AMERICAN UNIVERSITY OF BEIRUT

INCORPORATION OF MUNICIPAL SOLID WASTE INCINERATOR FLY ASH INTO CONCRETE: A SUSTAINABLE APPROACH

by
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ABSTRACT
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Title: Incorporation of Municipal Solid Waste Incinerator Fly Ash into Concrete: A Sustainable Approach

Municipal Solid Waste (MSW) Management is a major challenge facing countries worldwide. While landfilling is considered to be the cheapest and most efficient approach for MSW management, it has proven to have many environmental, social, and economic drawbacks. Therefore, many countries adopted alternative technologies to safely manage their MSW. Incineration, being one of these adopted technologies, demonstrated to be very effective in drastically reducing the quantities of waste (by weight and volume), in addition to the possibility of energy recovery in the form of heat and electricity. In this context, for a small country like Lebanon, generating more than 2.7 million tons of waste annually, controlled MSW incineration may prove to be a potential option. Incineration involves the combustion of waste materials resulting in the formation of flue gases, ash, and heat as by-products. The major environmental concern of incineration is flue gases, as they are hazardous and should be controlled using proper filters. Another environmental concern is the management of the ash residues, namely fly ash, as it contains most of the inorganic toxins and heavy metals. Unfortunately, the ash is often dumped in landfills posing a great threat to the groundwater and soil.

This work explores the potential of incorporating the MSW incinerator fly ash in concrete with the aim of partially replacing cement. Fly ash was acquired from SICOMO, a Lebanese MSWI located in Lebanon. It was characterized by analyzing its physical and chemical properties to ensure its compatibility as a replacement material to cement in cement mortars. Results indicated that fly ash from SICOMO showed characteristics similar to other MSWI fly ashes reported in the literature, enabling us to use it as a partial replacement to cement without any pretreatment. To investigate the compatibility of this partial incorporation, cement mortars containing 10% (by weight) replacement of cement with fly ash were prepared and tested for compressive strength. Results showed that cement mortars containing 10% cement replacement achieved 97% of the 28-day compressive strength of control cement mortars. To find the optimum percentage replacement and promote the use of fly ash, additional batches containing 15% and 20% (by weight) replacement of cement were prepared and tested for compressive strength, achieving 81% and 74% of the 28-day compressive strength of control cement mortars, respectively. Such replacement is advantageous with regards to reducing the carbon

footprint associated with the inclusion of cement. Lastly, leachability tests of different heavy metals (Pb, Cr, and Cd) were carried out on whole, demolished, and loose cement mortars incorporating fly ash, to check the environmental impact associated with this incorporation. All results indicated proper entrapment of metals in the hardened cement mixture, with concentrations of metals in the water not exceeding the allowable limit in waste set by the United States Environmental Protection Agency (USEPA).

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CHAPTER 1

INTRODUCTION

1.1. Waste Management

Municipal Solid Waste (MSW) generation rates have been increasing worldwide mainly due to the growing world population (Organization for Economic Cooperation and Development (OECD), 2018). Therefore, many solid waste disposal techniques have been adopted to properly treat or dispose of the ever-increasing quantities of the generated MSW. Among those techniques, landfilling has always been considered the easiest and most attractive option for MSW management, mainly because of its relatively cheap and efficient nature (Luo, Cheng, He, & Yang, 2019). However, landfilling is accompanied with several environmental, social, and economic drawbacks. Those include possible groundwater contamination, soil contamination, foul odors, toxic gaseous emissions, and large land requirements (Kjeldsen et al., 2002; Mukherjee, Mukhopadhyay, Hashim, & Sen Gupta, 2015). Incineration is another interesting and feasible approach for MSW treatment. Incineration has many advantages over landfilling; those include: a reduction in the quantities of waste by up to 90% by volume and 65-80% by weight (Hjelmar, 1996a), fast processing (Bie, Chen, Song, & Ji, 2016), and the possibility of energy recovery in the form of heat and electricity (Allegrini, Vadenbo, Boldrin, & Astrup, 2015). Nonetheless, several challenges are associated with incineration processes. Some of the most pressing include the fate of potentially hazardous byproducts such as: chemical gases, dust, fly ash, and bottom ash (Zhang, Zhang, & Liu, 2020). Despite that, incineration has been widely adopted worldwide, especially in countries with limited lands for landfilling. Japan, for example,

incinerated 78% (by mass) of the total MSW generated in 2017 (43 million tons), while the United Kingdom incinerated 39% (by mass) of its MSW generated in 2018 (31 million tons). Similarly, in Germany, 31% of the generated MSW in 2018 (51 million tons) was incinerated. On the other hand, only 13% of the waste generated in the United States in 2017 (243 million tons) was sent to Municipal Solid Waste Incinerators (MSWI) ("OECD iLibrary | Municipal waste," 2019).

1.2. Waste Management in Lebanon

Lebanon is considered a relatively small country, with an area of 10,452 square kilometers. El Fadel & Maalouf reported in 2019 that around 7,500 tons of MSW are generated daily in Lebanon; around 50% of the generated MSW are disposed of in about 940 uncontrolled dumpsites, 35% in sanitary landfills (Bourj Hammoud & Jdaideh, Ghadir River estuary, and Zahle), and the remaining 15% is converted into organic soil enhancer/fertilizer or recovered for recycling (e.g., plastic, metal, paper and cardboard, glass, etc.) in around 55 treatment facilities across the country (El-Fadel & Maalouf, 2019). In this context, and with the steadily increasing population, and limitations in the availability of lands suitable for landfill construction, Municipal Solid Waste incineration seems like a very appealing approach for dealing with the issue at hand.

Establishing that, it becomes vital to limit the possible adverse effects of MSW incinerators on the welfare of the population and environment. In this regard, and in addition to the toxic gaseous emissions resulting from incineration processes, one of the main environmental concerns of operating MSW incinerators is dealing with the ash residue from these incinerators. Moreover, despite the several advantages of

incinerators and the new technologies limiting emissions and hazardous byproducts, governments and health authorities have been pressured by the public opinion to prove the absence of any adverse health effects associated with establishing and operating incinerators (Domingo, Marquès, Mari, & Schuhmacher, 2020). Highlighting that, it becomes essential to deal with the byproducts of incineration in an environmentally sustainable manner.

1.3. Fly Ash: Definition, Application, and Source

Apart from toxic flue gases that may be released into the atmosphere, incineration processes produce Bottom and Fly Ash (FA) as solid residues. Bottom Ash (BA) comprised around 90% of the by-products of incineration, and fly ash comprises the remaining 10% (Keppert, Siddique, Pavlík, & Černý, 2015). However, FA has always been considered more toxic and hazardous than BA, since it typically contains most of the remaining toxic organic substances, heavy metals, and salts (Keppert et al., 2015).

The most common type of fly ash produced is Coal Fly Ash (CFA), which is generated during coal combustion in thermal power plants. Around 78 million tons of CFA were generated in 2012 in the United States, with over 39 million tons of it being utilized in different processes. Around 32% of the utilized ash was used in concrete and grout production, 29% in mining operations, 13% in structural fills and embankments, and 9% in cement production (Yao et al., 2015).

Another important source of fly ash is that coming from organic waste incineration. The waste incinerated can be municipal waste, medical waste, biomedical

waste, industrial waste, etc. MSWI ash typically represent around 1-30% by weight of the wet MSW, depending on the nature of the incineration process (Siddique, 2010b).

The chemical and physical properties of MSWI ash is known to vary according to the composition of the raw MSW, the type of incinerator used, and the air pollution control system applied (He, Zhang, Zhang, & Lee, 2004). Typically, CaO, SiO_2, Al_2O_3, Fe_2O_3, and Na_2O are the most abundant oxides present in MSWI bottom ash and fly ash. CaO is usually the most abundant oxide in MSWI fly ash constituting up to 46%, while SiO_2 is the most abundant in MSWI BA constituting up to 49% (Charles H.K. Lam, Ip, Barford, & McKay, 2010). Regarding heavy metals, the most common metals found in MSWI ash are Pb, Cr, Cd, Hg, Zn, with fly ash containing most of the heavy metal concentrations due to the vaporization of metals during combustion and their adsorption on fly ash particles. Moreover, fly ash contains more chloride content than bottom ash, probably due to the removal of acidic gases in the air pollution control system (Charles H.K. Lam et al., 2010).

Many approaches have been developed to properly utilize/dispose of MSW incinerator fly ash. These mainly include: disposal of a stabilized/solidified ash in landfills, utilization of fly ash as adsorbent for cleaning of flue gas, removal of mercury, removal of inorganic and organic components from wastewater (Ahmaruzzaman, 2010), utilization in Portland cement production (Charles Hoi King Lam, Barford, & McKay, 2011), ceramic tiles production (Haiying, Youcai, & Jingyu, 2007), asphalt concrete production (Xue, Hou, Zhu, & Zha, 2009), glass-ceramic synthesis (Cheng & Chen, 2003), and utilization of fly ash as a supplementary cementitious material (SCM), which seems to be very promising (Keppert et al., 2015). Note that MSWI fly ash can be used as a SCM since it contains compounds similar to those present in cement (Siddique,

2010a).SCMs are a group of synthetic, natural, and byproduct materials that are incorporated in Portland Cement Concrete (PCC) to enhance some of its performance characteristics such as strength, workability, and durability (Keppert et al., 2015). It has been reported in the literature that adding SCMs as a partial substitution for Portland cement enhances fresh concrete (workability) as well as hardened concrete properties (durability) (Vejmelková et al., 2010). In addition, the use of MSWI fly ash as a Portland cement substitute in concrete reduces the total required energy for building construction and also reduces CO_2 emissions generated during the construction works (Keppert et al., 2015), resulting in decreasing the overall carbon footprint of the construction industry. It also provides an economic incentive for stakeholders since it promotes the use of fly ash from incinerators rather than consuming more quantities of cement.

Cement is considered the most essential element in the production of concrete, a vital building material for the construction industry (Hanle, 2004). In 2016, cement production worldwide generated around 2.2 billion tons of CO_2, which was equivalent to around 8% of the global CO_2 emissions (Rodgers, 2018). Hence, any reduction in the consumption of cement in the construction industry will directly affect the associated global CO_2 emissions. Therefore, it is of great importance to investigate the possible replacement of cement with other eco-friendly substitutes, such as MSWI fly ash. This study focuses on utilizing fly ash acquired from SICOMO, a Lebanese company operating a MSW incinerator located in Beqaa - Lebanon. The incinerator at SICOMO is a Double Chambered Incinerator with a Heat Recovery System. In the primary chamber, the waste is introduced and burned at a minimum temperature of 850 ºC. Incomplete combustion occurs due to the low air-to-fuel ratios, and lower O_2

concentrations will result in reducing NO_x to produce natural Nitrogen. In the secondary chamber, the volatile/gasified residues are burned at 1100 ºC with excess O_2, resulting in complete combustion. The residence time in the secondary chamber is short, ensuring that all gaseous products (namely dioxins) are completely oxidized due to excess O_2 levels and the relatively high temperatures. In the heat recovery system, the temperature of the flue gas from the secondary chamber is reduced to 270 ºC (using a Heat Recovery Boiler) in few seconds, resulting in stabilizing the remaining toxic particles. After that, Granular Activated Carbon (GAC) is used to adsorb the remaining particles and heavy metals from the flue gas. Finally, Sodium Bicarbonate is applied to reduce excess HCl levels, resulting in a neutral and stabilized flue gas. The fly ash used in this study is taken from the residue of the Air Pollution Control (APC) system. **Error! Reference source not found.** summarizes the double-chambered combustion process.

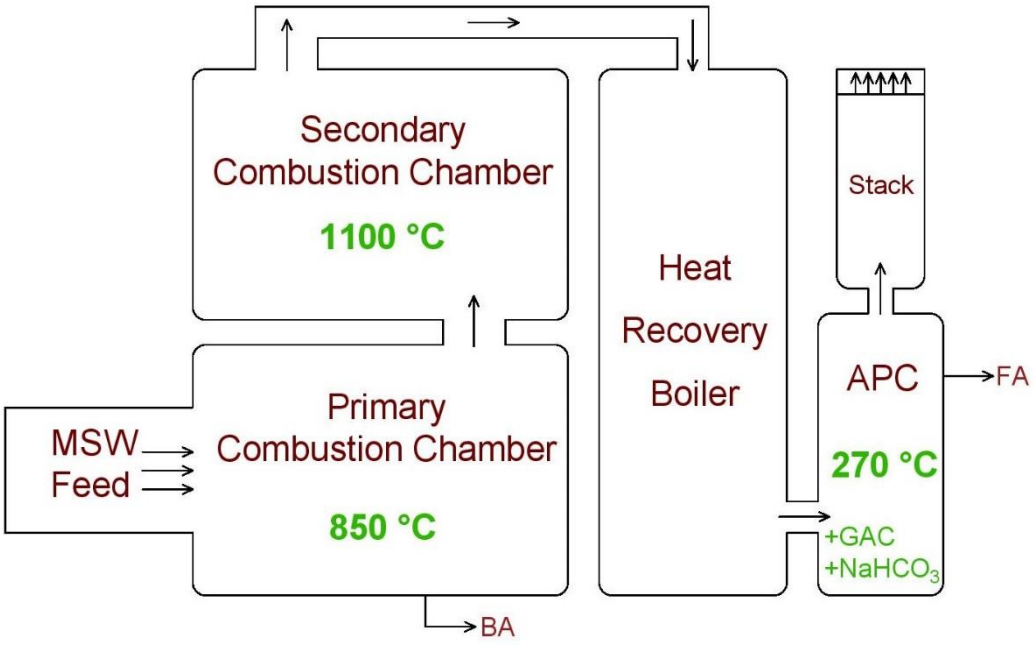

Figure 1 Double-chambered combustion process (BA: Bottom Ash, FA: Fly Ash)

CHAPTER 2

RESEARCH OBJECTIVES

This research aims at studying the mechanical feasibility of partially incorporating MSWI fly ash into Portland cement mortars and investigating the environmental implications of the resulting sustainable material. This will be done by achieving three main objectives.

The first objective is to analyze the content of the fly ash to check the compatibility of using it as a replacement material to cement in cement mortars. This was done through a series of tests that aim to characterize the acquired fly ash qualitatively and quantitatively.

Assessing the compatibility of the MSWI fly ash as a partial replacement of cement in cement mortars is the second objective of this study. This was investigated through the preparation of cement mortars incorporating 10% (by weight) replacement of cement with MSWI fly ash. The prepared samples were then tested to ensure that the mechanical properties of the mortars were not compromised. The percentage replacement of cement with fly ash was then increased to 15% and 20% to find the optimum percentage replacement and promote more use of fly ash.

Leachability of selected metals (Pb, Cd, and Cr) from the utilized fly ash after incorporation into the cement mortars was evaluated. This was done by first assessing the amount of metals present in the ash (as received) by digesting the ash. This was followed by quantitatively testing the leachability of control and ash-containing cement mortars cured in milli-Q water, these mortars were then demolished (to less than 1 cm)

and immersed in both acidic (pH~5.0) and milli-Q water, to assess the leachability of metals from the demolished cement mortars. Lastly, loose cement mortars containing different incorporation percentages of fly ash were prepared and immersed in water, followed by testing for the same selected heavy metals content in the curing water.

CHAPTER 3

RESEARCH SIGNIFICANCE

This study focuses on utilizing fly ash acquired from SICOMO, a Lebanese MSWI located in Beqaa, as a replacement of Portland cement in concrete mixes. This approach would promote environmental, economic, and social incentives, as such incorporation would reduce the amount of fly ash going into landfills. This study would also result in reducing the overall amounts of Portland cement that needs to be manufactured and utilized in the ever-growing construction industry in Lebanon, thus reducing CO_2 emissions and draining of natural resources associated with the production of Portland cement. The presented research promotes a green sustainable solution to managing toxic fly ash generated from MSW incinerators. Demonstrating that toxic metals leachability from the blended concrete is not detected highlights the significance of this work, as it will minimize concerns regarding the toxicity of entrapped fly ash in cement mortars and concrete mixes.

CHAPTER 4

METHODOLOGY

4.1. Characterization of Fly Ash

4.1.1. Chemical Properties

4.1.1.1. X-Ray Diffraction (XRD)

X-Ray Diffraction (XRD) was used for phase identification of crystalline materials. The peaks generated by the XRD analysis may be used to better characterize the chemical composition of the fly ash. The Burker X-Ray D8 advance was used to conduct the XRD measurements. The machine was operated under a voltage of 40 kV and at 40 mA. The scan type used was coupled two theta/theta, with 2θ ranging from 5 to 70 degrees, and an increment of 0.005º for 5 seconds.

4.1.1.2. Energy Dispersive X-Ray (EDX)

Energy Dispersive X-ray (EDX) analysis was performed on the sample to provide additional elemental identification and estimate compositional information. EDX determines which chemical elements are present in the sample and may be used to estimate their relative abundance. The EDX analysis is carried out while using the Scanning Electron Microscope (SEM), where a concentration of laser beams are focused on a point or a surface area of the sample until it's burned out, giving us an estimate on the chemical composition of that region of the sample. Please note that

EDX results are not necessarily representative of the chemical composition of the bulk sample.

4.1.1.3. Atomic Absorption Spectroscopy (AAS)

Atomic Absorption Spectroscopy (AAS) is a Spectro analytical procedure used for quantitatively determining the chemical elements in a sample, based on the absorption of light by free metallic ions. AAS requires standards with known analyte concentrations to establish a relation between the analyte concentration and the measured absorbance. The flame method was used to determine the concentrations of 3 different metals: lead, cadmium, and chromium.

Atomic Absorption Spectroscopy was used for two different purposes: 1) calculating the metal content of fly ash, and 2) testing the leachability of metals from cement mortars.

Figure 2 Analysis of samples using Atomic Absorption Spectroscopy

4.1.1.4. Acid Digestion of Fly Ash

To accurately calculate the metal content of the fly ash acquired from SICOMO, we performed a digestion procedure on several replicas of our sample. This was done by sieving the ash sample first using the #200 sieve and collecting the particles left in the pan. Then, 2 g of the sieved sample were taken and put in 100ml glass beaker, before adding 30 ml of 65% Nitric Acid (HNO_3) and gently boiling the mixture over a water bath (90°C) for 2 hours. During the digestion procedure, the inner walls of the beakers were washed with 8ml of mQ water to prevent loss and evaporation of sample.

The samples were then filtered using Whatman 42 (2.5 µm particle retention) filter paper. Lastly, a sufficient amount of mQ water was added to each beaker so that the final volume would be 200 ml. The digested fly ash samples before and after filtration are shown in Figures 3 and 4.

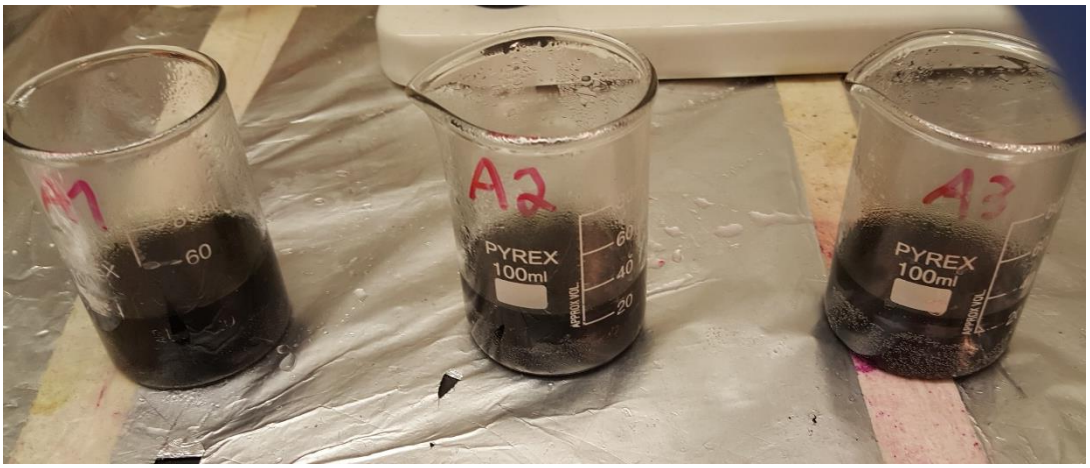

Figure 3 Acid digested fly ash samples before filtration

The final filtered solution needed further dilution so that it could be tested using AAS, so we diluted each solution using 4 different dilution factors: 1.5, 3, 10, and 20. The diluted samples were then tested for lead, cadmium, and chromium using AAS. This procedure was performed on six different replicas of the fly ash acquired by SICOMO.

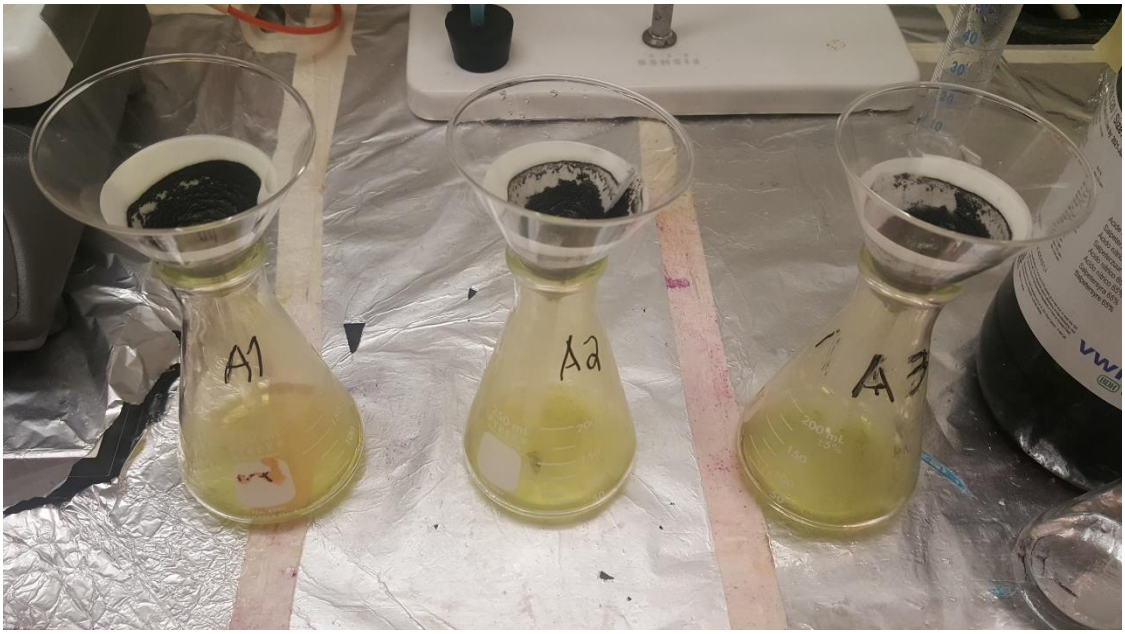

Figure 4 Filtration of digested ash samples using a 2.5 µm filter

4.1.2. Physical Properties

4.1.2.1. Brunauer-Emmett-Teller (BET)

Brunauer-Emmett-Teller (BET) test was conducted to determine the surface area, pore volume, and pore size of fly ash. These properties were studied to evaluate the adsorptive capacity of the fly ash for potential future work, and thus might not be needed directly for the current research. The samples were first degassed at 90 ºC to ensure no moisture is present, then the vacuum is applied to the tube containing the sample, followed by immersing the sample in liquid nitrogen at -196 ºC while Helium is being added, and finally, absorption and desorption of nitrogen is recorded. The 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.

4.2. Incorporation of Fly Ash in Cement Mortars

4.2.1. Mixing Cement Mortars

In this study, 4 different batches of cement mortars were prepared. The first batch was the control batch that contained no fly ash, while the 3 other batches contained different percentages of fly ash incorporated: 10%, 15%, and 20%. 50 mm x 50 mm x 50 mm molds were used to prepare the cement mortars.

First, we prepared the materials needed for mixing. We started by sieving the fly ash acquired from SICOMO using the #200 sieve and collecting the particles retained on the pan (Figure 5). Then, we sieved the coarse limestone aggregates using the #4 sieve and collected all particles passing the sieve. Finally, we acquired the sand (fine aggregate) and made sure it was not moist.

Figure 5 Fly ash used in the mixing of cement mortars

Second, we mixed each mortar's constituents in a separate zip lock bag, as shown in Figure 6, after carefully weighing each of them using a sensitive balance.

Figure 6 Mixing each mortar's components in a separate zip-lock bag in preparation of 50 x 50 x 50 mm cement cubes

For the mixing, we used a disposable aluminum pan to properly mix the constituents of each mortar with water. Plastic molds were used, and the samples were properly covered with a layer of plastic and kept in molds for 48 hours. Mixing of the 10% ash-replacement batch is demonstrated in Figure 7.

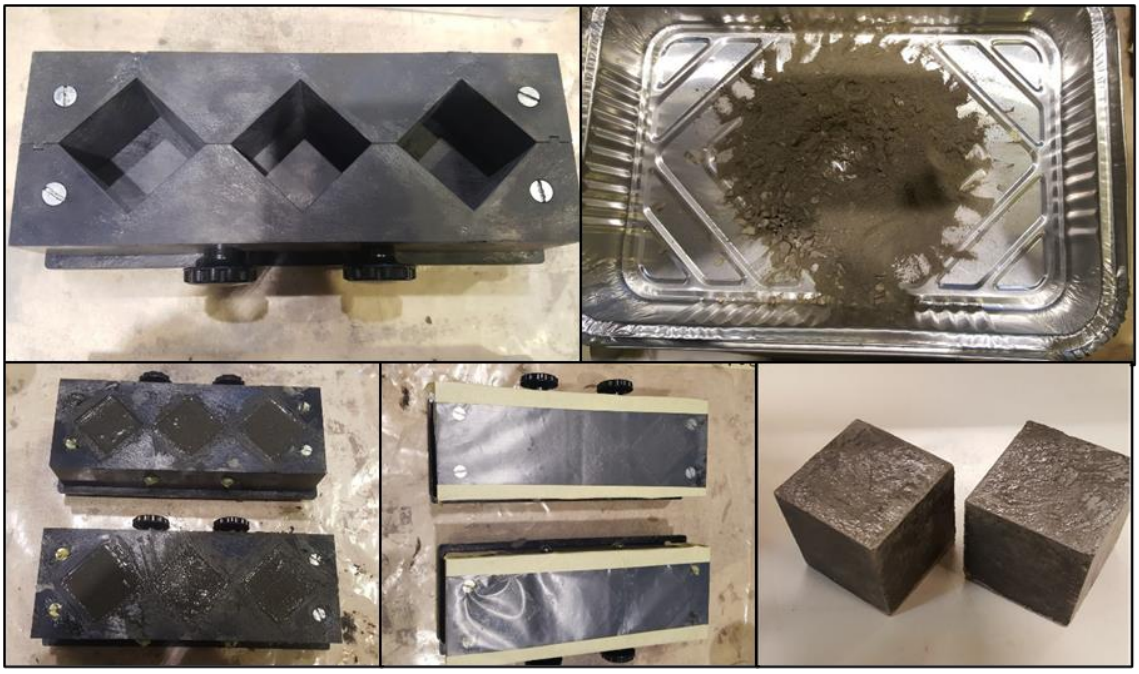

Figure 7 Preparation of cement mortars containing 10% ash

4.2.2. Curing and Compressive Strength Test of Cement Mortars

To ensure proper curing of cement mortars, the following procedure was applied. First after demolding the mortars after 48 hours, we immersed each cube in a separate beaker containing 150 ml of mQ water for 24 hours as shown in Figure 8. The water samples were then collected to be analyzed for metals using AAS. After that each

cube was covered with a piece of wet cloth until the 7th day after mixing the cloth was re-wetted every day to ensure proper curing.

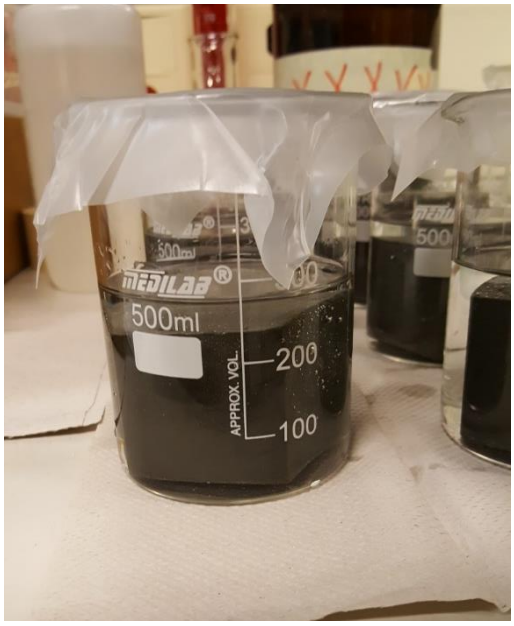

Figure 8 Curing cement mortars in 150 ml of mQ water for 24 hours

At the 7th day, some mortars were taken to be crushed in order to obtain their 7-day compressive strength and the rest of the mortars were cured in a container using tap water until the 28th day (Figure 9), that is when they were crushed to obtain their 28-day compressive strength.

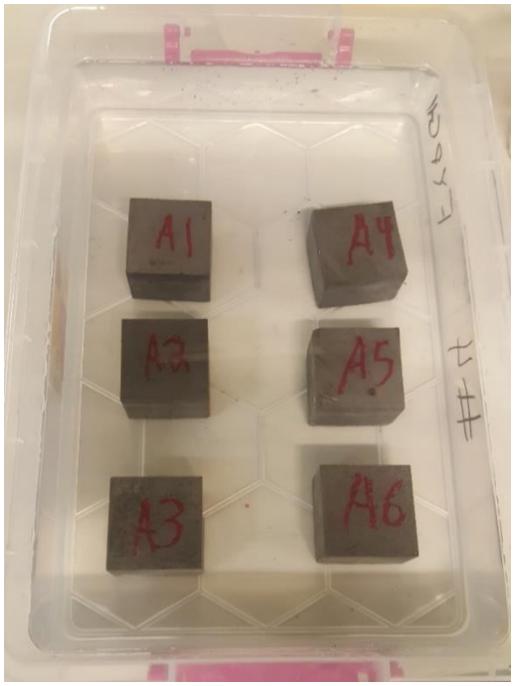

Figure 9 Curing cement mortars containing 10% ash for the 28th day

Prior to each compressive strength test, the cubes were removed from curing water/wet cloth 24 hours before the test. A summary of the mixing and curing process of cement mortars is shown in Figure 10.

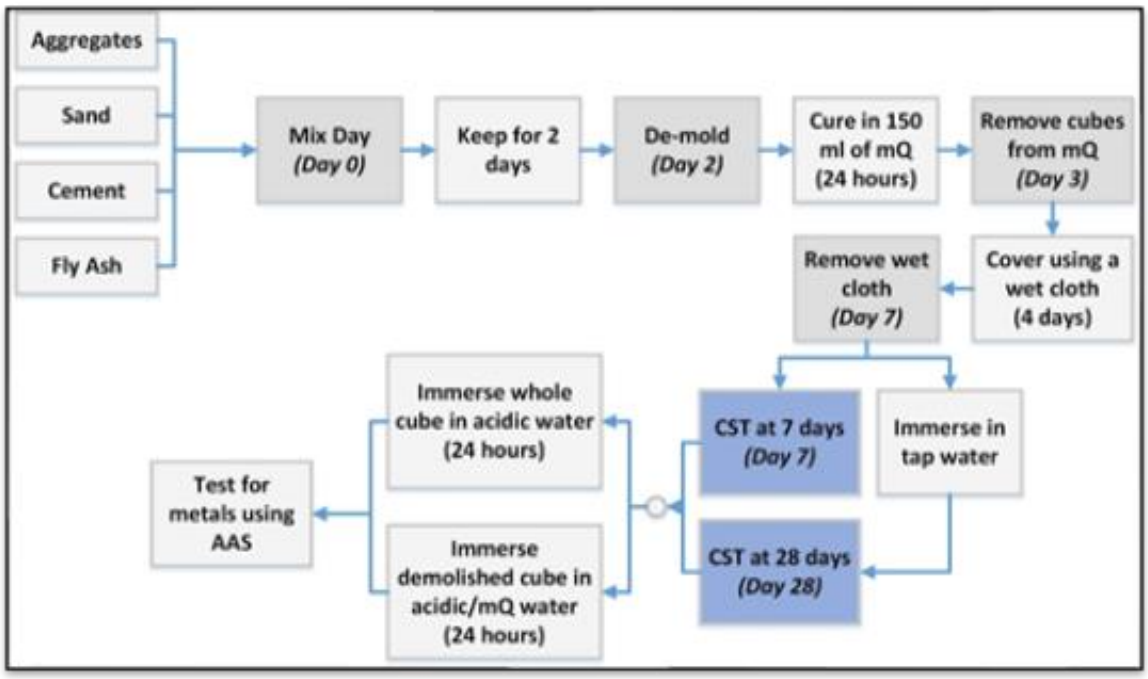

Figure 10 Cement mortars mixing and curing process description (CST: Compressive Strength Test; mQ: Milli-Q; AAS: Atomic Absorption Spectroscopy)

4.3. Testing Leachability of Metals

4.3.1. Cement Mortars

To test whether heavy metals would leach out of the ash-containing cement mortars at any stage of the process, we conducted leachability tests at different stages of the study. Figure 11 summarizes the fate of each cube as well as the number of replicas present in each stage. As shown in the figure below, a total of 12 replicas were prepared for the first batch (containing 0% ash), 6 of these replicas were cured for 7 days, while the remaining 6 replicas were cured for 28 days. Similarly, 12 replicas were also prepared for the second batch (containing 10% ash), with 6 of these replicas being cured for 7 days and the other 6 being cured for 28 days. However, for the 2 remaining

batches, containing 15% and 20% ash respectively, only 3 replicas were made of each since we only tested for the 28-day compressive strength.

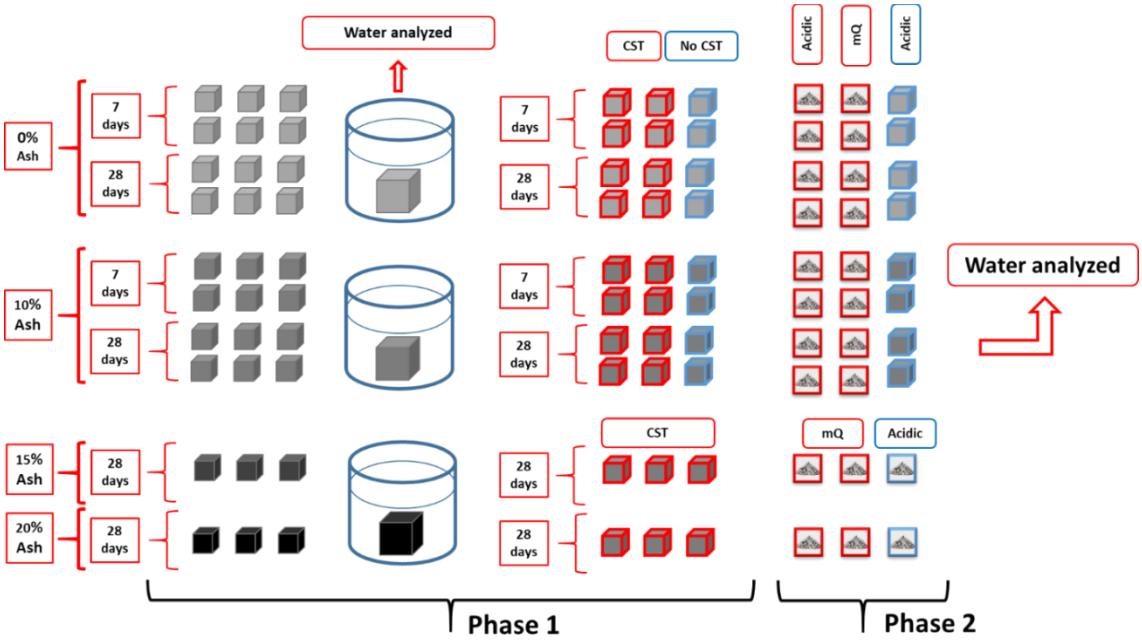

Figure 11 Preparation and fate (CST and leachability studies) of control and ash containing cement cubes

4.3.1.1. Phase I

In this phase, the water used for the curing of cement mortars from the 2nd day to the 3rd day was collected and analyzed for heavy metals (lead, cadmium, and chromium) using AAS. This yielded 12 replicas that were analyzed for each of the first two batches (0% and 10% ash replacement), and 3 replicas that were analyzed for the last two batches (15% and 20% ash replacement).

4.3.1.2. Phase II

For each of the first 2 batches (0% and 10% ash replacement), six cubes were cured for 7 days, after which four cubes were tested for compressive strength and two cubes were kept as whole. The two whole cubes were then submerged in 150 ml of acidic water (pH ~5.0) for 24 hours, while the four cubes that were tested for compressive strength were further crushed and demolished to a diameter of less than 1cm, with two of these demolished cubes being immersed in 150 ml of acidic water (pH ~5.0) for 24 hours, and the remaining two being immersed in 150 ml of mQ water for 24 hours. The same procedure was applied for the cubes that were cured for 28 days. The immersion of demolished and whole cement mortars for the first 2 batches is presented in Figures 12 and 13.

This was done to test if more leaching of heavy metals would occur from demolished mortars compared to whole mortars. This would help us predict the leachability behavior of heavy metals in case the concrete structural element containing fly ash was demolished (demolishing a building, natural disasters, accidents, etc.).

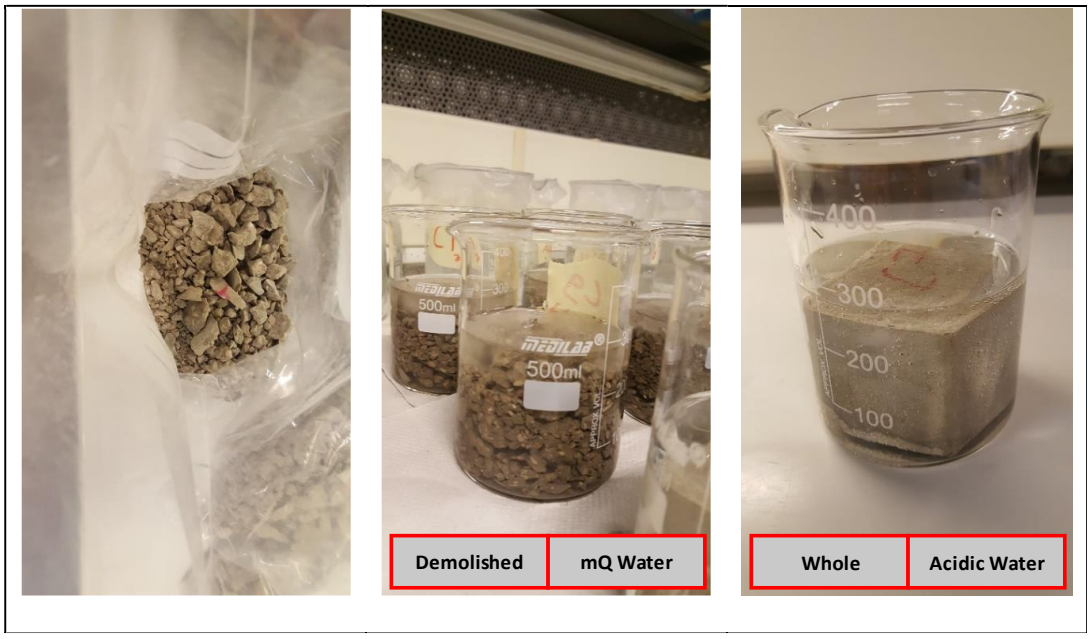

Figure 12 Immersion of demolished and whole control cement mortars for 24 hours in mQ and acidic water

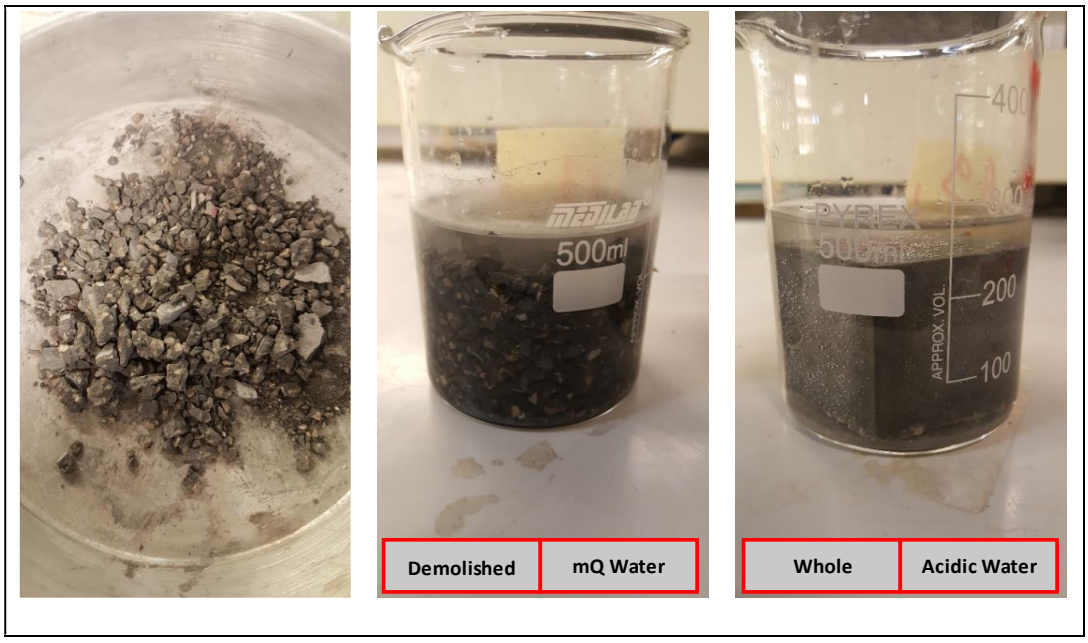

Figure 13 Immersion of demolished and whole cement mortars containing 10% ash for 24 hours in mQ and acidic water

Meanwhile, for each of the last 2 batches (15% and 20% ash replacement), three cubes were cured for 28 days and were tested for compressive strength at the 28th day. The tested cubes were then further crushed and demolished to a diameter of less than 1cm, with two of these cubes immersed in 150 ml of mQ water for 24 hours, and the remaining cube being immersed in 150 ml of acidic water for 24 hours also. The water used for immersion was then filtered using a coarse filter (Figure 14) and analyzed for lead, cadmium, and chromium using AAS.

Figure 14 Filtering the solution after 24 hours to analyze the water sample

4.3.2. Loose Cement Mortars

To better test for leachability of heavy metals from cement mortars, and to investigate the effect of an increased surface area on the leaching behavior of metals from ash-containing mortars, we prepared several batches of Loose Cement Mortars

(LCMs). Since both normal and loose cement mortars have the same mix design (same proportions), we can conclude whether metals are entrapped deep inside the cube mortar, or if they are able to escape and leach out regardless of the shape factor.

Four batches were prepared with two replicas in each batch, the first batch was a control batch that containing 0% ash, while the remaining three batches contained 10%, 15%, and 20% of ash respectively. The mix design is the same as that of the cement mortars before, the only difference is that we spread the mix over a disposable aluminum pan and left it to dry for 48 hours, before adding 250 ml of mQ water to each disposable pan and sealing it tightly using a plastic bag and leaving it for 96 days. The inside of the pans was lined with 2 layers of plastic to prevent unwanted reactions between the mix and the pan. As shown in Figure 15, the difference in color between batches was due to the varying ash content.

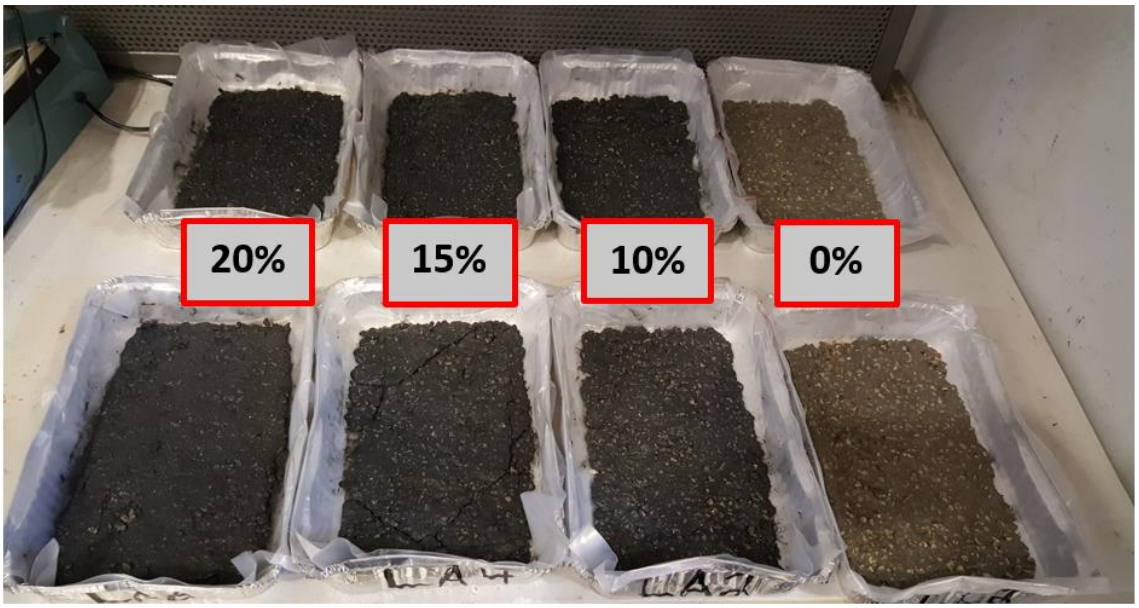

Figure 15 Freshly prepared duplicates of loose cement mortars with different ash replacement percentages

After 96 days, the pans were drained from the immersing water and left aside for further use (Figure 16), while the water was collected and filtered before being tested for lead, cadmium, and chromium using AAS.

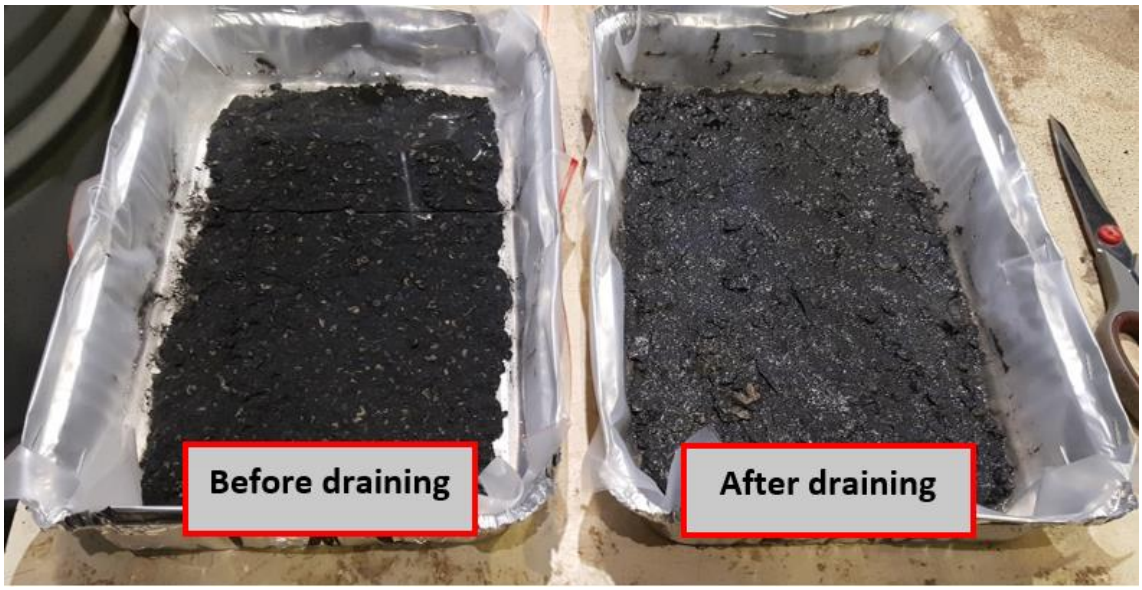

Figure 16 Loose cement mortars after 96 days of immersion in mQ (before and after draining the water)

To further investigate the leachability of the prepared loose mortars under acidic conditions, we added 250 ml of acidic water (pH ~5.0) to the dried LCMs, before properly sealing them and leaving them for 7 days (Figure 17). The acidic water was then drained from the LCMs, filtered, and analyzed for lead, cadmium, and chromium using AAS.

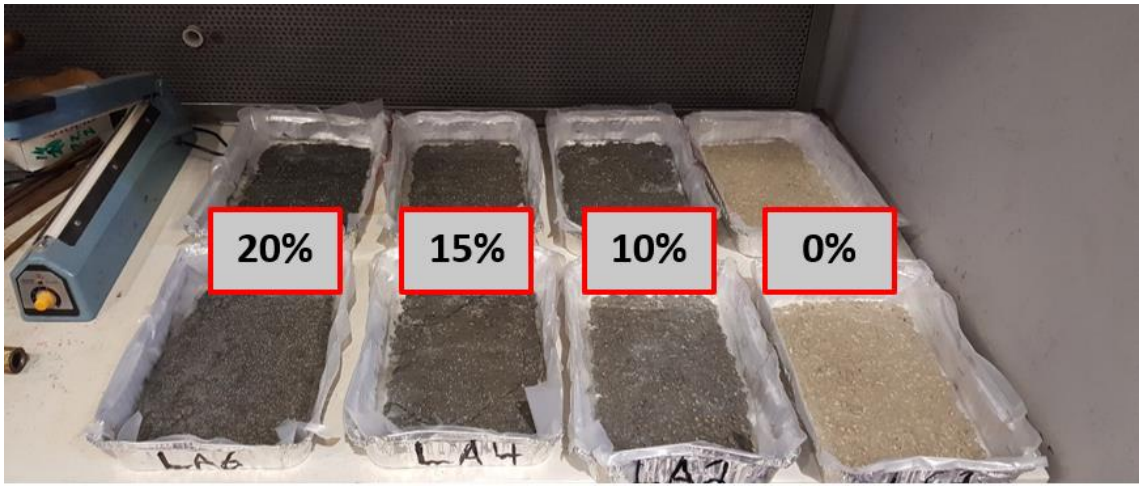

Figure 17 Loose cement mortars after immersion in acidic water for 7 days

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Characterization of Fly Ash

The application of incorporating fly ash, from different sources (coal power plants, medical waste incinerators, MSW incinerators, etc.), has been explored and reported in the literature. The source of the incinerated waste, however, defines the properties of the produced fly ash, hence, it is vital to characterize fly ash before using it. For this purpose, fly ash samples, collected from SICOMO, where characterized to assess their chemical and physical properties.

5.1.1. Physical and Chemical Properties

The chemical composition of the acquired fly ash was investigated with a focus on the metal content. Overall, the literature shows a large variability regarding the metal content of samples. This is expected given the dependency on the composition of the municipal wastes burnt, the incineration type/procedure followed, and the air pollution control system applied (He et al., 2004).. The chemical composition of different MSW fly ashes reported in the literature relative to the composition of SICOMO's fly ash is presented in Table 1. It is evident that CaO, SiO_2, Al_2O_3, Fe_2O_3 are the most abundant oxides in all studies, which is promising since these four oxides constitute up to 90% of Ordinary Portland Cement (OPC) (Shi & Kan, 2009). More data regarding the chemical composition of MSWI fly ash is found in the appendix. Similarly, the metal composition analysis of different MSW fly ashes reported in the literature relative to the composition of SICOMO's fly ash is presented in Table 2.

Similar to the chemical composition, the metal content of MSWI fly ash showed a large variability across the different studies (Table 2). This is also attributed to the fact that the metal composition of MSWI fly ash depends on the composition of the raw MSW, the type of incinerator used, and the air pollution control system applied (He et al., 2004). Some metals, like zinc and magnesium, were found at very high concentrations, however, they might not pose an environmental concern since they are not considered toxic metals. On the other hand, metals like lead, mercury, chromium, cadmium, silver, and selenium are considered very toxic, even at small concentrations. And while some of these toxic metals exist in relatively low concentrations, like selenium, other toxic metals exist in relatively higher concentrations, such as lead, chromium, and cadmium. In this context, we chose three representative metals to be tested for in this study, which are lead, chromium, and cadmium.

Reference	(Romero, Rincón, Rawlings, & Boccaccini, 2001)	(Lin, Wang, Tzeng, & Lin, 2003)	(Andreola et al., 2008)	(Ginés, Chimenos, Vizcarro, Formosa, & Rosell, 2009)	(Yang, Xiao, & Boccaccini, 2009)	(Keppert et al., 2013)	(Bie et al., 2016)	(Charbaji, Baalbaki, Elkordi, & Khatib, 2018)
Component	**Chemical Composition (% weight)**							
SiO_2	11.47	35.8	18.5	6.35	27.52	15.6	27.51	14.68
Al_2O_3	5.75	9.8	7.37	3.5	11	9.2	7.12	12.74
Fe_2O_3	1.29	4.9	2.26	0.63	5.04	2.6	5.11	4.35
CaO	29.34	14.7	37.5	43.05	16.6	23.9	23.25	26.32
MgO	3.02	0.8	2.74	1.38	3.14	1.8	3.13	2.25
Na_2O	8.7	5.9	2.93	5.8	8.24	9.4	-	5.94
K_2O	7.02	5.3	2.03	4.59	8.24	6.6	-	4.3

Cl^-	-	-	-	-	-	11.2	11.5	11.77
SO_3	-	2.2	14.4	4.64	8.34	11.5	12.23	3.05
P_2O_5	1.69	-	1.56	-	-	1.3	-	0.57
MnO	-	-	-	-	-	-	-	0.05
TiO_2	0.85	-	1.56	-	1.88	-	-	1.91
Cr_2O_3	-	-	-	-	-	-	-	0.026

Table 1 Chemical composition of different MSW fly ashes reported in the literature

Reference	(Hjelmar, 1996b)	(Youcai, Lijie, & Guojian, 2002)	(Chang, Wang, Mui, Cheng, & Chiang, 2009)	(Tyrer, 2013)	(Lindberg, Molin, & Hupa, 2015)	(Keppert et al., 2015)	(Bie et al., 2016)	This Study
Element	**Heavy Metals Concentration (mg/kg)**							
Ag	31–95	-	-	2.3–100	0.9-192	-	-	
Al	-	-	-	49000–90000	6400-93000	-	-	
As	31–95	-	93	37–320	18-960	BDL	-	
Ba	920–1,800	-	4,300	330–3100	34-14,000	317	-	
Ca	-	-	-	74000–130000	46000-361000	-	-	
Cd	250–450	25.5	470	50–450	16-1660	62	31	725
Cl	-	-	-	29000–210000	45000-380000	-	-	
Co	29–69	-	-	13–87	1.9-300	BDL	-	
Cr	140–530	118	863	140–1100	72-570	131.4	105	147
Cu	860–1,400	313	1,300	600–3200	16-2220	204.6	523	
Fe	-	-	-	12000–44000	760-71000	-	-	
Hg	0.8–7	52	-	0.7–30	0.1-51	-	33	

K	-	-	-	22000–62000	17000-109000	-	-	
Mg	-	-	-	11000–19000	1100-19000	-	-	
Mn	0.8–1.7	-	1,600	800–1900	200-1700	266.4	-	
Mo	-	-	-	15–150	9.3-49	BDL	-	
Na	-	-	-	15000–57000	6200-84000	-	-	
Ni	95–240	60.8	124	60–260	19-710	17.2	60	
P	-	-	-	4800–9600	1700-9600	-	-	
Pb	7,400–19,000	1496	10,900	5300–26000	254-27,000	998.4	945	13093
S	-	-	-	11000–45000	1400-32000	-	-	
Sb	-	-	-	260–1100		218.4	-	
Se	6.1–31	-	41	0.4–31	0.7-31	-	-	
Si	-	-	-	95 000–210 000	36000-190000	-	-	
Sn	1,400–1,900	-	-	550–2000	367-5900	302.4	-	
Sr	80–250	-	433	40–640	80-500	-	-	
Ti	-	-	-	6800–14000	700-12000	-	-	
V	32–150	-	37	29–150	4-150	22.2	-	
Zn	19,000–41,000	4,386	25,800	9000–70 000	4308-41,000	5912.8	2932	

Table 2 Metal composition analysis of different MSW fly ashes reported in the literature

In order to quantify metal content in the fly ash samples, acid digestion using 65% Nitric Acid (HNO_3) was carried out on 6 different replicas of the fly ash samples

acquired from SICOMO. After diluting and filtering the digested solution, the concentration of lead (Pb), cadmium (Cd), and chromium (Cd) was tested using Atomic Absorption Spectroscopy (AAS). Metal content of different digested fly ash replicas is presented in Figures 18- 20. Results indicate that lead prevails in the fly ash samples with a concentration of around 13000 mg/kg of ash, which is consistent with the literature values that range between 254-27000 mg/kg of ash. Similarly, cadmium and chromium showed concentrations of 725 and 147 mg/kg of ash respectively, falling well within the literature values that ranged between 16-1660 mg/kg for cadmium and 72-1100 mg/kg for chromium.

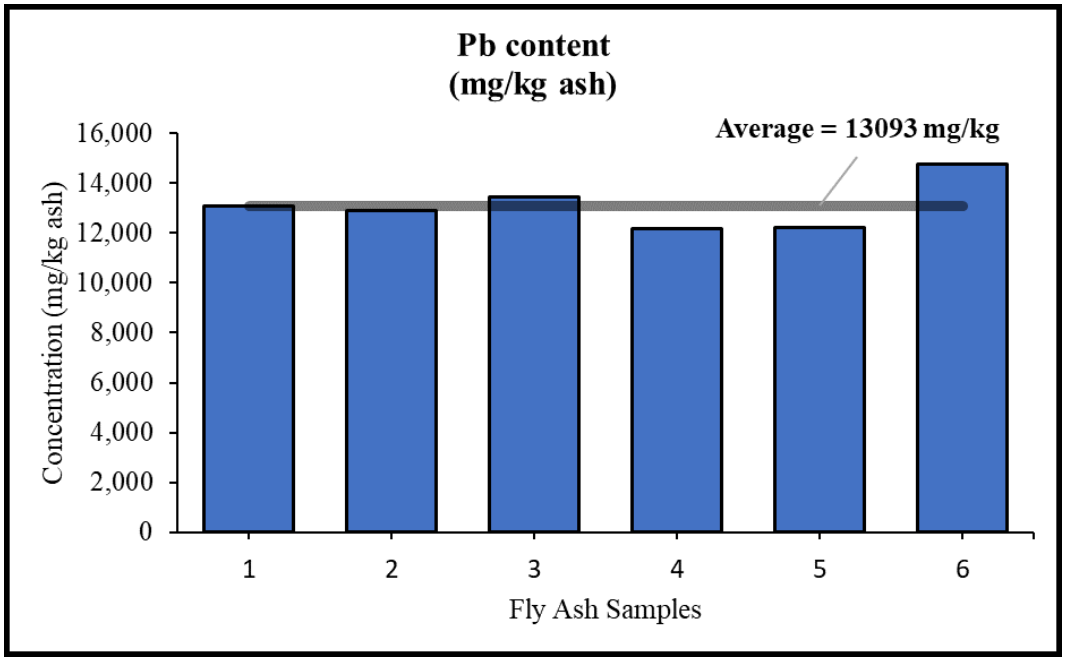

Figure 18 Lead content (expressed in mg/kg ash) in fly ash samples collected from SICOMO

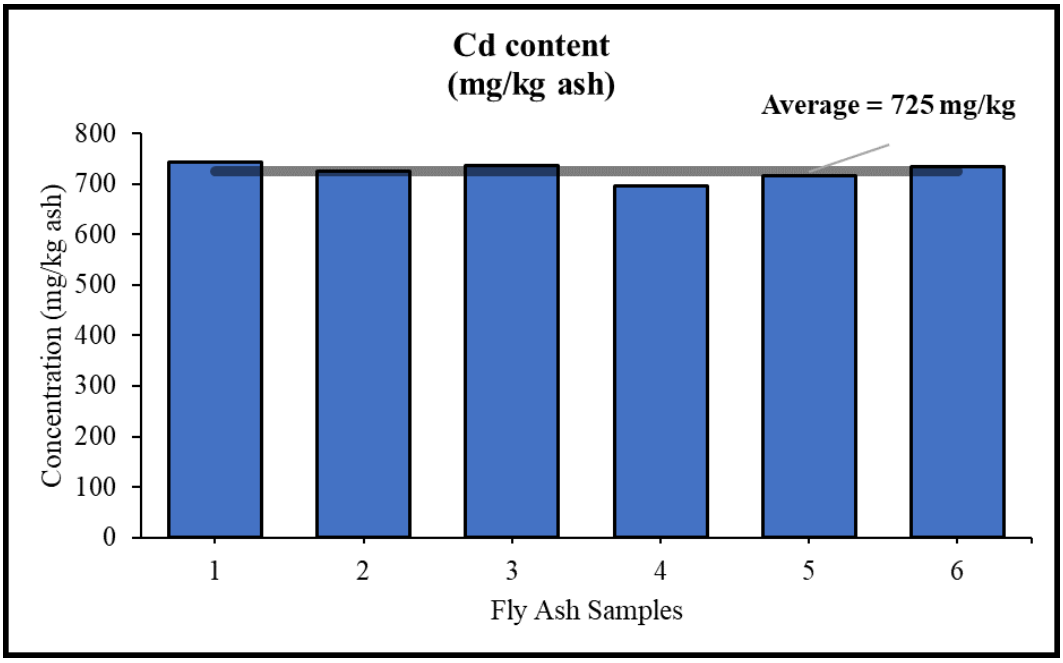

Figure 19 Cadmium content (expressed in mg/kg ash) in fly ash samples collected from SICOMO

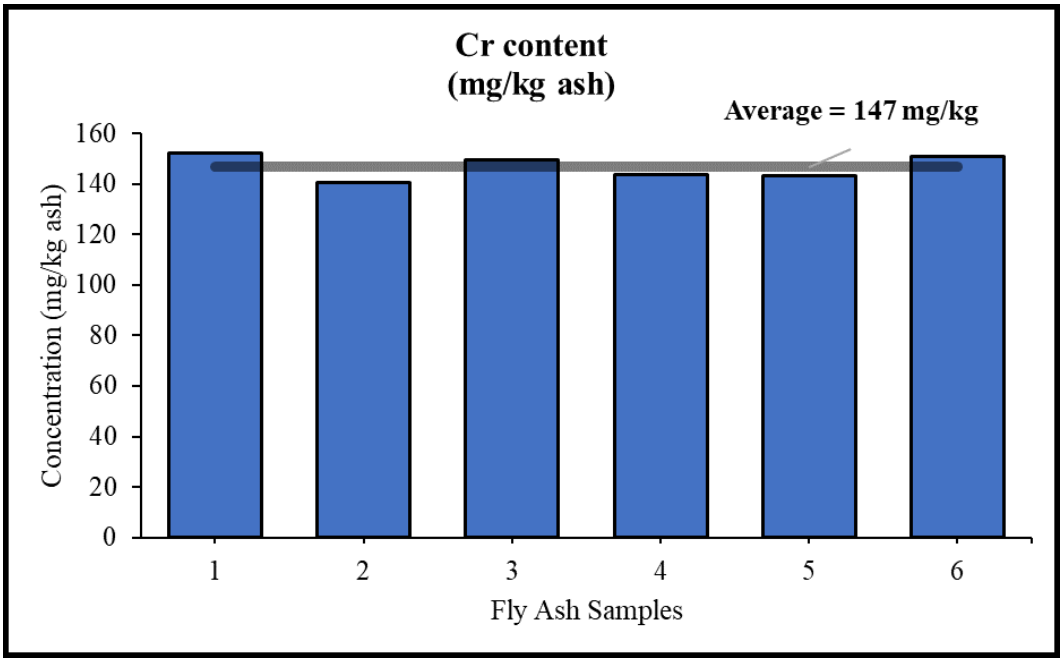

Figure 20 Chromium content (expressed in mg/kg ash) in fly ash samples collected from SICOMO

Furthermore, X-Ray Diffraction (XRD) analysis were carried out on the dried fly ash samples without washing or further chemical treatment. Results showed a crystalline pattern, which indicates that fly ash possesses the essential materials found in cement, and thus may be used as a partial replacement of Portland cement in mortars. Additionally, EDX spectra, presented in Figure 21, confirms the presence of the four main components of Portland cement (Ca, Al, Si, and Fe) in different regions of the tested SICOMO fly ash sample.

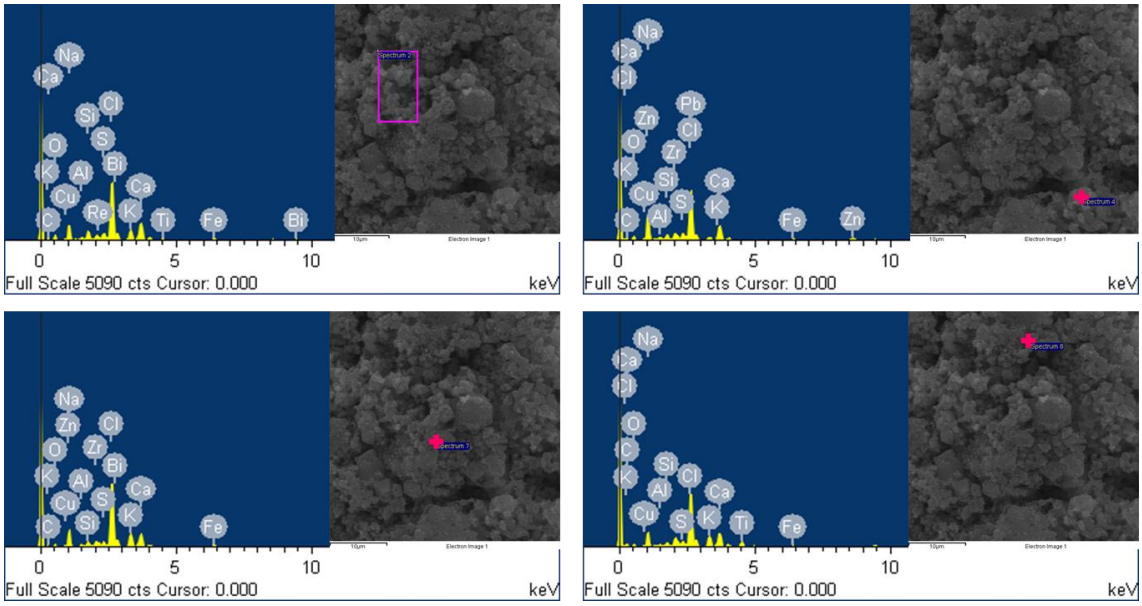

Figure 21 EDX spectra of the fly ash sample from SICOMO

Fly ash used in this study is described as a fine material with a blackish color. To better understand the physical properties of the acquired fly ash samples, we performed a BET test to quantify the surface area, micropore volume, and pore size of the sample. The BET surface area measured 3.134 m^2/g, the micropore volume

measured 0.21 mm^3/g, and the pore size measured 170.5 Å. These numbers indicate that metals are easily adsorbed on the surface of our fly ash sample, yielding a high metal content.

5.2. Incorporation of Fly Ash in Cement Mortars

Incorporating MSWI fly ash in cement mortars is not always successfully achieved, as many studies and trials reported that the resulting mortar would not always be of the desired consistency and durability. Several studies have reported expansion of cement mortars after partial replacement of fly ash (Charbaji et al., 2018; Siddique, 2010b; Tyrer, 2013).Therefore, to ensure the compatibility of such incorporation, we started by preparing a batch containing 10% (by weight) cement replacement by fly ash, as a minimum percentage incorporation, to assess whether foaming or bubbling would occur in ash-containing cement mortars. Most studies in the literature opted for a 10% ash replacement percentage as a start, before assessing higher incorporation percentages (Charbaji et al., 2018; Keppert et al., 2015; Sigvardsen & Ottosen, 2019). The prepared mixes were molded into cubes before curing them, no expansion or foaming was observed. Hardened cement mortars – containing 10% ash – two days after mixing are shown in Figure 22. These results show that the MSWI fly ash from SICOMO can be successfully incorporated in cement mortars.

Figure 22 Cement mortars containing 10% replacement of fly ash from SICOMO

After checking the compatibility of incorporating MSWI fly as a partial replacement to cement in cement mortars, we investigated the effect of this incorporation on the compressive strength of cement mortars. For this, we prepared two different batches of cement mortars; the first batch was a control batch that contained no fly ash, while the second batch contained 10% (by weight) replacement of cement with fly ash. The mix design is shown in Table 3.

Batch	**Description**	**Mass of aggregates (g)**	**Mass of sand (g)**	**Volume of water (ml)**	**Mass of cement (g)**	**Mass of ash (g)**
1	Control	108.54	90.45	34	63.33	-
2	10% replacement	108.54	90.45	34	57	6.33

Table 3 Mix design of batches 1 and 2

Replicas of batches 1 and 2 were prepared, where four cubes (50mm x 50mm x 50mm) were casted from each batch to be tested for compressive strength 7 days after curing, and four additional cubes were also casted from each batch to be tested for the compressive strength test after 28 days of curing. The compressive strength test was carried out after proper curing of the mortars and in accordance with ASTM C109. The results for the compressive strength tests carried out on batches 1 and 2 are shown in Figure 23.

The results show that after 7 days of curing, the 10% ash replacement batch had an average compressive strength of 20.8 MPa, which is 19% less than that of the control batch which averaged around 25.7 MPa. Moreover, the 10% ash replacement batch showed a higher variability in strength between replicas. After 28 days of curing, the compressive strength test was also performed on batches 1 and 2, the 10% ash-replacement batch showed high conformity in strength among its replicas. Moreover, the 10% replacement batch averaged approximately 42.3 MPa, which was very close to that of the control batch which achieved around 43.7 MPa. This indicates a 3% loss in the average compressive strength relative to the control sample. These results indicate that the cementitious capacity of fly ash may have not been completed at the 7^{th} day of mixing and curing, but it stabilized sometime between the 7^{th} and the 28^{th} day. A similar study reporting the preparation of 10% ash replacement mortars (Keppert et al., 2015), indicated a 17.5% loss of the 28-day compressive strength compared to the control mortars, while another similar study performed by (Charbaji et al., 2018) reported a 15% loss of the 28-day compressive strength in the 10% ash replacement mortars as

compared to the control mortars. Note that the study performed by (Charbaji et al., 2018) applied treatment to the MSWI fly ash prior to incorporation in cement mortars.

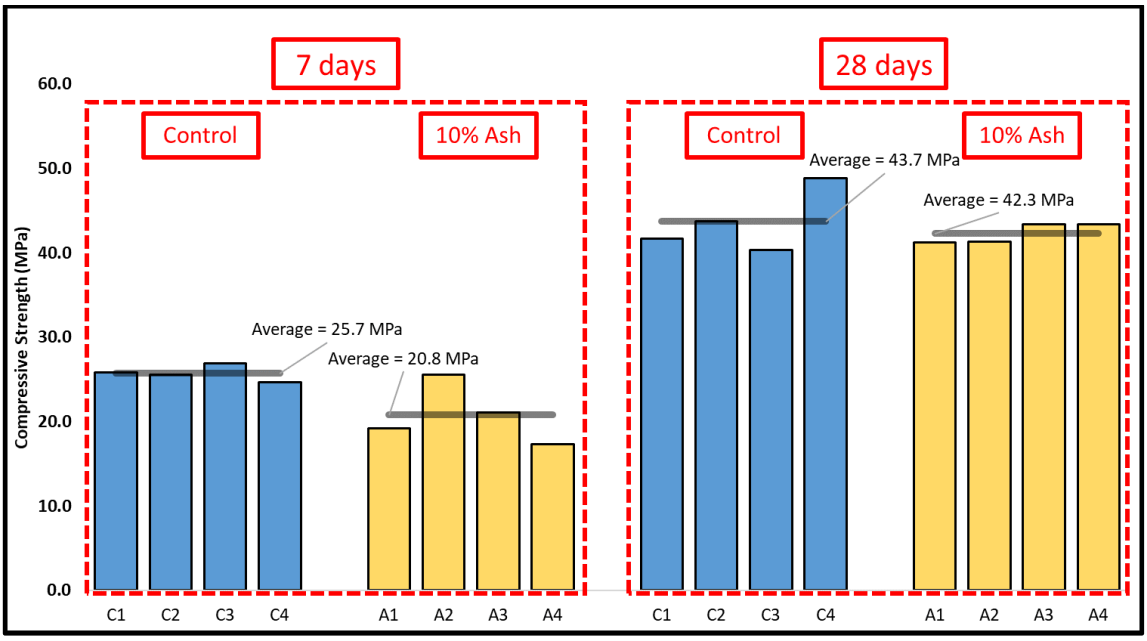

Figure 23 Development of compressive strength (MPa) at 7 and 28 days respectively for the control mortars and the 10% ash replacement mortars

Figures 24 and 25 demonstrate the compressive strength test carried on batches 1 and 2. The homogeneous black color of the cubes in Figure 25 indicates that full mixing of the components was achieved with no segregation along the area of the cube, moreover, the difference in color between the control batch and the 10% ash replacement batch is clear. It is also worth mentioning that the cubes were fractured in the same way in both batches, relieving us from concerns about segregation and inconsistency between the control batch and the ash replacement batch.

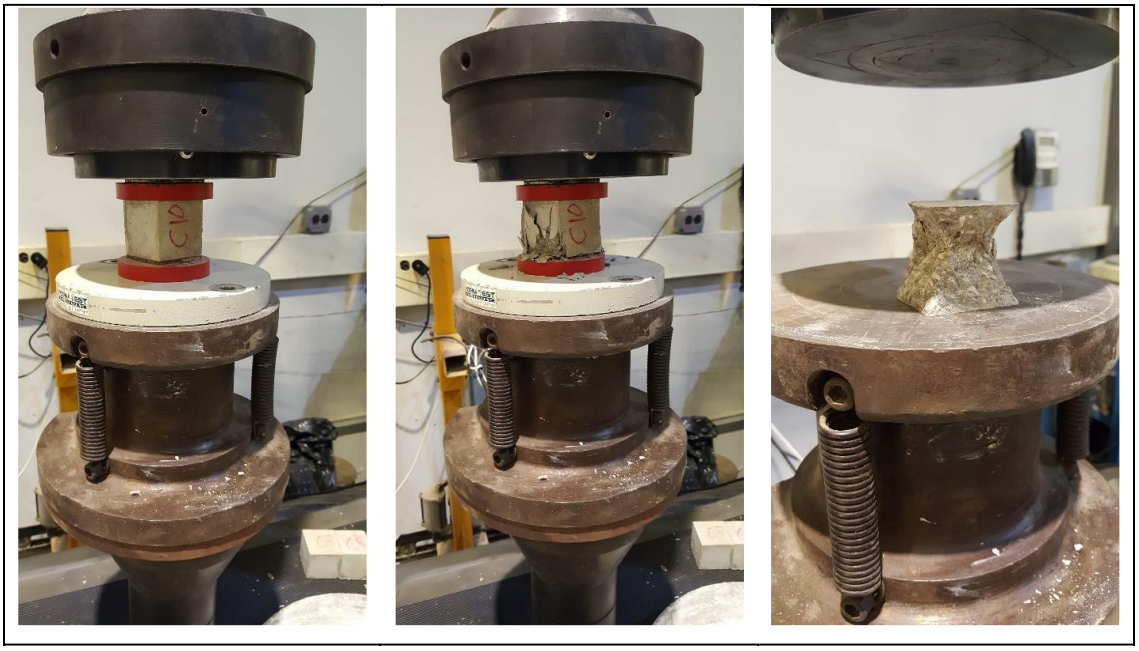

Figure 24 Compressive strength test of control cement mortars

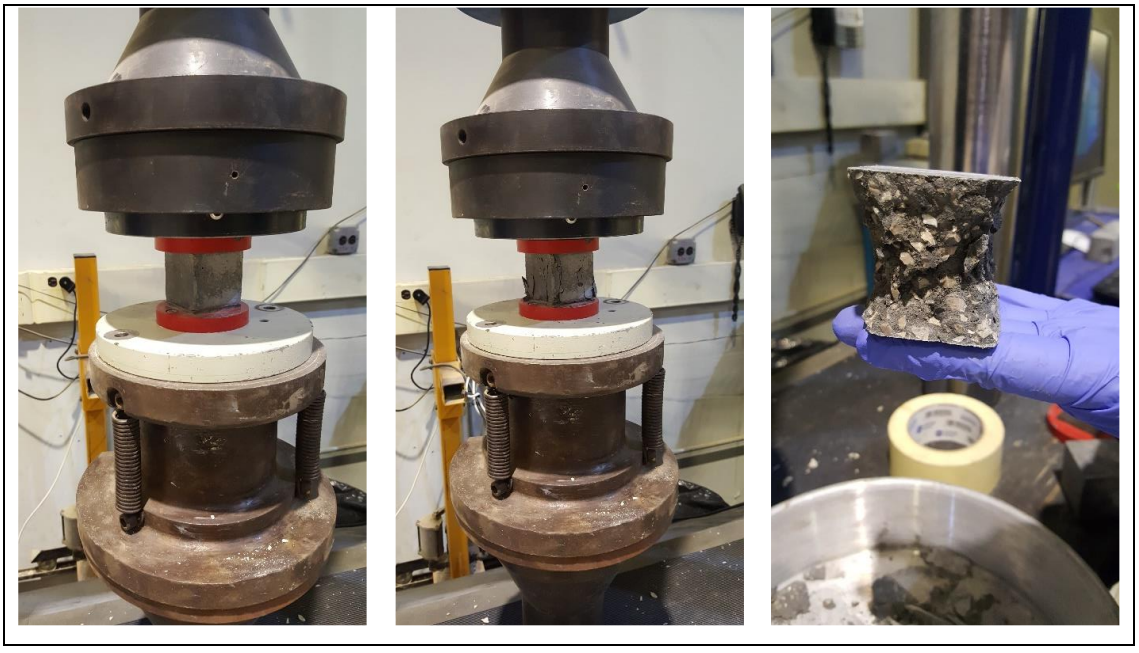

Figure 25 Compressive strength test of cement mortars containing 10% ash

After successfully achieving a 10% incorporation of fly ash in cement mortars, and to promote further use of the fly ash, we prepared two additional ash-containing batches: batches 3 and 4, respectively containing 15% and 20% fly ash replacement. The mix design of these batches is shown in Table 4.

Batch	**Description**	**Mass of aggregates (g)**	**Mass of sand (g)**	**Volume of water (ml)**	**Mass of cement (g)**	**Mass of ash (g)**
3	15% replacement	108.54	90.45	34	53.83	9.5
4	20% replacement	108.54	90.45	34	50.66	12.67

Table 4 Mix design of batches 3 and 4

Regarding batches 3 and 4, three cubes (50mmx50mmx50mm) were casted from each batch to be tested for compressive strength at the 28th day only. The compressive strength test results for all the batches carried out at the 28th day are presented in Figure 26. Results show that a 15% replacement of fly ash resulted in a 28-day average compressive strength of 35.6 MPa, which is equivalent to a loss of almost 19% of the 28-day average compressive strength of control batches. Similarly, the batch containing 20% replacement of fly ash resulted in a 28-day average compressive strength of 32.2 MPa, which is equivalent to a loss of almost 26% of the 28-day average compressive strength of the control batches. Two studies performed by (Charbaji et al., 2018) and (Keppert et al., 2015) reported a loss of 21% and 35% respectively in the 28-day compressive strength of cement mortars containing 20% ash replacement (Table 5).

Note that the study performed by (Charbaji et al., 2018) applied water treatment of the MSWI fly ash prior to incorporation in cement mortars.

Summary of the 28-day average compressive strength of all batches is shown in Figure 26.

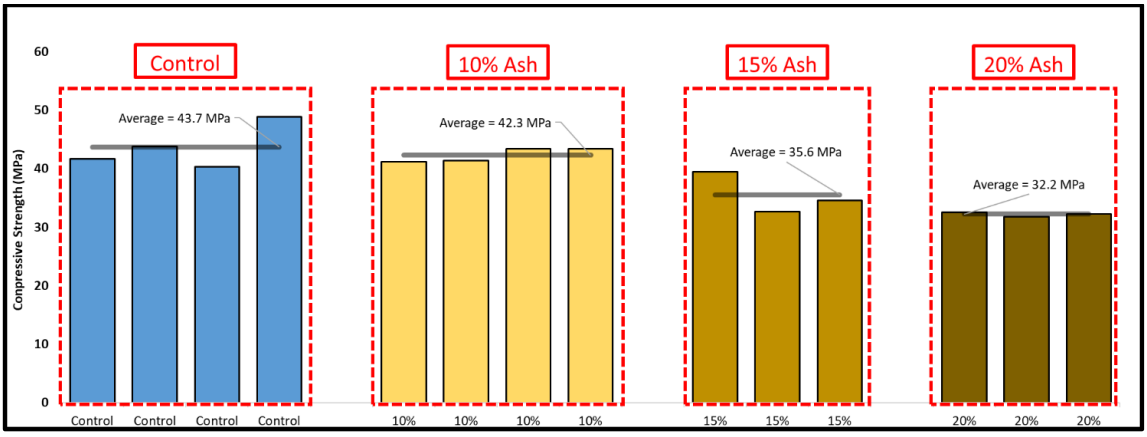

Figure 26 Compressive strength (in MPa) of the control, 10%, 15%, and 20% ash replacement mortars after 28 days

Reference	**Ash Used**	**Specimen (mm)**	**w/b**	**w/c**	**Replace-ment (% by weight)**	**Compres-sive Strength (28 days) (MPa)**	**% Loss of Strength**	**Notes**
(Keppert, Siddique, Pavlík, & Černý, 2015)	MSWI FA	160x40x40	0.52	-	**0**	40	-	-
					10	33	**17.5**	
					20	26	**35**	
(Charbaji, Baalbaki, Elkordi, & Khatib, 2018)	MSWI FA	50x50x50	-	0.32	**0**	48.4	-	Water Washed
					10	41	**15**	
					20	38	**21**	
			0.54	-	**0**	43.7	-	-

This Study	MSWI FA	50x50 x50			**10**	42.3	**2**	
					15	35.6	**19**	
					20	32.2	**26**	

Table 5 Comparative studies incorporating MSWI fly ash in cement mortars

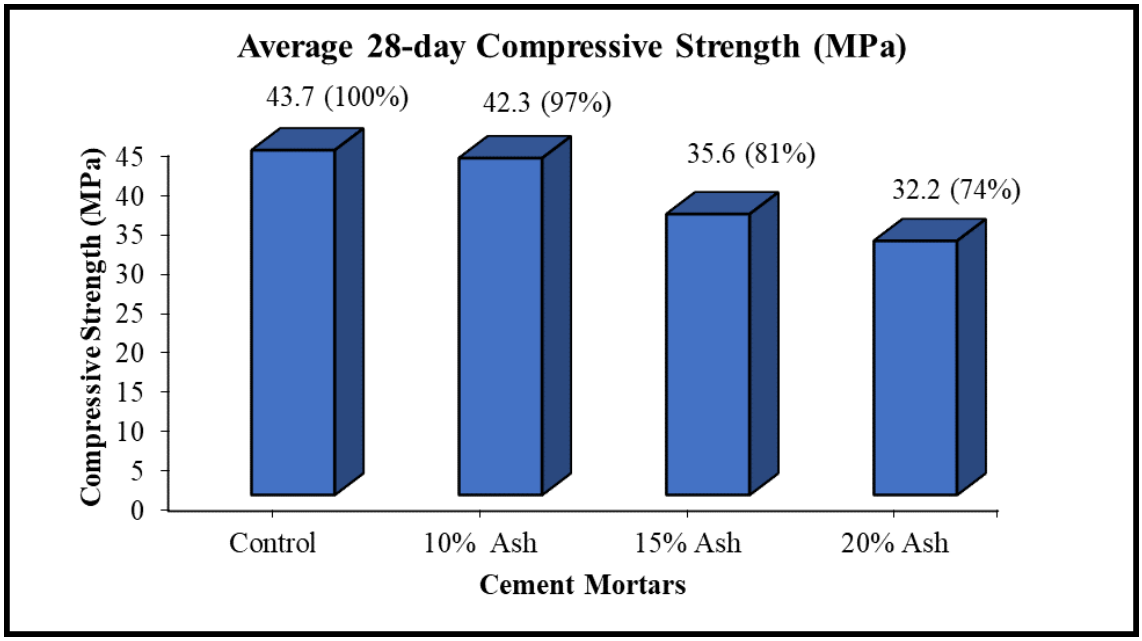

Figure 27 Average 28-day compressive strength (MPa) of cement mortars with various fly ash incorporation percentages

5.3. Testing Leachability of Metals

5.3.1. Cement Mortars

5.3.1.1. Phase I

In this phase, the cement mortars were demolded after 48 hours of mixing and immersed in 150 ml of mQ water to cure, cured samples were then sealed and left for 24 hours, before collecting the curing water and testing it for heavy metals (Pb, Cd, and Cr) using Atomic Absorption Spectroscopy. The results are presented in Figure 28. Please note that several replicas of the samples were tested to obtain these concentrations, as mentioned previously in the methodology section.

Cadmium was not detected in any of the batches, while lead and chromium were detected at different concentrations. Lead levels fluctuated between 0.1 mg/l and 0.663 mg/l, with no clear trend. Overall, the 10% ash replacement batch seems to have higher lead concentration leaching out relative to the rest of the batches. On the other hand, chromium levels were around 0.1 mg/l in the control batch, 0.325 mg/l in the 10% ash replacement batch and reached 0.356 mg/l in the 20% ash replacement batch. Chromium was detected in the control batch probably since Portland cement contains considerable chromium content, as shown in the appendix.

It is evident however, that despite the unexpected peak in lead concentration in the 10% ash replacement batch, all the resulting concentrations are well below the EPA standard for the leachability of lead and chromium in waste, which is 5.0 mg/l (US-EPA, 2009).

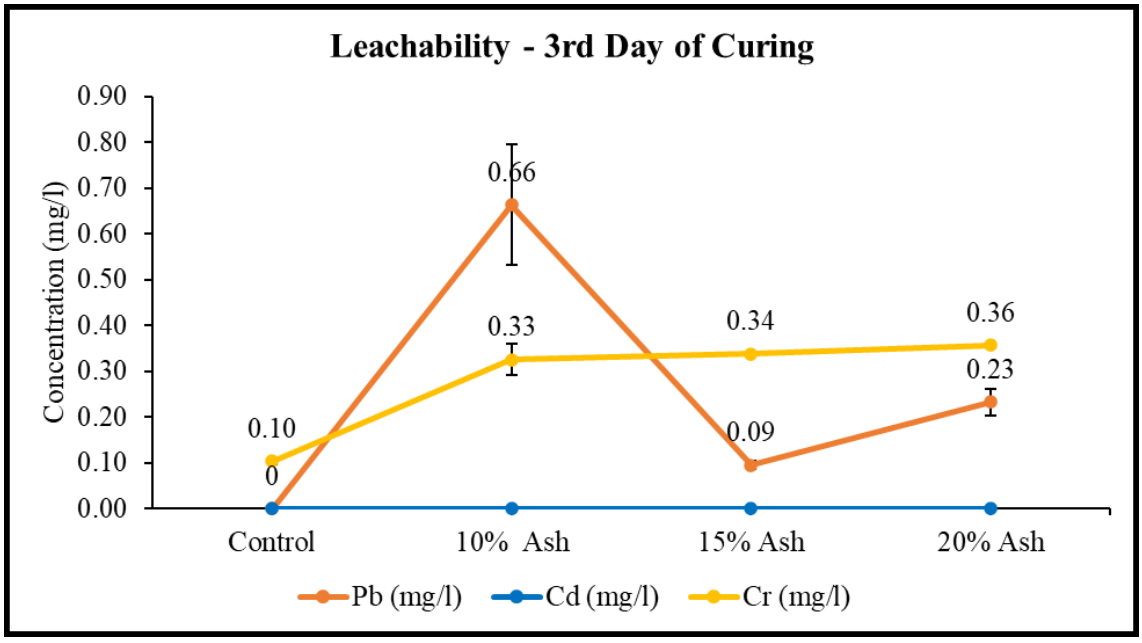

Figure 28 Leachability of metals from various cement mortars at the third day of curing

5.3.1.2. Phase II

In this phase, different conditions were applied on multiple replicas of cement mortars. Some mortars were demolished into small pieces (less than 1cm) before immersing them in either mQ water or acidic water (pH ~ 5.0). Other mortars were left intact and were immersed in acidic water. All cubes, demolished or whole, were immersed in 150 ml of water, and kept for 24 hours before filtering the water and testing it for heavy metals using Atomic Absorption Spectroscopy.

Please keep in mind that in this phase, only chromium was detected, and subsequently all the following figures represent chromium concentrations only.

The effect of demolishing the cement mortars on the leachability of chromium before immersing them in acidic water (pH ~ 5.0), and the difference between a 7-day old mortar and a 28-day old mortar is shown in Figure 29. First, it can be deduced that the 28-day mortars resulted in higher chromium concentrations than the 7-day mortars.

Secondly, demolishing the cubes before immersing them in water clearly increased the leachability capacity of chromium, which is expected because of the increased surface area due to demolishing the cubes. Lastly, it can be inferred that ash-containing cubes resulted in higher leachability of chromium than the control cubes, which is expected.

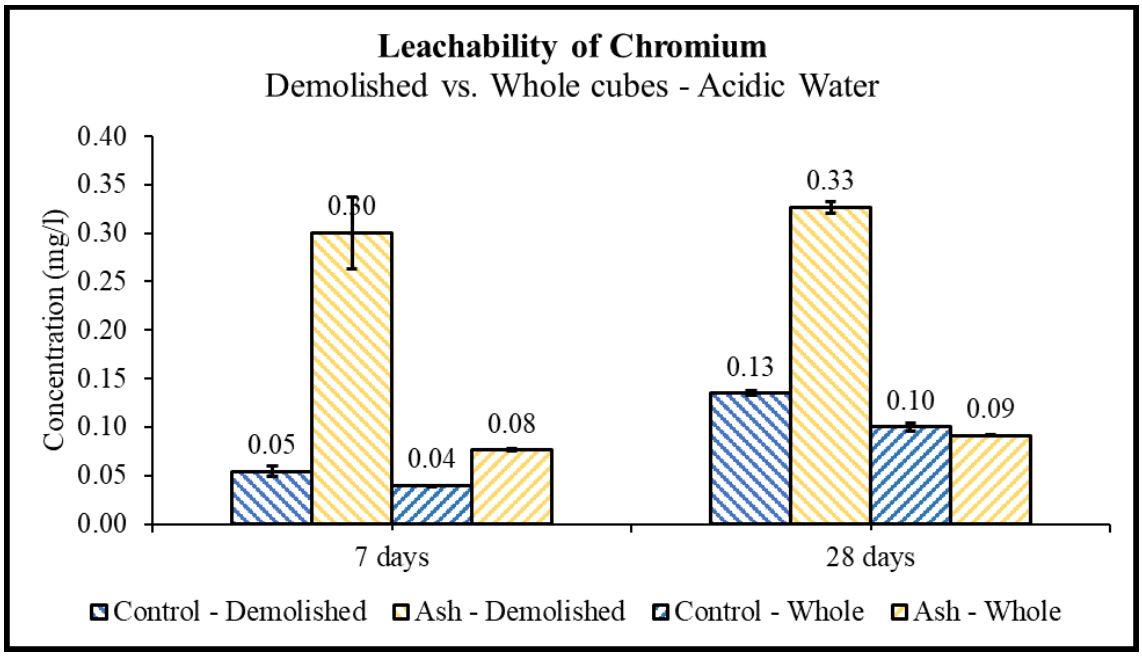

Figure 29 Leachability of chromium from demolished and whole cement mortars immersed in acidic water, at 7 days and 28 days, respectively (Ash replacement is 10%)

The difference between the leachability of demolished cubes immersed in acidic water (pH ~ 5.0) versus mQ water and the difference between a 7-day old mortar and a 28-day old mortar is demonstrated in Figure 30. First, it can be deduced that the 28-day mortars result in slightly higher chromium concentrations than the 7-day mortars. Secondly, it is evident that acidic water results in more leaching of chromium than mQ water, which is expected. Lastly, it can be inferred that ash-containing cubes result in higher leachability of chromium than the control cubes.

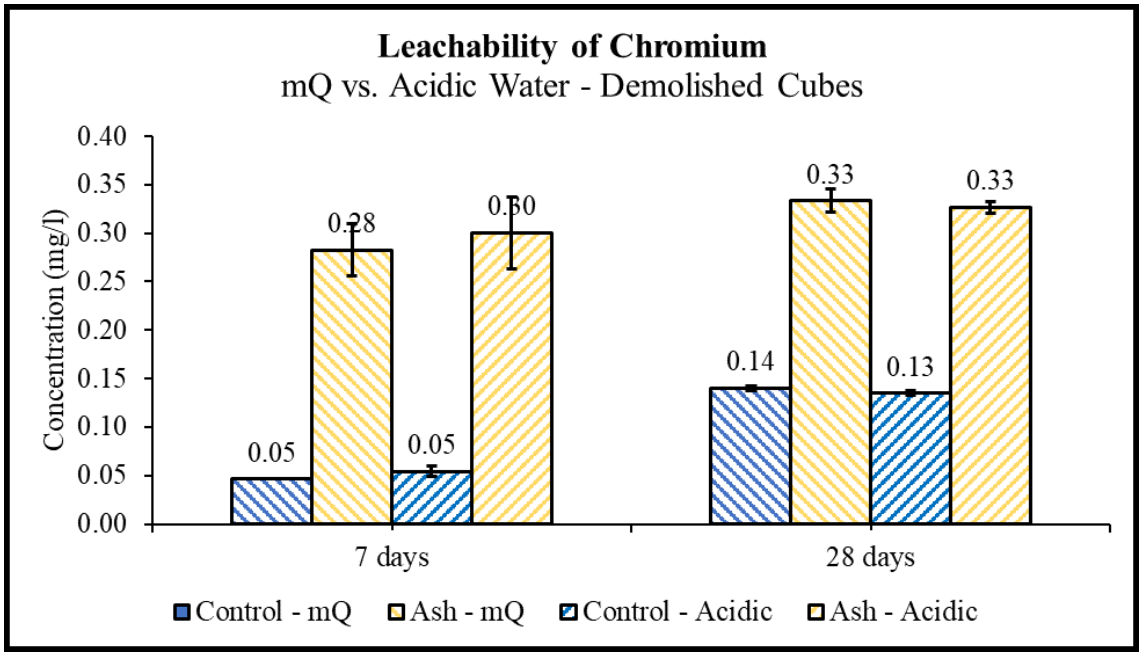

Figure 30 Leachability of chromium from demolished cement mortars immersed in mQ and acidic water, at 7 and 28 days, respectively (Ash replacement is 10%)

The effect of immersing the demolished cubes in mQ water versus acidic water (pH ~ 5.0) in addition to the effect of increased ash replacement percentages is demonstrated in Figure 31. Note that all cubes in this case are 28 days old. First, it is quite clear than incorporating ash in cement mortars will result in higher leaching concentrations of chromium than the control batches. It cannot be concluded, however, that acidic water would always result in higher leaching concentrations of chromium, hence, the effect of the slightly acidic water is negligible in this case. It is evident to mention that the leachability concentrations for all ash-containing mortars are similar and fluctuated within a narrow range of 0.06 mg/l.

Finally, it is important to mention that despite some fluctuation in the resulting concentrations at this phase, all the leaching concentrations are well below the EPA limit for the leachability of chromium in waste, which is 5.0 mg/l (US-EPA, 2009).

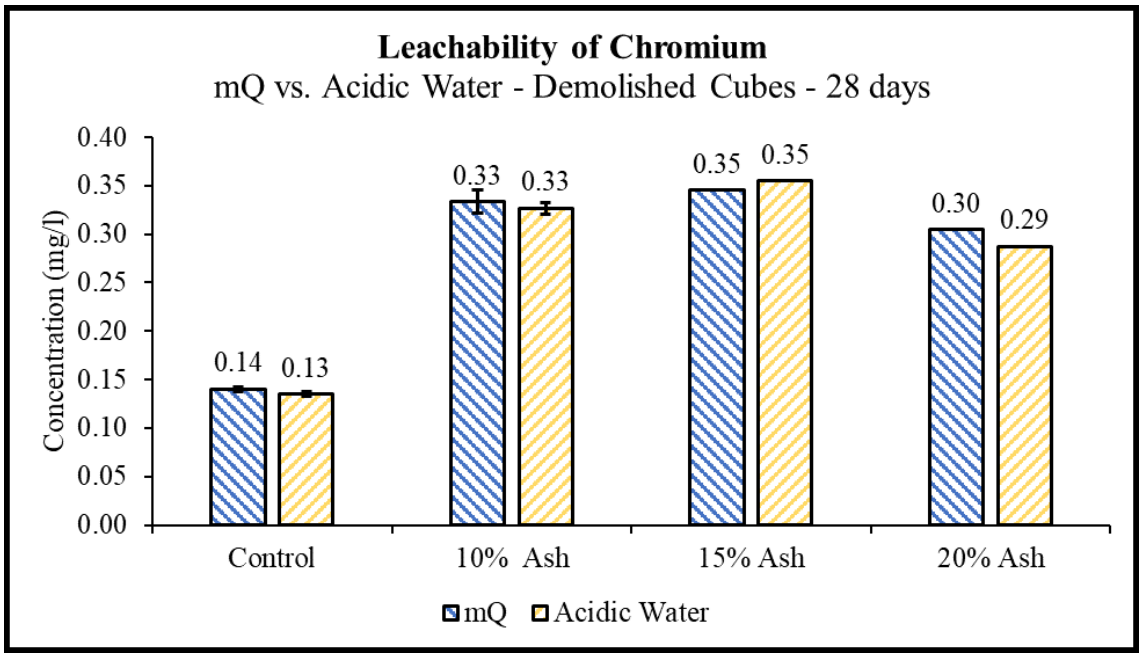

Figure 31 Leachability of chromium from demolished cement mortars immersed in mQ and acidic water at 28 days

5.3.2. Loose Cement Mortars

To further investigate the leachability of heavy metals from cement mortars incorporating fly ash, and to study the effect of increasing contact surface area, we prepared a batch of Loose Cement Mortars (LCMs) with different ash replacement percentages. Prepared LCMs were immersed in mQ water for 96 days. The mix design of the aforementioned loose mortars is the same as that described in Tables 3 and 4, with incorporation percentages of fly ash ranging from 0 to 20%. The results are shown in Figure 33. As seen in Figure 32, it is evident that the color of the loose cement

mortars darkens with the increased ash replacement percentages, moving from grey to black.

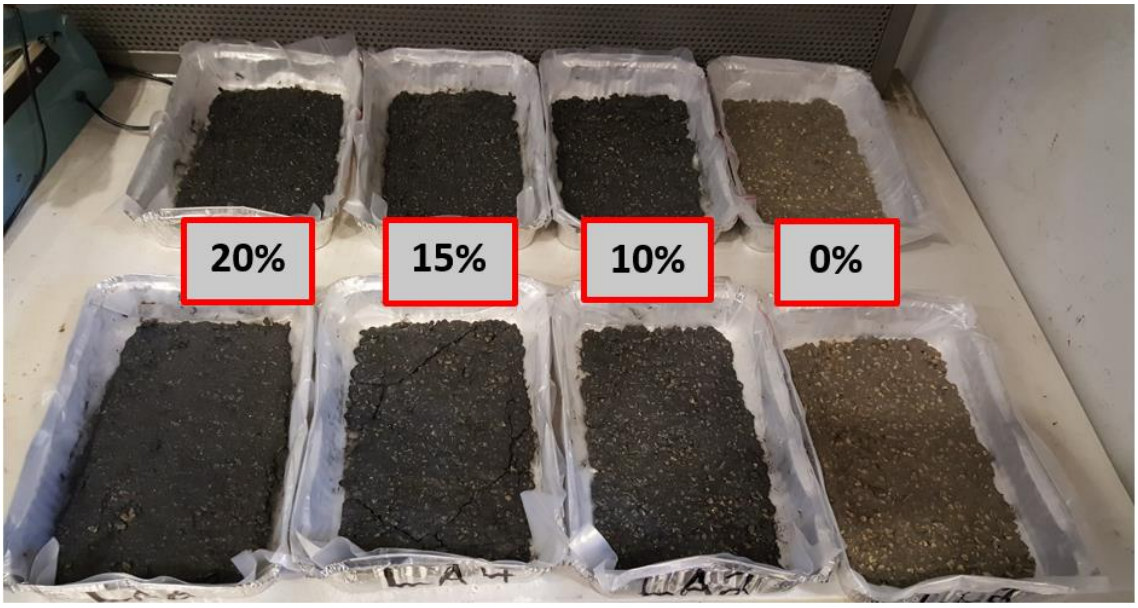

Figure 32 Freshly prepared duplicates of loose cement mortars (LCMs) with different ash replacement percentages

Regarding the leachability of heavy metals from the LCMs, the results showed that lead and chromium were the only metals detected at the ppm level after 96 days of immersion in water. Cadmium, on the other hand, was not detected in any of the batches. Leachability analysis of the control samples (with 0% ash replacement) indicated no detectable lead concentrations and 0.18 mg/l of chromium. This indicates that chromium might already be present in traditional cement mixes, even if at very negligible concentrations.

As the incorporation percentage of fly ash increases, we notice an increasing trend in the concentrations of lead and chromium, with lead steadily increasing from

0.14 mg/l at 10% ash replacement to 0.57 mg/l at 20% ash replacement. Moreover, despite chromium recording concentrations slightly higher than those of lead, with 0.74 mg/l at 10% ash replacement up to 1.08 mg/l at 20% ash replacement, we notice a very slight increase between the 15% and the 20% ash replacement batches. However, regardless of the difference in concentrations, all numbers are well below the EPA limit for the leachability of lead and chromium in waste which is 5 mg/l (US-EPA, 2009).

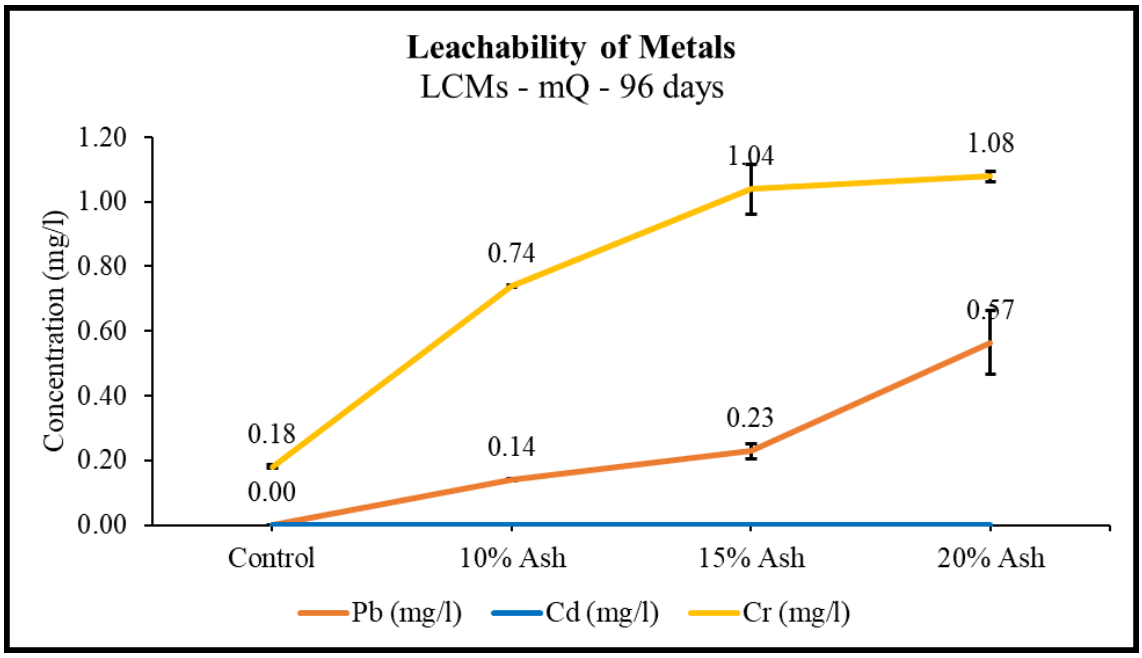

Figure 33 Leachability of Pb, Cd, and Cr metals from the LCMs after 96 days of immersion in mQ

Furthermore, to investigate the effect of acidic water on the loose cement mortars, we drained the LCMs and left them to dry before immersing them in 250 ml of acidic water (pH ~ 5.0) for 7 days. Leachates were analyzed by AAS and the results are illustrated in **Error! Reference source not found.**. As shown in the figure, lead and cadmium were not detected at all at the ppm level, while chromium was detected in

lower concentrations than when immersed in mQ water. At the control level, chromium recorded a concentration of 0.15 mg/l, before steadily increasing to 0.2 mg/l in the 10% ash replacement batch, followed by an in increase to 0.44 mg/l in the 15% ash replacement batch, before stabilizing a bit and recording a concentration of 0.49 mg/l in the 20% ash batch. This experiment showed that some metals – chromium in this case – can further leach from cement mortars under additional contact with a slightly more acidic water. These concentrations can be considered environmentally safe as they are well below the EPA limit for leachability of chromium in waste which is 5.0 mg/l (US-EPA, 2009).

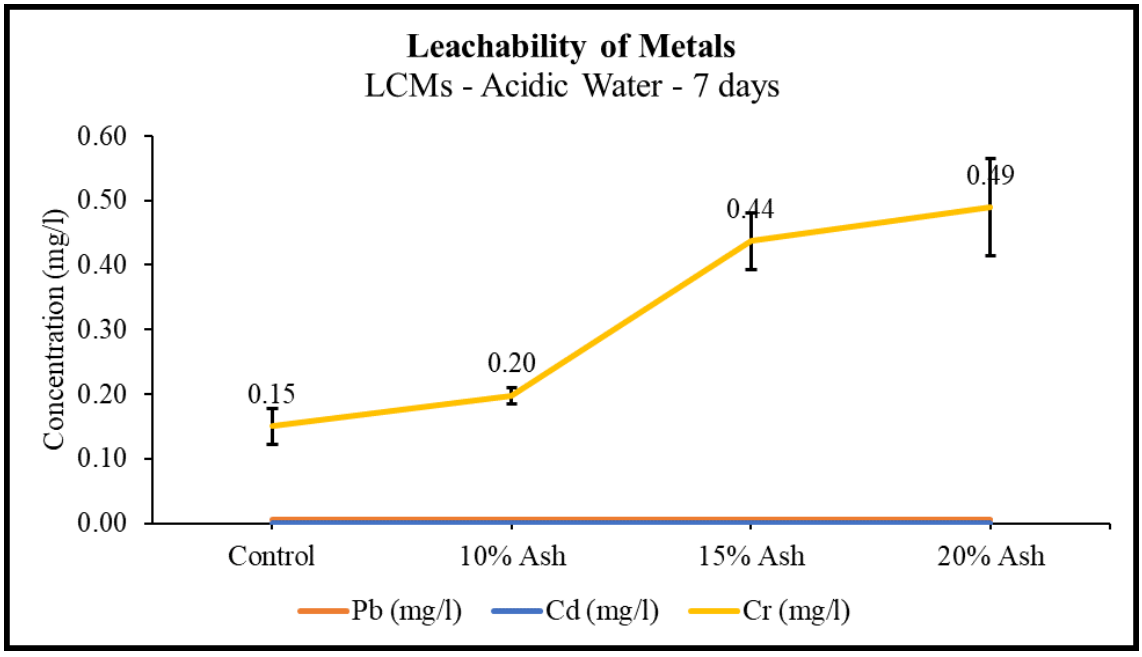

Figure 34 Further Leachability of metals from the LCMs after 7 days of immersion in acidic water

CHAPTER 6

CONCLUSIONS AND FUTURE RECOMMENDATIONS

This work utilizes fly ash (incineration by-product) in building material. Fly ash acquired from SICOMO, a Lebanese MSW incinerator, was characterized before its incorporation into cement mortars as a partial replacement to Portland cement. The effect of incorporating fly ash (without treatment), as a replacement to cement in cement mortars, on the mechanical properties of cement mortars was demonstrated in this study. Potential leachability of metals from incorporated fly ash can pose environmental threats, that was also addressed in this study. Detailed findings and conclusions are listed below:

- Acid digestion of fly ash samples (as received) was used due to its effectiveness in quantitatively analyzing the metal content of fly ash. Metal content of the acquired fly ash was well within the values obtained from the literature.
- MSWI fly ash acquired from SICOMO can be successfully incorporated in cement mortars, as no foaming or expansion of cement mortars was observed, along with promising and consistent compressive strength values.
- The 7-day compressive strength tests have shown that the cementitious capacity of the acquired fly ash was fully reached between the 7th and the 28th day of curing.
- A 10% (by weight) incorporation of fly ash in cement mortars resulted in a 3% loss of average compressive strength after 28 days of curing. Similarly, incorporation percentages of 15% and 20% (by weight) resulted in 19% and

26% loss of average compressive strength after 28 days of curing, respectively. Studies in the literature with similar incorporation percentages generally reported higher percentage loss of average compressive strength.

- The breaking pattern of the ash-containing mortars was similar to that of the control mortars, meaning no segregation has occurred in the ash-containing samples.
- Regarding leachability of metals from cement mortars, it was observed that all metal concentrations in the leaching water at different stages of the study are well below the EPA allowable limit in waste. Most metals, however, have leached out during Phase I (on the 3rd day of curing).
- The investigation of the leachability of metals from cement mortars indicated that ash-containing mortars resulted in higher leachability of metals compared to control mortars. Similarly, demolished cubes also resulted in relatively higher leachability of metals compared to whole cubes (around 4 times more). Immersing mortars in acidic water also showed relatively higher leachability of metals compared to immersing mortars in milli-Q water.
- Regarding leachability of metals from loose cement mortars, results indicated that all tested metal concentrations in the water are well below the EPA allowable limit in waste. During the first stage, only lead and chromium were detected in the leaching water, following a pattern of increased leachability with increased ash replacement percentages (10%, 15%, and 20%). Lead was measured to be 0.6 mg/l and chromium 1.1 mg/l at 20% incorporation. At the second stage, however, after adding acidic water, only chromium was detected in the leaching water in negligible concentrations, reading 0.5 mg/l at 20%

incorporation, indicating that most of the leachable metals had leached out during the first stage.

We can now conclude that incorporating MSWI fly ash acquired from SICOMO into cement mortars is an effective, safe, and sustainable approach to managing fly ash disposal challenge associated with incineration processes. We recommend carrying out studies that extend this work to a larger scale, permitting the incorporation of more ash in concrete structures (such as cylinders and subsequently, walls and small columns). Moreover, the adsorptive capacity of the acquired fly ash should be further studied and implemented to assess the possibility of using fly ash as a green adsorbent to various pollutants and metals.

APPENDIX

Reference	(Alba, Gassó, Lacorte, & Baldasano, 1997)	(Rémond, Pimienta, & Bentz, 2002)	(Cheng & Chen, 2004)	(Haiying et al., 2007)	(Pan, Huang, Kuo, & Lin, 2008)	(Shi & Kan, 2009)	(Kepperet et al., 2015)
Component	**Chemical Composition (% weight)**						
SiO_2	18.8	27.23	19.4	20.5	13.6	24.5	15.6
Al_2O_3	12.7	11.72	10.1	5.8	0.92	7.42	9.2
Fe_2O_3	1.6	1.8	1.8	3.2	3.83	4.01	2.6
CaO	24.3	16.42	19.7	35.8	45.42	23.37	23.9
MgO	2.6	2.52	2.8	2.1	3.16	2.72	1.8
Na_2O	5.8	5.86	8.9	3.7	4.16	4	9.4
K_2O	4.3	5.8	8.1	4	3.85	4.6	6.6
C^{l-}	-	7.2	-	-	-	10	11.2
SO_3	6.4	3	-	-	5.18	12.03	11.5
P_2O_5	2.7	0.34	-	-	-	-	1.3
TiO_2	1.5	0.84	1.9	-	3.12	-	-
Mn_2O_3	-	0.05	-	-	-	-	-

Table 6 Chemical composition of different MSW fly ashes reported in the literature

(Continued)

Reference	(Rémond et al., 2002)	(Wu & Ting, 2006)	(Shi & Kan, 2009)
Element	**Heavy Metals Concentration (mg/kg)**		
As	21	-	-
Ba	-	539	-
Cd	270	95	36.71
Co	21	14	-
Cr	450	72	157
Cu	670	570	563.2
Mn	600	309	-
Mo	25	-	-
Ni	50	22	-
Pb	4000	2,000	1515

Sb	110	-	-
Se	50	-	-
Sn	180	-	-
Sr	-	151	-
V	32	-	-
Zn	11000	6,288	3269

Table 7 Metal composition analysis of different MSW fly ashes reported in the literature (Continued)

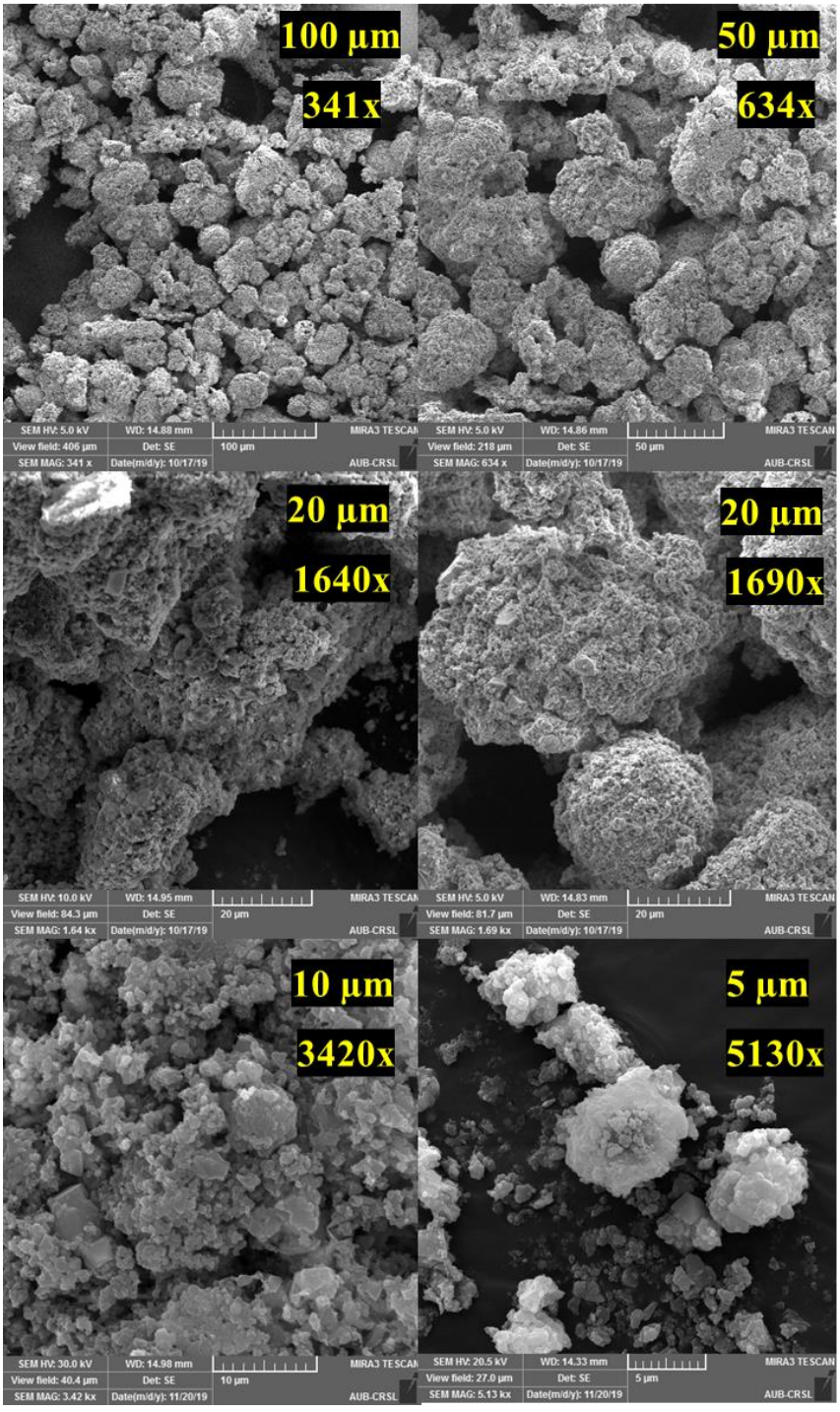

Figure 35 Scanning Electron Microscopy images of fly ash sample at various magnifications

Property	(Bie et al., 2016)	(Ginés et al., 2009)	(Keppert et al., 2015)	(Wu & Ting, 2006)	This Study (SICOMO)
BET Surface Area (m^2/g)	5.28	6.04	0.394	9.7	3.1339
Micropore Volume (mm^3/g)	22	-	-	-	0.21
Pore Size (Å)	-	-	-	-	170.496

Table 8 BET surface area, micropore volume, and pore size of the fly ash sample

Phase I	**Sample**	**10% Ash**	**15% Ash**	**20% Ash**
	Pb (% leaching)	0.120056	0.01142	0.020995
	Cr (% leaching)	5.243346	3.627945	2.867521
Phase II	**Sample**		**10% Ash**	
	Cr (% leaching)	**State**	**7 days**	**28 days**
		Demolished-mQ	4.802544	5.670166
		Demolished-Acidic	5.105361	5.554484
		Whole-Acidic	1.29633	1.554915
LCM (96 days) (mQ)	**Sample**	**10% Ash**	**15% Ash**	**20% Ash**
	Pb (% leaching)	0.042532	0.046027	0.085148
	Cr (% leaching)	19.8547	18.61797	14.4833
	Sample	**10% Ash**	**15% Ash**	**20% Ash**

LCM (7 days) (Acidic Water)	Cr (% leaching)	6.637524	9.612846	7.675452

Table 9 Leachability of metals at different phases of the study represented as a percentage (by weight)

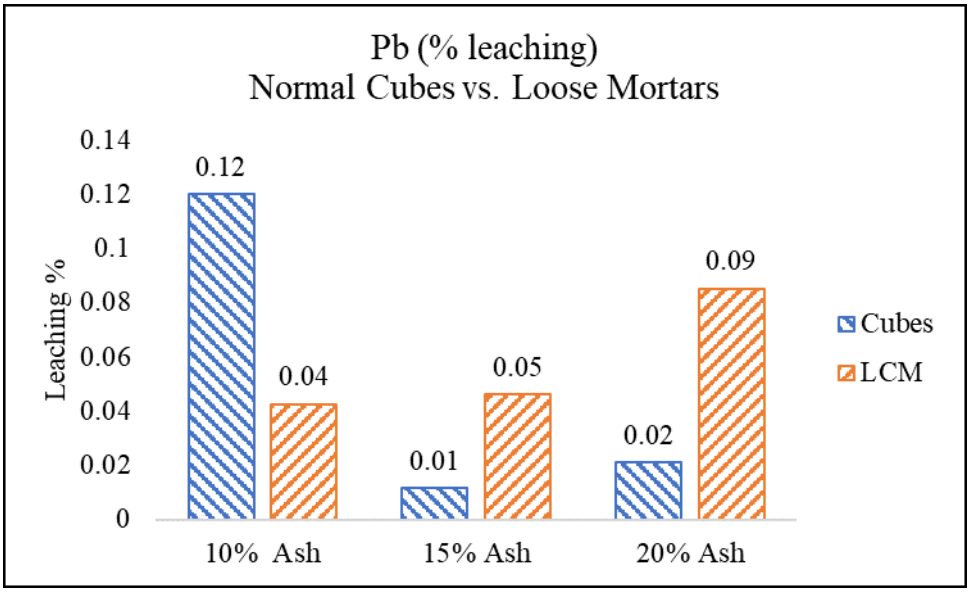

Figure 36 Leachability of lead (% weight) in normal and loose mortars

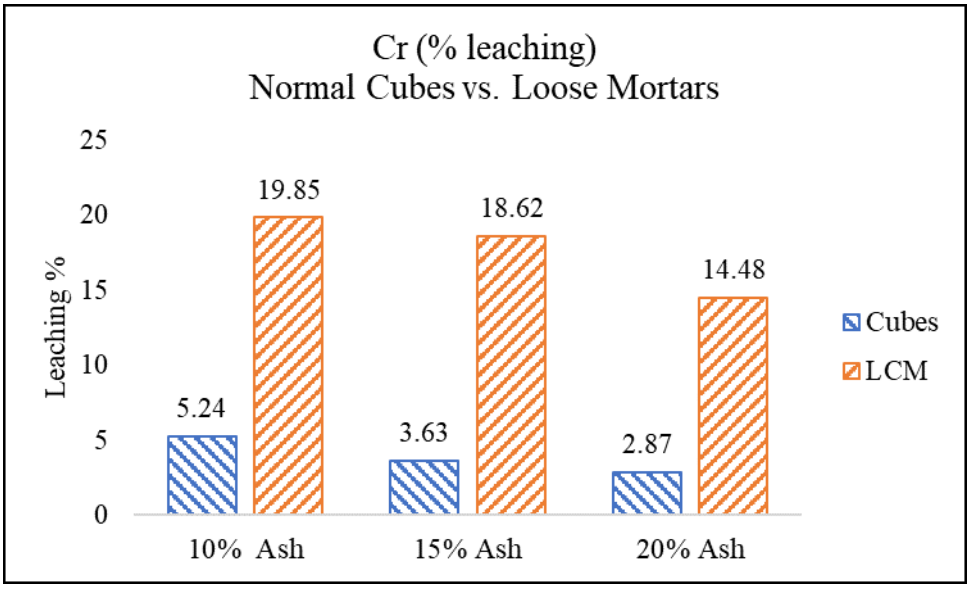

Figure 37 Leachability of chromium (% weight) in normal and loose mortars

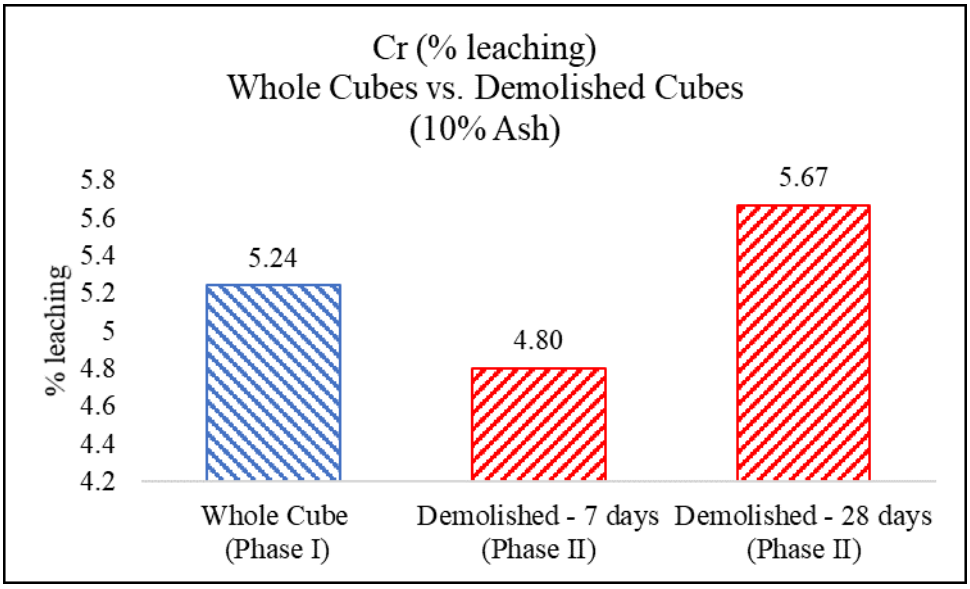

Figure 38 Leachability of chromium (% weight) in whole and demolished mortars

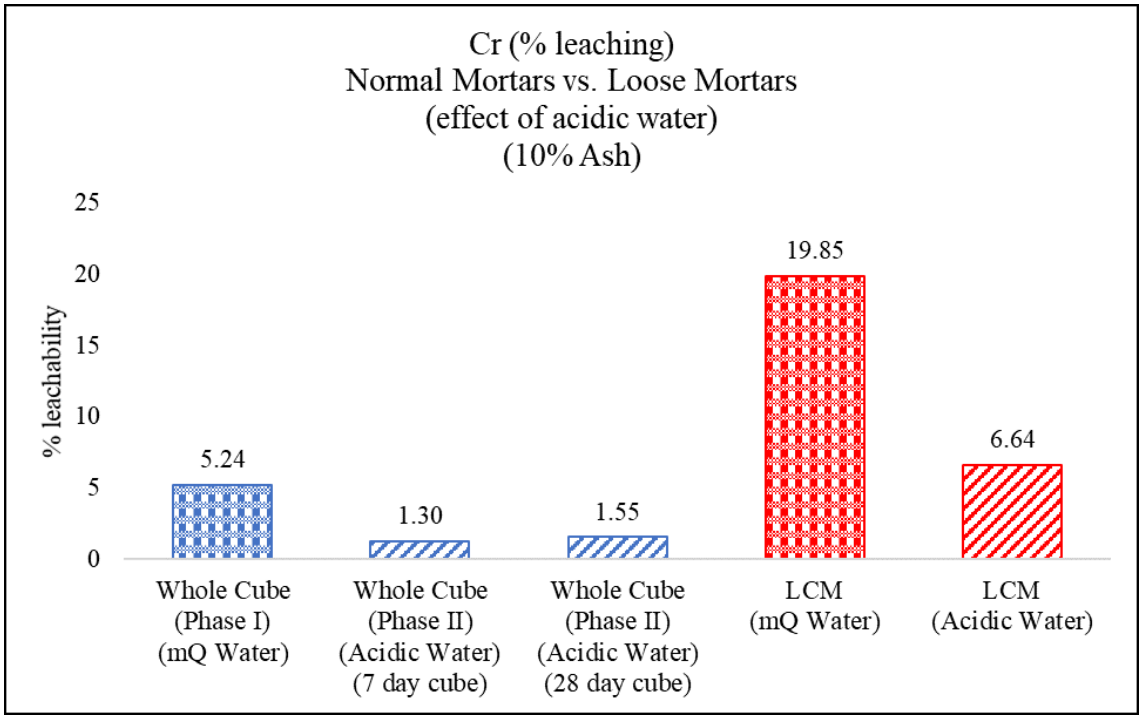

Figure 39 Leachability of chromium (% weight) in normal and loose mortars

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