the physical characteristics of pervious concrete. In a study by Dash et al. [45], PC cubes made with single sized BA aggregates (4.75, 9.5 and 12.5 mm) with admixtures resulted in almost constant compressive strength and air void content of 15 MPa and 28%, respectively, for all samples. In another study by Kuo et al. [20], PC cylinders made using single sized BA and NA showed no great variation in terms of connected porosity and compressive strength (around 28% and 9 MPa respectively). These results are very similar to those obtained in our study.

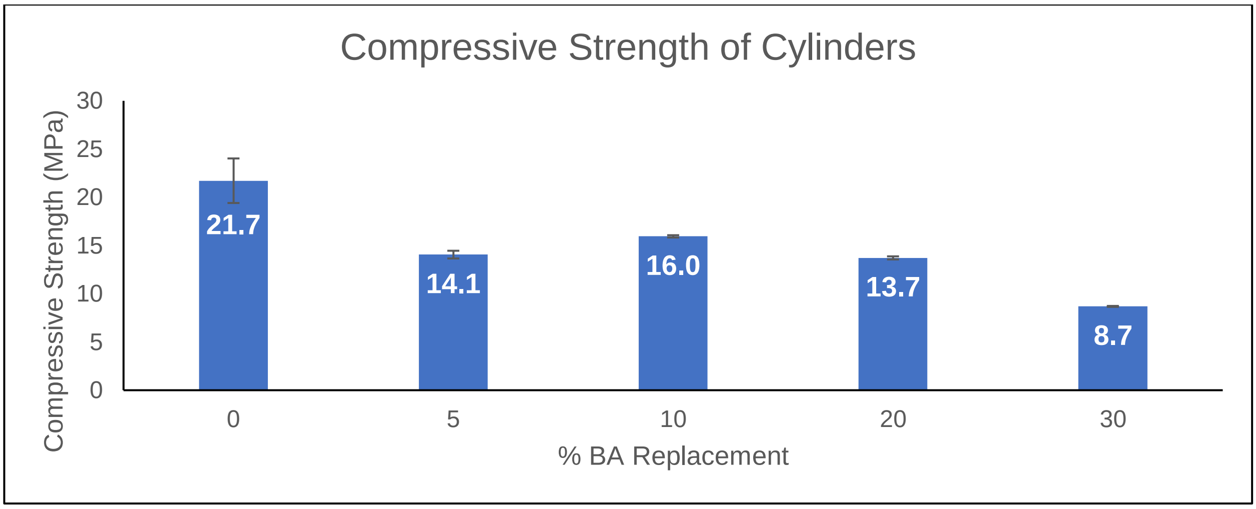


Figure 22: Compressive strength of cylinders with varying BA replacement % (results from previous studies by our group)

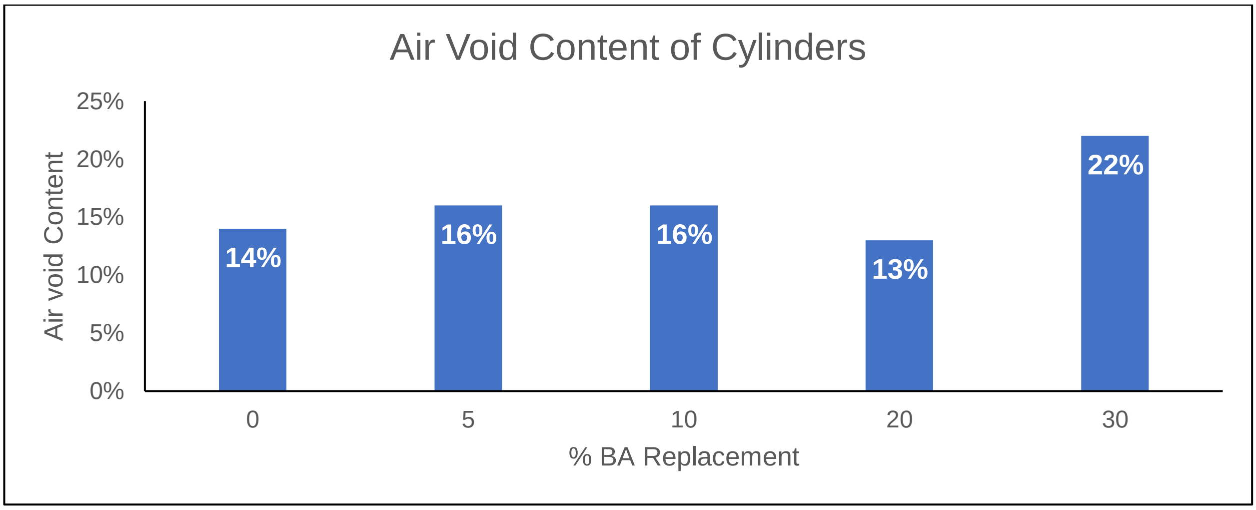


Figure 23: Air void content of cylinders with varying BA replacement % (results from previous studies by our group)

4.4. Chemical Analysis of Pervious Concrete Leachate

4.4.1. Leachability of Heavy Metals

4.4.2. Curing Water

After curing the pervious concrete specimens in around 12 L of distilled water for 28 days, a 50 ml sample of the curing water was tested using ICP-MS to detect any leached heavy metals from the specimens. The metals to be detected in this study were Cr, Cu, Zn, Cd, Pb and Hg which have a minimum limit of quantification in ICP-MS of 0.5, 5, 20, 1, 1, and 1 ppb, respectively. That being said, the only detected metal in curing water was chromium for all samples with a concentration ranging from 21 to 39 ppb in all the samples. In addition to that, sample S1 leached 35 ppb of Zn, S3 1.59 ppb of Hg and S4 2 ppb of Pb. Compared with the acid digestion results of BA, the concentration of leached heavy metals was much lower than the metal content of the BA detected previously indicating that the heavy metals are, to an extent, fixed within the PC specimen. This is illustrated in the Figure 24. Table 1 explains the labelling of each PC cylinder.

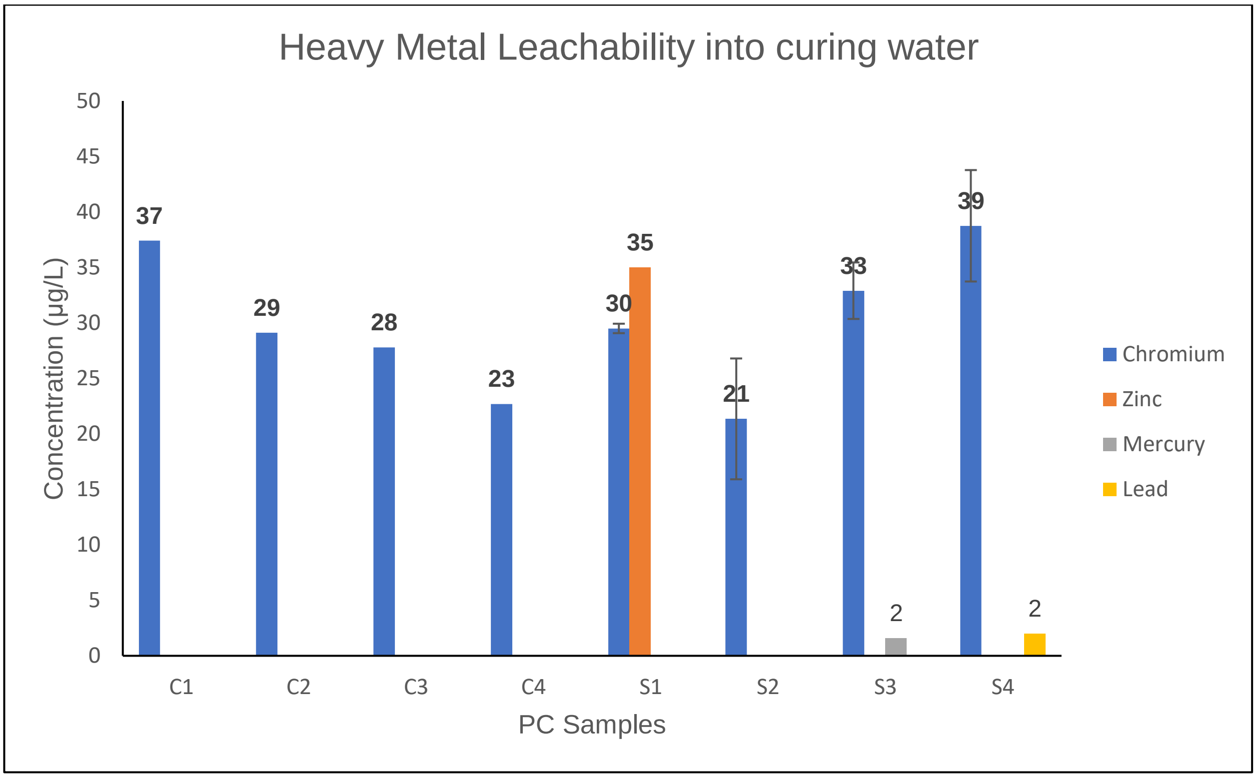


Figure 24: Heavy metal leachability into curing water.

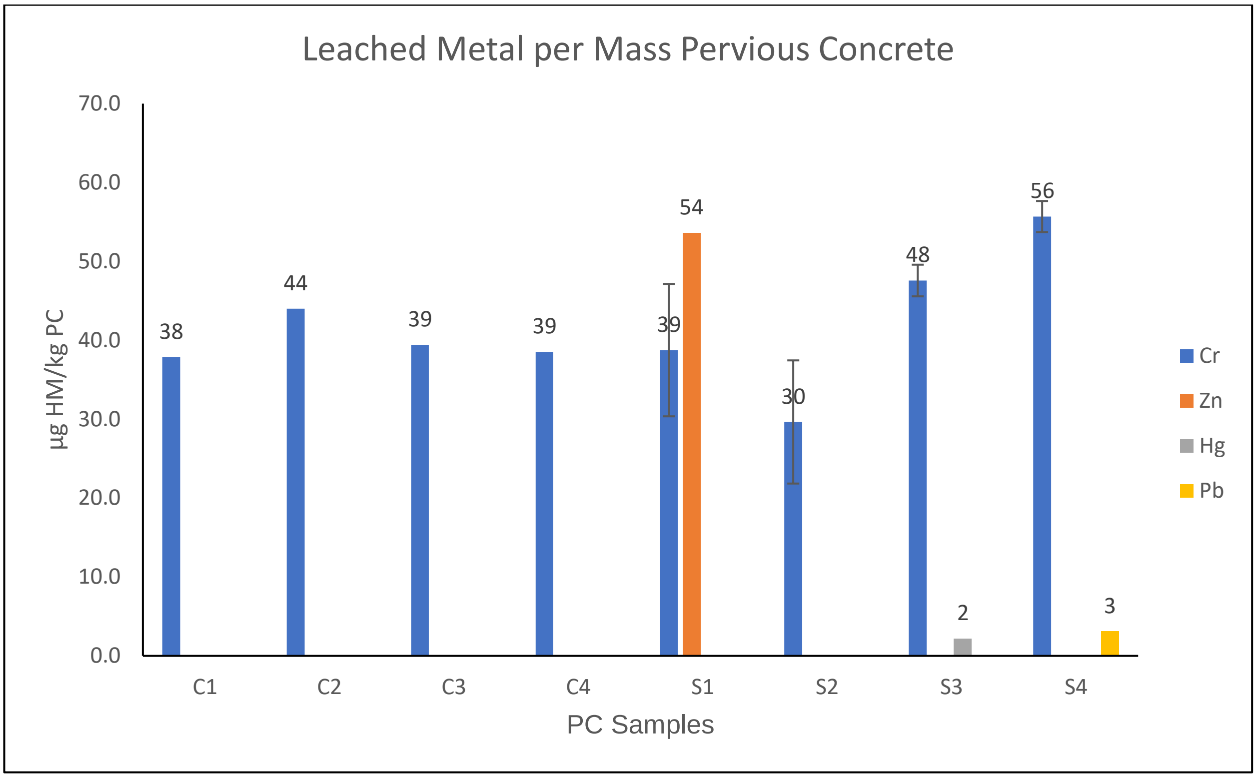


Figure 25: The Amount of heavy metal leached per unit mass of pervious concrete specimen

In terms of chromium, no correlation was observed between the specimens for the source of its leachability which indicates that BA was not the primary source of chromium in the specimens. In fact, chromium is known to be one of the chemicals present in Portland cement [46, 47, 48]. A similar conclusion was reached in a previous study performed by our group where chromium was leached into curing water in concentrations between 0.103 and 0.13 ppm from all PC samples indicating its presence in cement. One study by Estokova et al. observed leached Cr(VI) from cement composites [47], a maximum concentration of Cr of 1.44 mg/kg composite was reported in that study. In our study, however, the highest value obtained was 55.6±2 µg/kg which is much lower than that reported previously. In addition, the leached concentrations of Cr are all within the safe limits set by the EPA for drinking water, aquatic life, and waste (100, 50, 5000 ppb, respectively) [49, 50, 51, 52, 41]. As for the other leached metals (Zn, Hg, Pb), they only leached from samples containing bottom ash, but no relation between the size of the BA aggregate used and the leaching of the heavy metals could be established. The leached concentrations for Zn and Pb (35 and 2 ppb) were below the acceptable limit set by the EPA for drinking, aquatic life, and wastewater. As for Hg (1.59 ppb), it is within the standards for drinking and wastewater, but slightly exceeds that of aquatic life which is about 1 ppb.

4.4.3. Infiltrated Water

The leachability of heavy metals was also tested on infiltrated water to ensure that the water does not get polluted as it passes through the pervious concrete. Distilled water and acidic water (pH 5) were used in this experiment. This was meant to simulate the passing of rain as well as acid rain into pervious concrete. Quantities of chromium ranging between 4 and 13 ppb were detected in distilled water. However, these concentrations are still considered safe as they are lower than the limits set by the EPA [49, 50, 51, 52, 41]. As for acidic water, the samples leached more chromium compared to curing and infiltrated water for some of the samples. The concentration ranged between 10 and 46 ppb. This result was expected as the acid weakens the interaction between the metals and the concrete resulting in higher leached quantities compared to distilled water [53]. Some copper was also leached from samples S2 (30 ppb) and S4 (19 ppb), as well as some traces of mercury in S2 in acidic water. The results are illustrated in Figure 26 andFigure 27. Figure 28 shows the difference between the leached concentration of chromium, as it is the most leached metal present in the samples, in the different water samples compared to the standard set by the EPA for drinking water. As the figure illustrates, all the samples are below the acceptable limit and are therefore, considered safe to be used in PC [54].

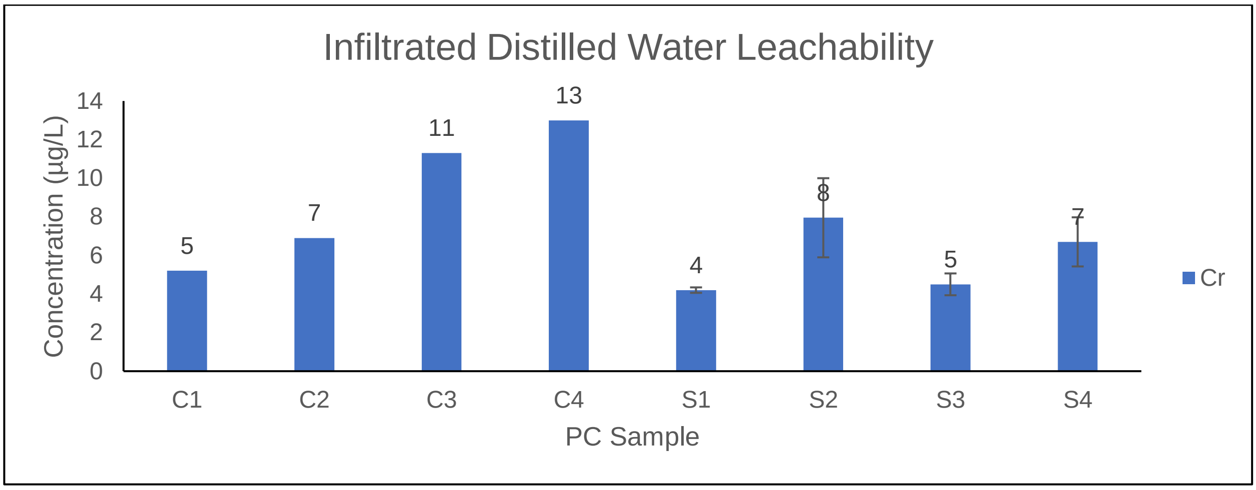


Figure 26: Leachability of heavy metals from PC cylinders into infiltrated distilled water

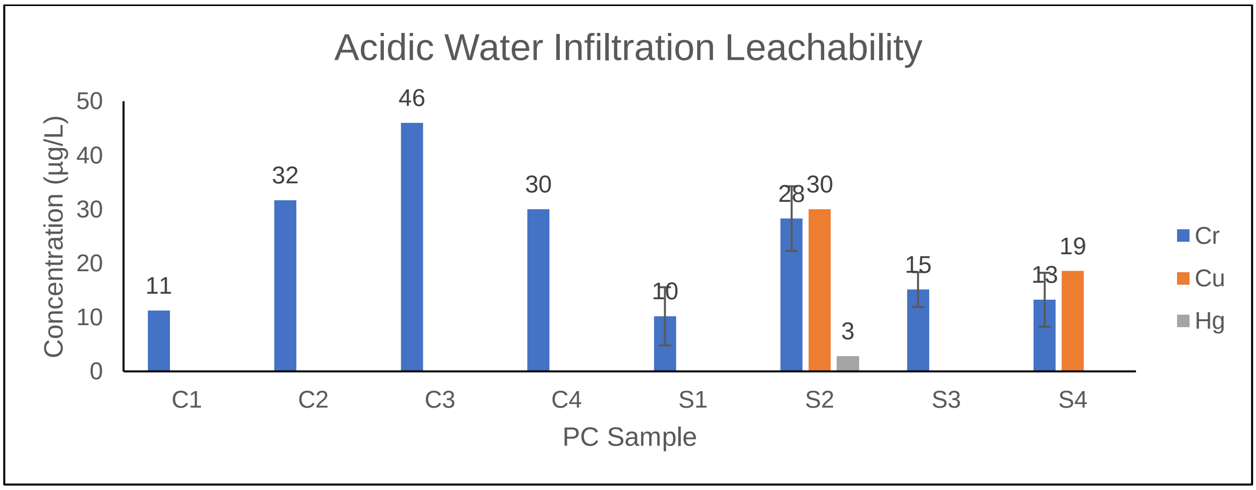


Figure 27: Leachability of heavy metals from PC cylinders into infiltrated acidic water

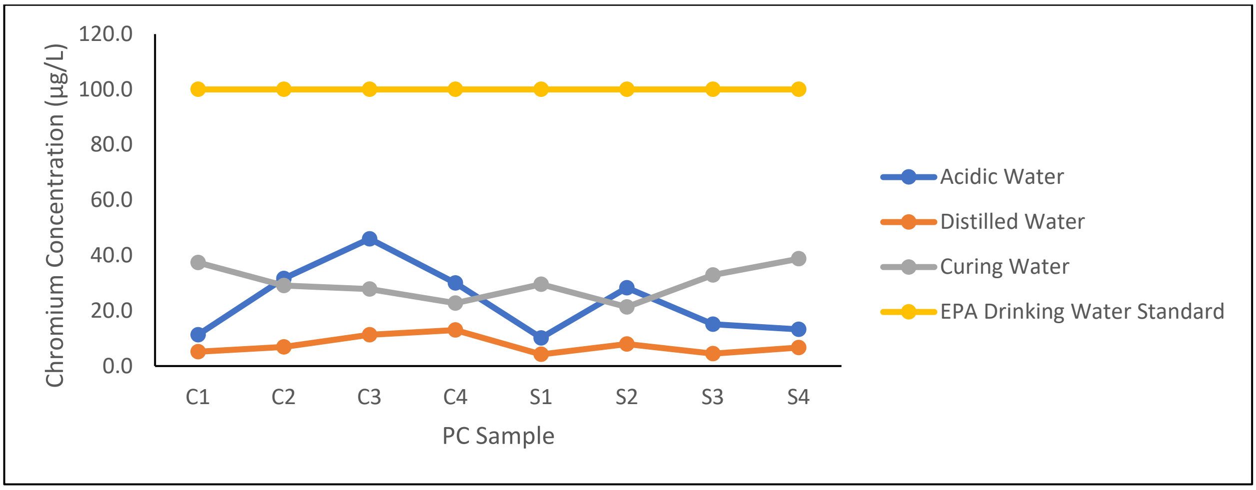


Figure 28: Comparison between chromium levels leached from PC cylinders to the drinking water standard set by the EPA [41]

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

The increase in the quantities of produced municipal solid waste as well as the depletion of natural resources from traditional construction materials introduced the idea of replacing natural construction material with municipal solid waste incinerator bottom ash. The use of multiple particle sizes of MSW incineration BA, from SICOMO, as a 20% replacement of natural aggregates in PC is investigated in this study. This provides a sustainable solution for waste disposal in small countries while generating electricity from heat produced by incineration. The use of BA in PC provides an alternative solution to disposing of these aggregates in landfills, while reducing overexploitation of natural resources thus providing an environmentally friendly source of construction materials. However, a deep understanding of the characteristics and constituents of BA prior to incorporating them into PC is required. Several tests are conducted to make sure that this application meets environmental guidelines as well as ACI guidelines for the use of pervious concrete.

The physical and chemical characteristics of BA are assessed and compared to natural limestone aggregates to verify their viability for aggregate replacement into PC. Characterization included particle size distribution, specific gravity, water absorption, SEM, EDX, heavy metal quantification and heavy metal adsorption capabilities. The PC specimens were prepared with 80% of the aggregates being single sized limestone aggregates (12.5 mm) and 20% BA of varying particle sizes (4.75, 9.5, 12.5 and 4.75 & 9.5 mm mixture). The curing water and infiltrated distilled and acidic water were tested for leachability of heavy metals. The PC specimens were then subjected to air void content and compressive strength tests.

5.1. Concluding Remarks

- Physical and chemical characterization confirmed that BA particles are porous, adsorptive and have a jagged and rough surface. Their chemical composition includes $CaCO_3$, SiO_2, MgO and FeO, which are identical to the composition of limestone, along with other oxides. An inverse correlation between the heavy metal content and the particle size was established as the smaller particle size provided a larger surface area for the adsorption of heavy metals during the incineration process. This might be an indication that heavy metals are present on the surface of the BA aggregates. Also, adsorption of 99%, 70% and 48% of Pb(II), Cd(II) and Hg(II), respectively, onto 4.75 mm BA was observed indicating different affinities of BA towards different heavy metals. This shows that BA has great potential for its use for adsorbing heavy metals from polluted water.
- Air void content results for BA containing samples ranged between 21% and 24%. The highest void content was for the sample containing 12.5 mm BA aggregates as 20% replacement whereas the remaining specimens recorded an air void content of around 21%. In addition, the test specimens containing BA exhibited somewhat similar void contents compared to their control samples. Compressive strength results for BA-containing samples ranged between 8.3 and 9.7 MPa with the highest value being for the sample containing 20% 4.75 mm BA aggregates. The remaining samples were fairly unchanged similar to what was seen in the air void content. This indicates that varying the particle size of the BA used as 20% replacement did not have any drastic effects on the void content and compressive strength of the specimens. As expected, the test samples exhibited 15 to 34 % lower compressive strengths compared to the control samples as BA is porous and has lower strength

compared to natural limestone aggregates. Nevertheless, results for both void content and compressive strength lie within the range set by the ACI (15-35% and 2.8-28 MPa, respectively) for pervious concrete use indicating that BA is a viable alternative to limestones in pervious concrete preparation.

- The leachability of heavy metals was investigated in curing water and infiltrated acidic and distilled water. All samples leached trace amounts of chromium, the highest detected in acidic water as the acid weaken the interaction between the heavy metals and the concrete. The concentration of Cr in acidic water ranged between 10 and 46 ppb. Pb, Hg and Zn appeared in some of the samples but in negligible concentrations. That being said, all the leachability test results were below the standards set by the EPA for heavy metals in water for aquatic life, drinking water and wastewater. This further establishes that BA can be used in pervious concrete as a sustainable alternative to limestones as it does not pose threats to the environment.
-

5.2. Recommendations for Future Work

Further investigations can be performed to further expand on the findings of this project.

- Heavy metal adsorption: Further studies could be explored on the heavy metal adsorption capacity of bottom ash. The study could include experimentation on other heavy metals such as arsenic. The study can also include different BA particle sizes to study the effect surface area has on heavy metal adsorption. BA can also be tested for their selectivity to different heavy metals by performing the adsorption experiment using a heavy metal solution containing multiple heavy metals instead of one.

- Pervious concrete sample optimization: the compressive strength of BA containing pervious concrete samples could be further optimized by the use of admixtures such as plasticizers. This could introduce the option of increasing the percentage aggregate replacement thus improving on the objective of safely disposing of bottom ash in an environmentally safe manner. This is similar to what was introduced in the study by Dash et al. where the compressive strength of PC samples prepared using 100% BA aggregates was maintained at around 15 MPa by the use of admixtures such as silica fume and super plasticizer [45].
- Water purification potential of BA-containing PC samples: The ability of pervious concrete samples containing BA to remove heavy metals or other pollutants from water could be investigated by analyzing the content of pollutants in the infiltrated water.
- Leachability study: This experiment may be expanded by studying the effect of infiltrating basic water on the leachability of heavy metals to simulate other types of pollutants.

APPENDIX A

PARTICLE SIZE DISTRIBUTION

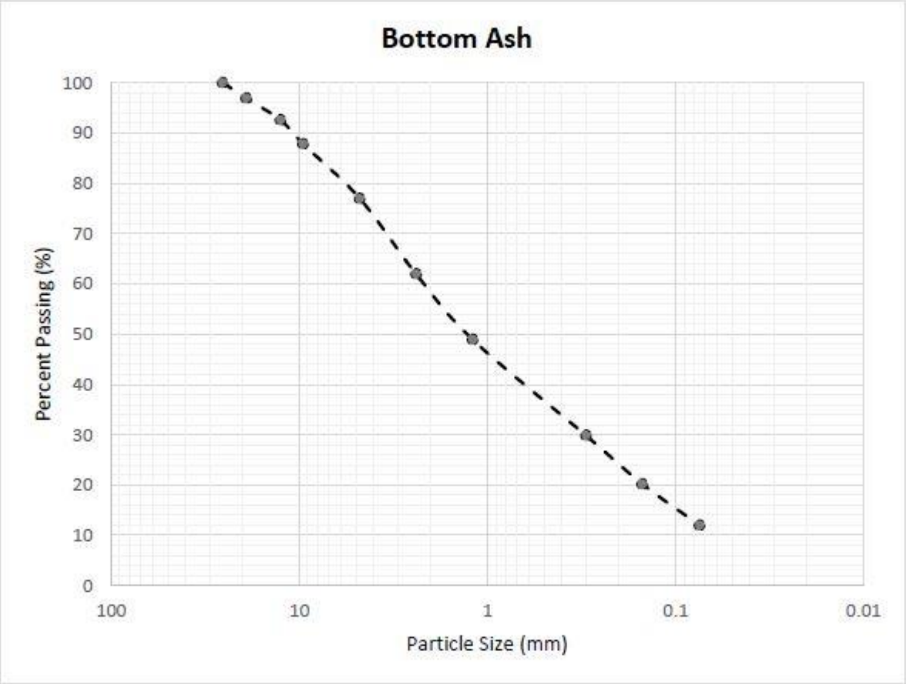


Figure 29: Particle size distribution of municipal solid waste incineration bottom ash from SICOMOs incinerator

APPENDIX B

SPECIFIC GRAVITY & WATER ABSORPTION

Table 3: Weight Measurements for Limestones Aggregates (kg)

Material	*OD*	*SSD*	*SUB*
N3 (9.5)	0.9945	1.0051	0.6327
N4 (9.5)	1.0142	1.0236	0.6371
N1 (4.75)	1	1.0112	0.631
N2 (4.75)	0.9906	1.0016	0.6174

Table 4: Weight Measurements for Bottom Ash Aggregates (kg)

Material	*OD*	*SSD*	*SUB*
B1 (4.75)	0.8845	0.9925	0.5589
B2 (4.75)	0.8862	1.013	0.5603
B3 (9.5)	0.9638	1.0332	0.6109
B4 (9.5)	0.8882	0.9497	0.5597
B6 (4.75 Sorted)	0.95	1.0228	0.6043
B7 (4.75 Sorted)	0.9518	1.0215	0.6107

Table 5: Specific Gravities & water Absorption Values for Limestone Aggregates

Material	*God*	*Gssd*	*Gapp*	*% Absorption*
N1 (9.5)	2.671	2.699	2.749	1.07
N2 (9.5)	2.624	2.648	2.689	0.93
N3 (4.75)	2.630	2.660	2.710	1.12
N4 (4.75)	2.578	2.607	2.654	1.11
N5 (12.5)	2.65	N/A	N/A	0.59

Table 6: Specific Gravity & Water Absorption Values for Bottom Ash Aggregates

Material	*God*	*Gssd*	*Gapp*	*% Absorption*
B1 (4.75)	2.040	2.289	2.717	12.2
B2 (4.75)	1.958	2.238	2.719	14.3
B3 (9.5)	2.282	2.447	2.731	7.2
B4 (9.5)	2.277	2.435	2.704	6.9
B4 (12.5)	2.240	N/A	N/A	6.82
B6 (4.75 Sorted)	2.270	2.444	2.748	7.7
B7 (4.75 Sorted)	2.317	2.487	2.790	7.3

APPENDIX C

LOS ANGELES ABRASION TEST

The Los Angeles abrasion test was conducted in accordance with ASTM C131/C131M. The test was performed to assess the aggregates resistance to abrasion. First, the samples were washed, and oven dried to a constant mass of 5 kg. The samples were then placed into the machine set to 33 rpm for 500 revolutions. The discharged material was then sieved using No. 12 sieve and the retained aggregates washed and oven dried then weighed. The test is to be conducted on the BA and the limestone aggregates for comparison.

The percentage loss in mass due to abrasion is calculated using equation 1. The standard dictates that the acceptable loss in mass should be below 40%.

$$\%\,Loss = \frac{C-Y}{C} \times 100 \qquad (1)$$

Where C is the mass of the original sample and Y is the final mass of the test sample (g).

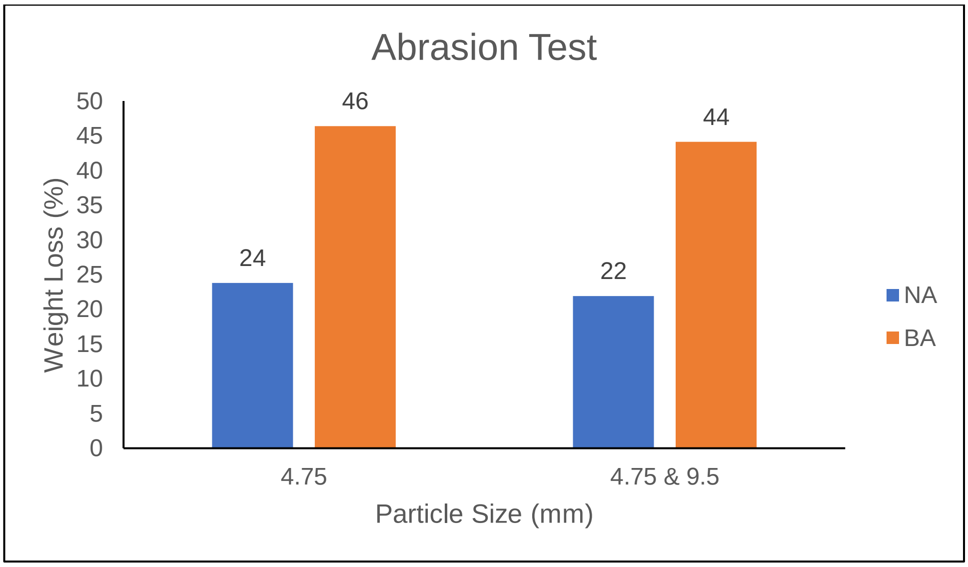


Figure 30: LA abrasion test results for 4.75 mm and a 1:1 mixture of 4.75 and 9.5 mm bottom ash (BA) and limestone (NA) aggregates

APPENDIX D

BRUNAUR, EMMETT AND TELLER SURFACE AREA & POROSITY: METHODOLOGY AND RESULTS

The BET method is used to determine the specific surface area and porosity of materials by measuring the amount of physically adsorbed Nitrogen Gas. It was done in accordance with ISO 9277.

For this experiment, the crushed particles were sieved using #200 Sieve. The material passing the sieve was placed in the vacuum degassing oven at 70˚C for 24 hours and then degassed at 90˚C for 3 hours. This was done to remove any adsorbed gases on the surface on the particles that can interfere with the BET reading. Finally, the sample was placed in the BET device. The adsorption was measured at -196˚C which is the boiling point of nitrogen.

The BET device used was the micrometrics Gemini VII Version 3.04. The evacuation pressure and equilibrium time were set to 40 kPa/min and 5 s, respectively.

BET was performed on both limestone and bottom ash aggregates. The experiment was performed to supplement the results of the previous experiment The BET results obtained show that the bottom ash aggregates have a much higher surface area and pore volume than the natural aggregates. The specific surface area for bottom ash was found to be 3.601 m^2/g which is about 6 times larger than that of the natural aggregates. Also, the specific pore volume was found to be 0.03 cm^3/g which is 13 times larger than that for the natural aggregates. This supports the conclusion in the previous section that indicated the bottom ash are more porous than the limestone aggregates which makes them capable of absorbing water.

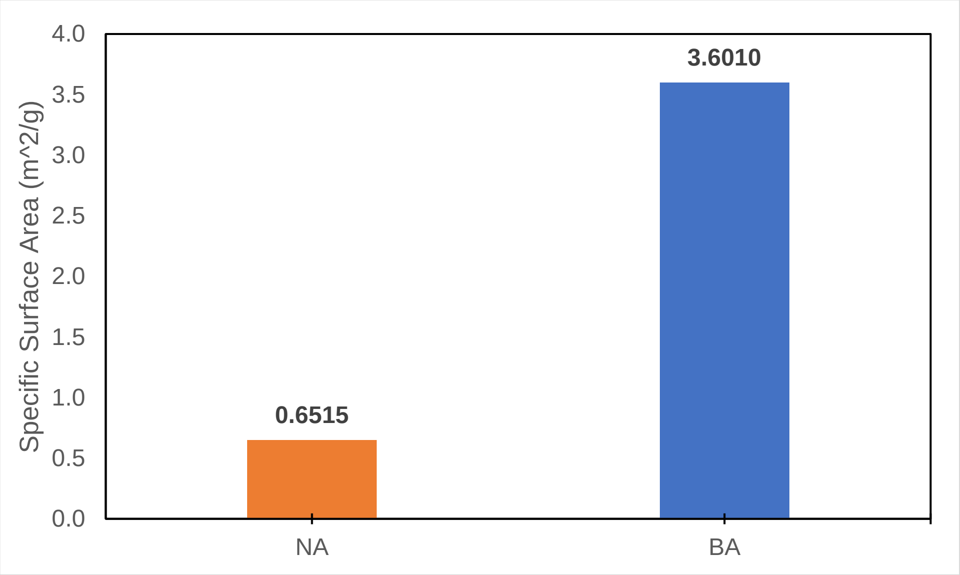


Figure 31: Comparison of the specific surface area of natural (NA) and bottom ash (BA) aggregates

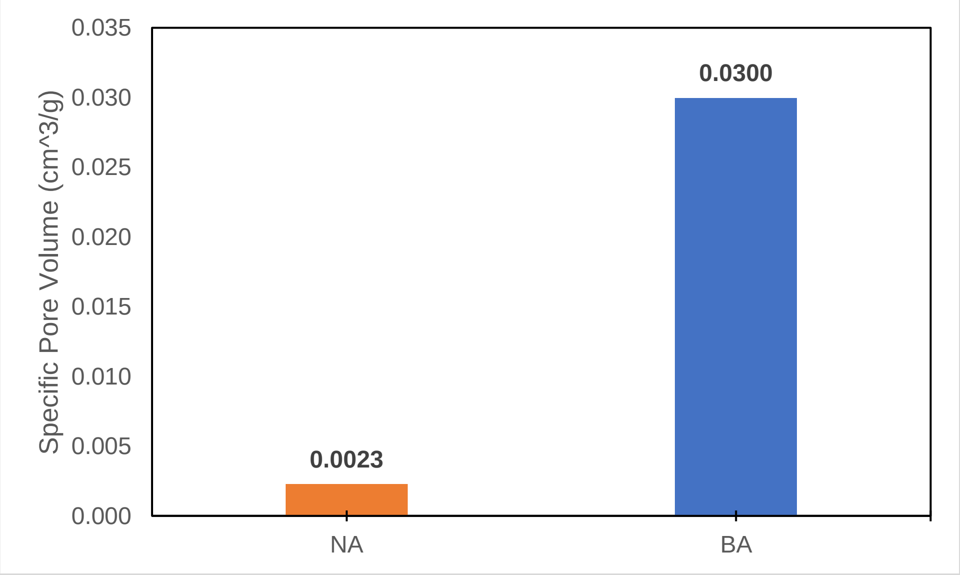


Figure 32: Comparison of the specific pore volume of natural (NA) and bottom ash (BA) aggregates

Table 7: BET Results

	Mass (g)	***Specific Surface Area (m^2/g)***	***Specific Pore Volume (cm^3/g)***	***Pore Width (nm)***

NA	0.0883	0.6515	0.0023	16.6281
BA	0.0239	3.6010	0.0300	33.6391

APPENDIX D

PERVIOUS CONCRETE SAMPLE CALCULATIONS

Table 8: Mix Design Parameters

Aggregates (Kg/m^3)	Sand (Kg/m^3)	Water (Kg/m^3)	Cement (Kg/m^3)	W/C	A/C
1,338.70	**0**	**162.9**	**397.3**	**0.41**	**3.37**

Table 9: Materials for Pervious Concrete Samples with BA (2 replicas)

Samples	*Water (kg)*	*Cement (kg)*	*CA 12 mm (kg)*	*BA 4.75 mm (kg)*	*BA 9.5 mm (kg)*	*BA 12.5 mm (kg)*	*Added Water (kg)*
1	**1.7272**	**4.2125**	**11.3553**	**0.0**	**0.0**	**2.8288**	**0.1936**
2	**1.7272**	**4.2125**	**11.3553**	**2.8388**	**0.0**	**0.0**	**0.2126**
3	**1.7272**	**4.2125**	**11.3553**	**0.0**	**2.8388**	**0.0**	**0.2004**
4	**1.7272**	**4.2125**	**11.3553**	**1.4194**	**1.4194**	**0.0**	**0.2065**

Table 10: Materials for Control Samples

Control	*Water (kg)*	*Cement (kg)*	*CA 4.75 mm (kg)*	*CA 9.5 mm (kg)*	*CA 12 mm (kg)*	*Added Water (kg)*
1	**0.8636**	**2.1063**	**0.0**	**0.0**	**7.097**	**0.0**
2	**0.8636**	**2.1063**	**1.4194**	**0.0**	**5.6776**	**0.0**
3	**0.8636**	**2.1063**	**0.0**	**1.4194**	**5.6776**	**0.0**
4	**0.8636**	**2.1063**	**0.7097**	**0.7097**	**5.6776**	**0.0**

APPENDIX E

ACID DIGESTION DATA

Table 11: Acid digestion raw data

Particle Size	Sample Label	Weight BA (g)	Initial volume (ml)	Diluted Volume (ml)
4.75 mm	1A	4.0214	60	200
4.75 mm	2A	4.0066	60	200
4.75 mm	3A	4.0300	60	200
9.5 mm	1B	4.1709	60	200
9.5 mm	2B	4.1420	60	200
9.5 mm	3B	3.9620	60	200
12.5 mm	1C	4.3908	60	200
12.5 mm	2C	3.5713	45	150
12.5 mm	3C	3.9324	60	200

Table 12: Acid digestion raw data cont.

Diluted (ppm) (reported from ICP)						Undiluted (ppm)					
Cr	**Cu**	**Zn**	**Cd**	**Pb**	**Hg**	**Cr**	**Cu**	**Zn**	**Cd**	**Pb**	**Hg**
0.229	1.3	1.12	0.01	0.184	0.005	0.763	4.333	3.733	0.033	0.613	0.017
0.149	0.53	1.6	0.004	0.185	0.725	0.497	1.767	5.333	0.013	0.617	2.417
0.058	0.121	0.422	0.015	0.039	0.008	0.193	0.403	1.407	0.050	0.130	0.027
0.264	0.119	0.139	0.003	0.371	0.006	0.880	0.397	0.463	0.010	1.237	0.020
0.018	0.07	0.266	0.001	0.041	0.001	0.060	0.233	0.887	0.003	0.137	0.003
0.031	0.032	0.219	0.001	0.035	0.001	0.103	0.107	0.730	0.003	0.117	0.003
0.078	0.14	1.84	0.001	1.056	0.002	0.260	0.467	6.133	0.003	3.520	0.007
0.029	19.7	0.744	0.001	0.054	0.001	0.097	65.667	2.480	0.003	0.180	0.003
0.067	0.024	0.092	0.001	0.017	0.002	0.223	0.080	0.307	0.003	0.057	0.007

Table 13: Average adsorption with standard deviation

Size (mm)	Cr (mg/g)	Cu (mg/g)	Zn (mg/g)	Cd (mg/g)	Pb (mg/g)	Hg (mg/g)
4.75	0.0072± 0.00426	0.0456± 0.02701	0.0522± 0.02964	0.0005± 0.00027	0.0092± 5.92E-05	0.0003± 0.00011
9.5	0.0051± 0.00663	0.0045± 0.00165	0.0119± 0.00127	0.0001± 5.46E-05	0.0019± 0.00015	0.0001± 0.00014
12.5	0.0027± 0.00131	0.0038± 0.00365	0.0047± 0.0000	0.0000± 4.46E-06	0.0016± 0.00099	0.0001± 3.19E-05

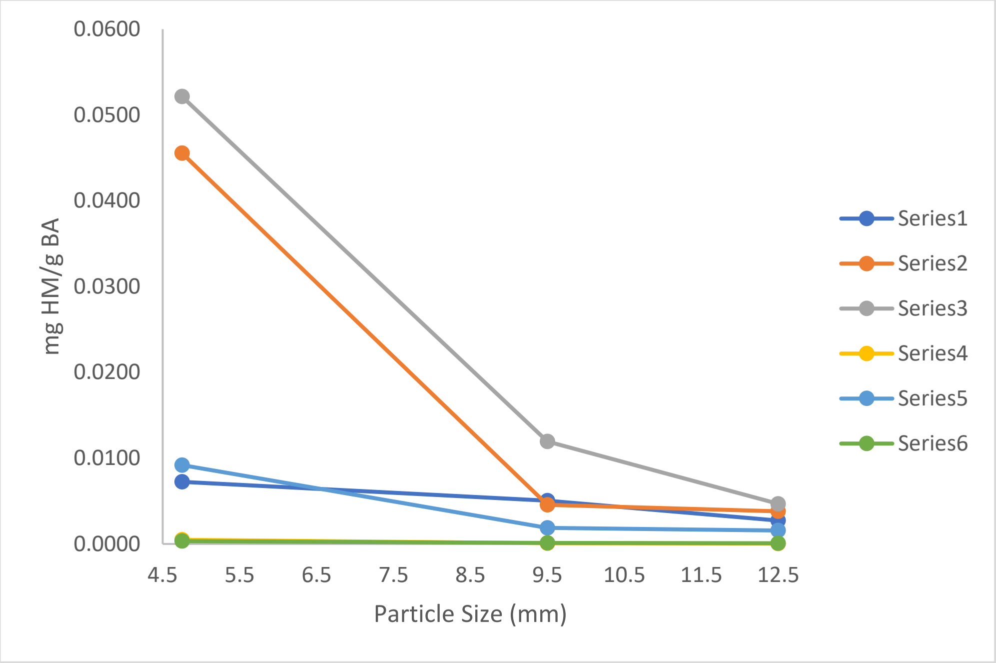


Figure 33: Variation of heavy metal concentration with BA particle size (line graph)

APPENDIX F

AAS CALIBRATION CURVES

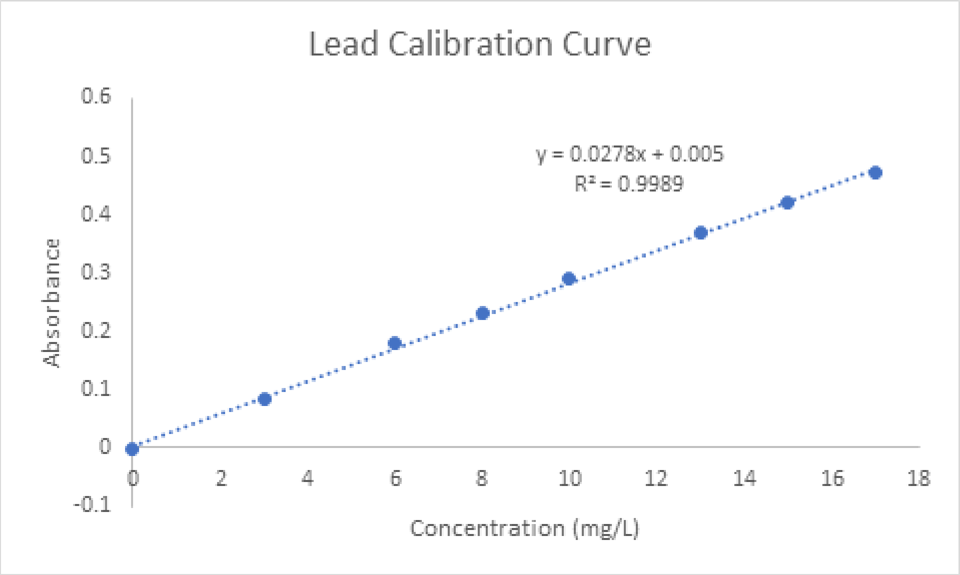


Figure 34: AAS Pb calibration curve (0-17 ppm)

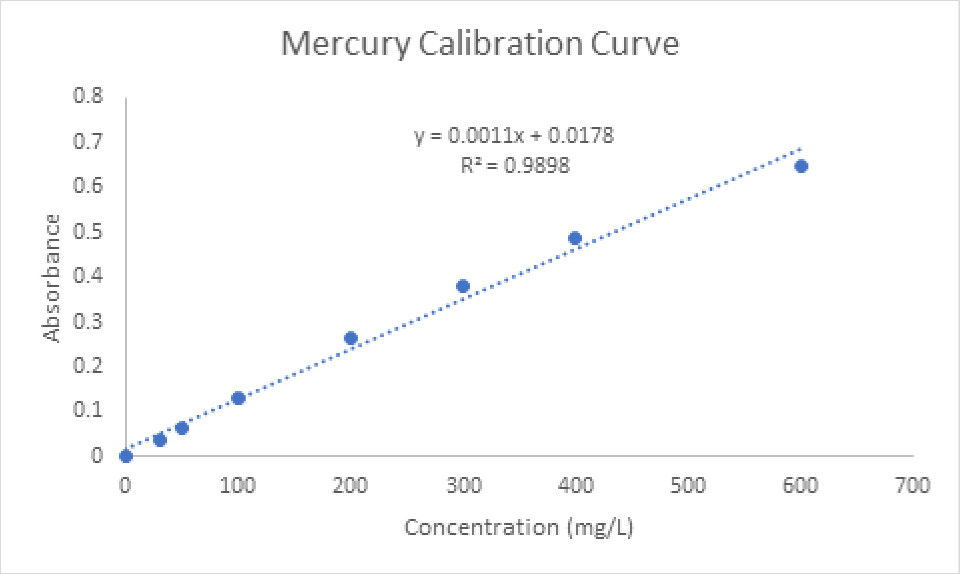


Figure 35: AAS Hg calibration curve (0-600 ppm)

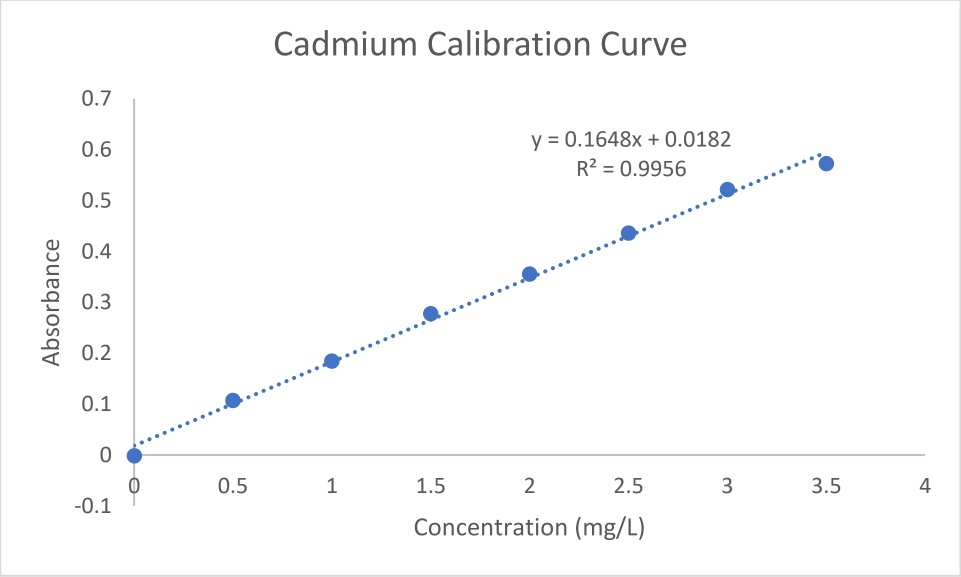


Figure 36: AAS Cd calibration curve (0-3.5 ppm)

APPENDIX G

AIR VOID CONTENT TEST RAW DATA

Table 14: Raw data for air void content result calculations where A is the dry mass and B is the submerged mass of the specimen

		D (cm)	*L (cm)*	*A (g)*	*B (g)*	*Density (kg/m^3)*	*Void Content (%)*
Control	C1	152	284	9218.4	5378.4	1789	23%
	C2	152	271	8550.1	5074.5	1739	27%
	C3	152	276	9218.4	5189.6	1841	17%
	C4	152	270	8794.4	5177.1	1795	24%
Sample	S1.1	152	278	8776.2	5088.7	1740	24%
	S1.2	152	271	8550.1	4917.1	1739	24%
	S2.1	152	273	8757.4	5023.1	1768	22%
	S2.2	152	276	9016.5	5126.9	1800	20%
	S3.1	152	260	8206.2	4641.2	1739	22%
	S3.2	152	262	8532.2	4823.7	1795	19%
	S4.1	152	277	9087.8	5145.5	1808	19%
	S4.2	152	269	8488	4848.6	1739	23%

APPENDIX H

COMPRESSIVE STRENGTH TEST RAW DATA

Table 15: Raw data for compressive strength test calculations where F is the force exerted by the machine, A is the surface area of the cylinders, and P is the compressive strength

		F (KN)	***A (mm^2)***	***P (MPa)***
Control	C1	205.1	17671	11.6
	C2	203.5	17671	11.5
	C3	176.4	17671	10.0
	C4	220.7	17671	12.5
Sample	S1.1	150.7	17671	8.5
	S1.2	154.8	17671	8.8
	S2.1	185.2	17671	10.5
	S2.2	157.7	17671	8.9
	S3.1	159.0	17671	9.0
	S3.2	143.1	17671	8.1
	S4.1	149.2	17671	8.4
	S4.2	142.7	17671	8.1

APPENDIX I

ENVIRONMENTAL PROTECTION AGENCY WATER QUALITY STANDARDS

Table 16: EPA allowable limits for heavy metals in different types of water

CATEGORY	**EPA ALLOWABLE LIMITS**					
	Hg	**Cd**	**Pb**	**Zn**	**Cr**	**Cu**
DRINKING WATER (PPM)	0.002	0.005	0.015	0.047	0.1	1.3
FRESHWATER AQUATIC LIFE (PPB)	0.77	0.72	2.5	120	11	NA
SALTWATER AQUATIC LIFE (PPB)	0.94	7.9	8.1	81	50	3.100
WASTE (PPM)	0.2	1	5	NA	5	NA

REFERENCES

[1] Organization for Economic and development (OECD), "Municipal Waste Generation and Treatment," 2018. [Online]. Available: https://stats.oecd.org/. [Accessed 20 7 2021].

[2] S. Kaza, L. C. Yao, P. Bhada-Tata and F. Van Woerden, What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050, Washington DC.: World Bank, 2018.

[3] The World Bank, "Trends in Solid Waste Management," 2021. [Online]. Available: https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html. [Accessed 20 7 2021].

[4] H. Luo, Y. Cheng, D. He and E.-H. Yang, "Review of Leaching Behavior of Municipal Solid Waste Incineration (MSWI) Ash," *Science of the Total Environment,* vol. 668, pp. 90-103, 2019.

[5] P. Kjeldsen, M. A. Barlaz, A. Baun, A. P. Rooker, A. Ledin and T. H. Christensen, "Present and Long-Term Composition of MSW LAndfill Leachate: A review," *Critical reviews in Environmental science and Technology,* vol. 32, no. 4, pp. 297-336, 2010.

[6] S. Mukherjee, S. Mukhopadhyay, M. A. Hashim and B. S. Gupta, "Contemporary Environmental Issues of Landfill Leachate: Assessment and Remedies," *Critical reviews in Environmental Science adn Technology,* vol. 45, no. 5, 2015.

[7] E. Allegrini, C. Vadenbo, A. Boldrin and T. F. Astrup, "Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash," *Journal of Environmental Management,* vol. 151, pp. 132-143, 2015.

[8] J. Zhang, S. Zhang and B. Liu, "degradation technologies and mechanisms of dioxins in municipal solid waste incineration fly ash: A review," *Journal of Cleaner Production,* vol. 250, 2020.

[9] M. El Fadel and A. Maalouf, "Challenges of Waste Management in a Developing Context: Lessons from Lebanon," *Sustainable Waste Management Challenges in developing countries,* 2019.

[10] M. Jay and R. Russel, "Lebanon garbage crisis pollutes Mediterranean," *DW.com,* 14 6 2017.

[11] I. Tiseo, "Global incinerated waste generation per capita by select country 2015," 3 April 2017. [Online]. Available: https://www.statista.com/statistics/691854/leading-countries-by-per-capita-waste-incineration/. [Accessed 12 August 2021].

[12] C. Klein, "Number of waste incineration facilities Japan FY 2010-2019," 6 May 2021. [Online]. Available: https://www.statista.com/statistics/689599/japan-number-of-waste-incineration-facilities/. [Accessed 12 August 2021].

[13] O. S. San, "Waste-to-Energy Experience: The Case of Singapore," National Environment Agency, 2016.

[14] Mordor Intelligence, "The Japan Waste-to-energy market is segmented by Technology," 2021. [Online]. Available: https://www.mordorintelligence.com/industry-reports/japan-waste-to-energy-market-industry. [Accessed 17 August 2021].

[15] M. H. Wu, C. L. Lin, W. C. Huang and J. W. Chen, "Characteristics of pervious concrete using incineration bottom ash in place of sandstone graded material," *Construction and Building Materials,* vol. 111, pp. 618-624, 2016.

[16] E. Loginova, P. M. F. Wouw, M. V. A. Florea and H. J. Brouwers, "Detailed characterization of particle size fractions of municipal solid waste incineration bottom ash," *Journal of Cleaner Production,* vol. 207, pp. 866-874, 2019.

[17] M. Syc, F. G. Simon, J. Hyks, R. Braga, L. Biganzoli, G. Costa, V. Funari and M. Grosso, "Metal recovery from incineration bottom ash: State-of-the-art and recent developments," *Journal of Hazardous Materials,* vol. 393, 2020.

[18] A. Vatikus, J. Grazulyte, O. Sernas, V. Vorobjovas and r. Kleiziene, "An algorithm for the use of MSWI bottom ash as a building material in road pavement structural layers," *Construction and Biulding Materials,* vol. 212, pp. 456-466, 2019.

[19] A. M. Joseph, R. Snellings, P. V. d. Heede, S. Matthys and N. D. Belie, "The Use of Municipal Solid Waste Incineration Ash in Various Building Materials: A Belgian Point of View," *Materials,* vol. 11, no. 1, p. 141, 2018.

[20] W.-T. Kuo, C.-C. Liu and D.-S. Su, "Use of washed municipal solid waste incinerator bottom ash in pervious concrete," *Cement & Concrete Composites,* vol. 37, pp. 328-335, 2013.

[21] C. J. Lynn, G. S. Ghataora and R. K. Dhir, "Municipal incinerated bottom ash (MIBA) characteristics and potential for use in road pavements," *International Journal of Pavement Research Technology,* vol. 10, no. 2, pp. 185-201, 2017.

[22] J. S. Chen, P. Y. Chu, J. E. Chang, H. C. Lu, Z. H. Wu and K. Y. Lin, "Engineering and Environmental Characterization of Municipal Solid Waste Bottom Ash as an Aggregate Substitute Utilized for Asphalt Concrete," *Journal of Materials in Civil Engineering,* vol. 20, no. 6, p. 432, 2008.

[23] C. H. Weng and C. P. Huang, "Adsorption Characteristics of Zn(II) from dilute aqueous solution by fly ash," *Colloids and Surfaces,* vol. 247, pp. 137-143, 2004.

[24] Y.-S. Shim, Y.-K. Kim, S.-H. Hong, S.-W. Rhee and W.-K. Lee, "The Adsorption characteristics of heavy metals by various particle sizes of MSWI bottom ash," *Waste Management*, vol. 23, pp. 851-857, 2003.

[25] H. A. Kassem, D. Z. Al Hassanieh, M. Mrad, G. R. Chehab and M. Abou Najem, "Method to Investigate Mix Design Parameters of Pervious Concrete Mixtures," *Journal of the Transportation Research Board*, pp. 43-52, 2016.

[26] A. K. Chandrappa and K. P. Biligiri, "Pervious concrete as a sustainable pavement material – Research findings and future prospects: A state-of-the-art review," *Construction and Building Materials*, vol. 111, pp. 262-274, 2016.

[27] R. Zhong, Z. Leng and C. S. Poon, "Research and application of pervious concrete as a sustainable pavement meterial: A state-of-the-art and state-of-the-practive review," *Construction and Building Materials,* vol. 183, pp. 544-553, 2018.

[28] ACI Committee 522, "522R-10: Report on Pervious Concrete," *International Concrete Abstracts Portal*, p. 38, 2010.

[29] M. Tijani, W. Ajagbe, A. Ganiyu and O. Agbede, "Effect of Aggregate Type on Properties of Pervious Concrete," *Journal of Medern Technology and Engineering,* pp. 37-46, 2019.

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

[31] G. M. Kim, J. G. Jang, H. R. Khalid and H. K. Lee, "Water purification characteristics of pervious concrete fabricated with CSA cement and bottom ash aggregates," *Construction and Building Materials,* vol. 136, pp. 1-8, 2017.

[32] Y. Zaetang, A. Wongsa, V. Sata and P. Chindaprasirt, "Use of lightweight aggregates in pervious concrete," *Construction adn Building Materials,* vol. 48, pp. 585-591, 2013.

[33] A. L. Welker, J. D. Barbis and P. A. Jeffers, "A Side-by-Side Comparison of Pervious Concrete and Porous Asphalt," *Journal of the American Water resources Association,* vol. 48, no. 4, 2012.

[34] ThermoFisher Scientific, "Trace Elemental Analysis (TEA) Information," 2021. [Online]. Available: https://www.thermofisher.com/lb/en/home/industrial/spectroscopy-elemental-isotope-analysis/spectroscopy-elemental-isotope-analysis-learning-center/trace-elemental-analysis-tea-information.html. [Accessed 12 August 2021].

[35] A. H. Uddin, R. S. Khalid, M. Alaama, A. M. Abdulkader, A. Kasmuri and S. A. Abbas, "Comparative study of three digestion methods for elemental analysis in

traditional medicine products using atomic absorption spectrometry," *Journal of Analytical Science and Technology,* vol. 7, no. 6, 2016.

[36] R. Xie, Y. Xu, M. Huang, H. Zhu and F. Chu, "Assessent of municipal solid waste incineration bottom ash as a potential road materia;," *Road Materials and Pavement Design,* vol. 18, no. 4, pp. 992-998, 2017.

[37] Z. T. Chang, X. J. Song, r. Munn and M. Marosszeky, "Using limestone aggregates and different cements for enhancing resistance of concrete to sulphuric acid attack," *Cement and Concrete research,* vol. 35, pp. 1486-1494, 2005.

[38] S. Pavia and M. Aly, "Influence of aggregate and supplementary cementitious materials on the properties of hydrated lime (CL90s) mortars," *Materiales De construccion,* vol. 66, no. 324, 2016.

[39] A. Meawad, D. Bojinova and Y. Pelovski, "Study on elements leaching from bottom ash of Enel Maritsa East 3 thermal power plant in Bulgaria," *Journal of the Universit of Chemical Technology and Metallurgy,* vol. 45, no. 3, pp. 275-282, 2010.

[40] C. H. K. Lam, A. W. M. Ip, J. P. Barford and G. McKay, "Use of Incineration MSW Ash: A Review," *Sustainability,* vol. 2, pp. 1943-1968, 2010.

[41] S. Martin and W. Griswold, "Human Health Effects of Heavy Metals," *Environmental Science and Technology Briefs for Citizens,* no. 15, 2009.

[42] X. G. Li, Y. Lv, B. G. Ma, Q. B. Chen, X. B. Yin and S. W. Jian, "Utilization of municipal solid waste incineration bottom ash in blended cement," *Journal of cleaner production,* vol. 32\, pp. 96-100, 2012.

[43] J. H. Park, J. H. Eom, S. L. Lee, S. W. Hwang, S. H. Kim, S. W. Kang, J. J. Yun, J. S. Cho, Y. H. Lee and D. C. Seo, "Exploration of the potential capacity of fly ash and bottom ash derived from wood pellet-based thermal power plant for heavy metal removal," *Science of the Total Environment,* vol. 740, 2020.

[44] H. Cho, D. Oh and K. Kim, "A study on removal characteristics of heavy metals from aqueous solution by fly ash," *Journal of Hazardous materials,* pp. 187-195, 2005.

[45] S. Dash, B. Kar and P. S. Mukherjee, "Pervious Concrete Using Fly ash Aggregate As Coarse Aggregate-An Experimental Study," AIP Conference Proceedings 1953, 2018.

[46] A. Cipurkovic, I. Trumic, Z. Hodzic, V. Selimbasic and A. Djozic, "Distribution of heavy metals in Portland cement production process," *Advances in Applied Science Research,* vol. 5, no. 6, pp. 252-259, 2014.

[47] A. Estokova, L. Palascakova and M. Kanuchova, "Study on Cr(VI) Leaching from Cement and Cement Composites," *Environmental Research and Public Health,* vol. 15, no. 4, 2018.

[48] A. Estokova, L. Palascakova and M. Kovalcikova, "Chromium-Leaching Study of Cements in Various environments," *International Journal of Civil and Environmental Engineering,* vol. 10, no. 6, pp. 727-730, 2016.

[49] EPA, "Ambient Water Quality criteria for Zinc," Office of Water Regulations and Standards Criteria and Standards Division, Washington DC, 1980.

[50] EPA, "Lead and Copper Rule," 1991.

[51] EPA, "What EPA is Doing to Reduce Mercury Pollution, and Exposures to Mercury," 18 November 2019. [Online]. Available: https://www.epa.gov/mercury/what-epa-doing-reduce-mercury-pollution-and-exposures-mercury. [Accessed 10 February 2020].

[52] EPA.gov, "National Recommended Water Quality Criteria - Aquatic life Criteria Table," 2021. [Online]. Available: https://epa.gov/wqc. [Accessed 21 July 2021].

[53] K. Phoungthong, Y. Xia, H. Zhang, L. Shao and P. He, "Leaching toxicity characteristics of municipal solid waste incineration bottom ash," *Frontiers of Environmental Science & Engineering,* vol. 10, pp. 399-411, 2016.

[54] X. Li, Z. Liu, Y. Lv, L. Cai, D. Jiang and W. Jiang, "Utilization of municipal solid waste incineration bottom ash in autoclaved aerated concrete," *Construction and Building Materials,* vol. 178, pp. 175-182, 2018.