Title: Aggregate material formulated with MSWI bottom ash and APC fly ash for use as secondary building material.

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Abstract

The main goal of this paper is to obtain a granular material formulated with Municipal Solid Waste Incineration (MSWI) bottom ash (BA) and air pollution control (APC) fly ash to be used as secondary building material. Previously, an optimum concrete mixture using both MSWI residues as aggregates was formulated. A compromise between the environmental behaviour and the economy of the process was considered. Unconfined compressive strength and abrasion resistance values were measured in order to evaluate the mechanical properties. From these results, the granular mixture was not suited for certain applications owing to the high BA/APC fly ash content and low cement percentages used to reduce the costs of the final product. Nevertheless, the leaching test performed showed that the concentrations of all heavy metals were below the limits established by the current Catalan legislation for their reutilization. Therefore, the material studied might be mainly used in embankments, where high mechanical properties are not needed and environmental safety is assured.

Keywords: bottom ash, air pollution control residues, aggregate, road construction, MSWI

Introduction

The global increase in the residues from Municipal Solid Waste Incineration (MSWI) residues has become a major concern in many countries. Achieving the 3 Rs (Reduce, Reuse and Recycle) has become a priority in modern disposal strategies.

Incineration reduces waste mass by 70% and volume by up to 90%. Moreover, it produces energy from the heat combustion (Lam et al., 2010). However, the two main types of ash generated, known as bottom ash (BA) and air pollution control (APC) residues, which are a mixture of fly ash (FA), organic pollutants and alkaline salts in powder form, require appropriate management in order to minimize their effect on the environment. The former (BA) is classified as non-hazardous waste by the European Waste Catalogue and Catalan legislation, as it is typically rich in calcium oxide and silica with minimum amounts of heavy metals. Consequently, it is available to be reused as secondary building material (Chimenos et al., 2003; Fernández Bertos et al., 2003; Polettini et al, 2001). On the other hand, APC fly ash is classified as hazardous waste, owing to its high contents of heavy metals, soluble salts, chlorinated organic compounds, and lime from the air pollution treatment process (Polettini et al., 2001).

One of the most usual strategies for the management of APC residues is treatment followed by landfill. Their chemical composition requires proper stabilisation to prior disposal. Stabilisation methods include separation from BA, solidification/stabilization (S/S) and thermal treatments (Quina et al., 2008). The method applied depends on the legislation in force in each country. In USA most of the FA is mixed with BA prior to disposal in either monofills, monocells or mixed landfills (Eighmy et al., 1996). In Sweden, Denmark and Germany APC residues are disposed of in secure landfills after special treatment. Great efforts have been made to achieve successful ash management with beneficial use in France, Italy and The Netherlands (Quina et al., 2008). Catalan environmental legislation restricts landfill disposal of APC residues because of the leaching of the high heavy metal content (DOGC 5370), as well as their possible revalorisation (DOGC 2181). Landfill disposal is no longer a feasible choice, as land availability in many countries is an important limitation. Millrath et al. (2004) categorize the beneficial use of MSWI residues after application of the above-mentioned stabilization methods, in four main applications: i) in landfills as daily cover or road-base material; ii) as construction material; iii) in underground disposal sites like mine remediation; and iv) in agriculture. Utilisation of BA and APC residues as road-base material has been proposed by several authors (Schreurs et al., 2000). The release of contaminants such as road leachates entails a substantial risk for the environment due to the high toxicity of the heavy metals involved. For this purpose, evaluation of emissions in laboratory and field tests has been carried on with very promising results (Hjelmar et al., 2007; Johnson et al., 1999; Lidelöw et al., 2007). It appears that geochemical processes determine the concentration ranges and hydrological factors govern the fluctuations in concentration, with liquid-to-solid ratio (L/S) and pH being the major factors affecting mobility (Åberg et al., 2006; Johnson et al., 1999). Åberg et al. (2006) concluded that leaching at pilot scale is a more complex process than controlled leaching in the laboratory, and suggested that percolation tests should be performed. Furthermore, other factors have a significant impact on the mobility of certain metals, like redox chemistry for Cr, formation of organic ligands in the case of Cu, and mineral precipitation and adsorption reactions for Pb (Åberg et al. 2006).

On the other hand, APC residues including FA could be used in CO_2 capture and storage (CCS) technology, owing to the high alkaline content susceptible to form stable carbonates (Prigiobbe et al., 2009). However, great efforts to understand the kinetics of carbonation of BA and APC residues have to be made in order to put it on practice. Other stabilization processes include the addition of chemicals like soluble phosphates, by which most metals are stabilized. In spite of this, the concentration of soluble salts is barely depleted and the final mass of the residue to be landfilled is severely increased (Quina et al., 2010). Hydrothermal solidification of FA was carried out by Shan et al. (2011), who obtained solidified bodies with significant strength and a high potential to be recycled as this treatment dramatically reduces the concentration of the heavy metals dissolved. Composites made from a ternary blend of APC residues, concrete and polymer also appear to show improved retention properties (Massardier et al., 1997).

Apart from the abovementioned MSWI management techniques, solidification with hydraulic binders has been evaluated for both types of ash. Portland cement and concrete mixtures appear to be the most widely used. Promising results were obtained owing of the high ash content, which provided a longer setting time and chemical immobilisation of some heavy metals. This indicates that there is a strong potential for the use of these mixtures in non-structural concrete as a result of the suitable compressive strength values and the retainer properties observed (Collivignarelli et al., 2002; Lampris et al., 2009; Pan et al., 2008; Polettini et al., 2001; Sorlini et al., 2011). Nevertheless, an application has only been tested using the two ashes separately and binding them with natural aggregates, in order to improve mechanical resistance. Ginés et al. (2009) studied the suitability of some concrete formulations obtained from mixing BA and APC residues as aggregates. In this study mechanical properties as well as environmental behaviour were taken into account with promising results. They concluded that some of the formulations studied might be suitable for use as a non-structural concrete, like pavers, mud slab concrete or Jersey concrete barriers (Ginés et al. 2009).

Following the path opened by this preliminary study, the aim of this research is to assess the viability of new crushed concrete mixture, formulated exclusively from weathered BA and APC residues, as secondary building material. As road sub-base material, the cast concrete mixture requires granulation prior to use and thus a high compressive strength is not mandatory. Accordingly, in order to economize the process, a low-priced concrete can be used with a lower binder-aggregate ratio. Thus, higher weathered BA/APC fly ash additions imply a greater reuse of MSWI, as long as the environmental parameters imposed by current legislation are maintained. For this study, different mix proportions were assayed in order to determine the mechanical properties and the environmental effects of the granular material, and thus establish the optimum formulation.

2. Methods and materials

2.1 Materials

MSWI residues including weathered BA and APC fly ash were collected from a single municipal solid waste incinerator facility located in Tarragona, Spain. The feed stream is mainly composed of household rubbish, with a small input from commercial sources. Each year, 35,000 tons of BA and 3,000 tons of APC residues are produced in this facility. The former is currently fully reused as a secondary building material and the latter is stabilized with Portland cement prior to landfill disposal (Ginés et al., 2009). Following the combustion process, fresh BA is homogenized prior to storage in the open for natural weathering. Thus, the quality of the material is improved and recovery of the revalorized metals becomes possible. Moreover, when fresh BA is exposed to the atmosphere, the formation of more stable mineral phases is favored, which then controls the release of heavy metals (Gori et al., 2010). On the other hand, the flue gases from combustion are cooled through heat exchange with a boiler and sent to a semi-dry scrubbing system, where acid gases are neutralized by the addition of lime grout. Acid gas scrubbing residue and fly ash particles are later captured by a fabric filter producing 8 t per day of APC residue, which is kept closed in a collection system.

Around 600-700 kg of BA was taken from different points of the stockpiled BA that had been naturally weathered in the open for up to four months. About 150 kg of APC fly ash was taken from the collection system. After homogenization, the weathered BA samples were screened to a particle size < 25 mm and quartered by riffle-type sample splitter. Representative subsamples of about 1 kg were taken from both kinds of residue for physical and chemical characterization.

The chemical composition of the major and minor elements in the bulk weathered BA and APC fly ash was determined in duplicate by X-Ray Fluorescence Spectroscopy (XRF) using a Philips PW2400 X-ray sequential spectrophotometer. The results are shown in Table 1. As previously reported by other authors, BA is mainly composed of amorphous and vitreous phases, with Si being the most abundant constituent coming from lime-soda glass, followed by Ca from ceramic materials (Galiano et al., 2011; Lidelöw et al., 2007; Onori et al., 2011; Pan et al., 2008). As for APC fly ash composition, the major presence of calcium is attributed to the use of the lime-slurry in the scrubber units in the air pollution control system and the products generated during the gas cleaning process (i.e. calcium carbonate, calcium chloride, calcium sulfate, etc.).

Particle size distribution for weathered BA was determined by sieving the samples according to the standard EN 933-2. Figure 1 shows two replicates of the corresponding grading curve. Comparison with respect to an optimum size distribution depicted by Fuller curve is also presented. Fuller curves are grading curves that give the minimum void space and closest packing for sands and mineral aggregates with different particle sizes (Ginés et al., 2009). They are commonly used as a reference in concrete mixture formulations (Fuller et al., 1907). As can be seen, weathered BA is similar to the optimum distribution, with a sand-like fraction below the ideal and a slight excess on the coarse particles. A low proportion of sand-like material helps the drainage and the absence of large particles avoids segregation. Therefore it can be classified as a 0-25 mm material with good graduation (Izquierdo et al., 2002).

In order to evaluate the leaching behaviour of both residues and therefore the potential impact on the environment, the leaching test EN-12457-4 was carried out as follows: samples of weathered BA and APC fly ash were taken separately and reduced when necessary to a particle size below 10 mm and brought into contact with ten times the weight of water under continuous stirring for 24 hours. The corresponding eluates were passed through 45 µm polypropylene membrane filters, acidified by adding a few drops of HNO_3 and preserved in a fridge at 4ºC for subsequent analysis. Trace metal concentrations were determined by inductive coupled argon plasma mass spectrometry (ICP-MS). The results are shown in Table 2. The threshold established by the Catalan Government for landfill disposal and the regulatory limit values for utilization of MSWI BA as secondary building materials are also displayed for their corresponding classification (DOGC 2181; DOGC 5370). As can be seen, weathered BA is a non-hazardous waste that can be disposed of in landfills without any previous treatment or reused as secondary building material, mainly as road sub-base aggregates or embankments. In contrast, APC fly ash must be catalogued as hazardous due to its high lead concentration. The composition of APC fly ash strongly depends on the technology adopted. The semi-dry process used in the gas treatment is highly alkaline due to the lime grout added to neutralize the gases coming from the combustion chamber (Chimenos et al., 2005). High alkalinity promotes the leaching of strongly amphoteric heavy metals, such as lead and zinc (Polettini et al., 2001).

The cement used for concrete formulations was Portland CEM II 32.5 N B-L. In order to minimize the water content and therefore improve workability and mechanical properties, a concrete admixture named MIRA 43 was added in certain formulations. It consisted of a fluidizer polymer-based aqueous solution of complex organic compounds and was provided by Grace Construction Products.

2.2. Methods

Different formulations were cast based on variations in the percentage of APC fly ash and cement, with the remainder corresponding to weathered BA. The consistence was fixed in the range of 5-8 cm according to the Abrams cone method (UNE-EN 83313:90) with different water-to-cement ratios. Experimental trials were run with and without admixture (Table 3). In all cases, admixture dosages were 1.9% of the cement content, as previous tests showed this was the optimum amount. Three cylindrical specimens with dimensions of 15 cm diameter and 30 cm height were cast for each formulation. Just after the concrete was cast and compacted the specimens were kept in a climatic chamber, then demolded and stored in the curing room at a constant temperature of 20ºC (± 2ºC) and a relative humidity of 95% for 28 days, according to UNE-EN 12390-2. Subsequently, compressive strength was tested for each specimen following UNE-EN 12390-3. The optimum formulation with respect to mechanical properties was later ground and separated into two groups, one to determine the leaching behavior of the formulations and the other for the abrasion test. Density and porosity of the hardened concrete were also measured according to EN 12390-7. As for the potential release of heavy metals by leaching, the aforementioned batch test was used. The abrasion test is defined by the Los Angeles coefficient according to the standard UNE-EN 1097-2. This coefficient measures the ability of an aggregate material to maintain its physical integrity under defined abrasive conditions (Chandler et al., 1997). A particle size distribution between 10-14 mm is required for the abrasion test; additionally, 60%-70% of the granular material must be <12.5 mm. Meeting these requirements reduces the sample's mass and conditions the number of replicates. Each sample of around 5 kg was placed in a drum with 11 steel balls and rotated 500 times at 30-33 rpm. The material extracted was passed through a 1.6 mm sieve and compared to the original mass in order to express the "percentage loss" (Los Angeles coefficient). The abrasion resistance of weathered BA, commonly used nowadays as secondary building material, was also measured for comparison.

3. Results and Discussion

3.1 Mechanical and physical properties

Figure 2 shows the compressive strength values obtained for all formulations without admixture as a function of the APC fly ash percentage. APC fly ash has been regarded as a potential cement replacement due to its highly similar composition (Lam et al., 2010). However, as shown in Figure 2, the addition of APC fly ash to the mixture depleted the compressive strength considerably. High APC fly ash percentages promote high water-to-cement ratios (see Table 3) due to an increase in the specific surface and therefore reduce the mechanical properties. Moreover, a high APC fly ash content also increases the porosity, as discussed below. The results for the formulations with admixture are shown in Figure 3. A similar decay in the compressive strength was observed as the APC fly ash proportions increased. Nevertheless, higher compressive strength values were reported when using a greater cement content in both trials. Likewise, the addition of MIRA 43 admixture slightly diminished the water consumption to raise desired consistence (see Table 3) and therefore improved the mechanical properties.

Although the best mechanical properties were obtained for the formulations with lower amounts of APC fly ash (i.e. 5% APC fly ash), economic viability for a future industrial project was also considered. To this end, the use of 10% APC fly ash seemed to be the most appropriate. Taking this into account, the most suitable formulation was 10/10 (APC fly ash %/Cement %) with the addition of MIRA 43 admixture, as it showed good results. This formulation has similar compressive strength values to those obtained using 5% APC fly ash (see Figure 3) and allows the use of twice the amount of APC fly ash. Moreover, in order to compare the addition of the two cement percentages used in this study, 10/8 formulation was also considered to assess the effectiveness of the binder in stabilization. Accordingly, apparent and relative densities (ρ_a and ρ_r respectively) as well as porosity for the hardened concrete were determined for these formulations (Table 4). As reported by Ginés et al. (2009) the apparent density increases with the amount of BA in the mixture, whilst the relative density decreases (Ginés et al., 2009). The former depends on the degree of compacting, and the latter depends on porosity. Thus, high APC fly ash contents promote the creation of pores and therefore increase relative density, with a subsequent depletion in mechanical properties.

Abrasion resistance was evaluated for the formulations with admixture added and 10% of cement as a function of the APC fly ash content (Figure 4). Values for simply weathered BA are typical for recycled aggregates (Izquierdo et al., 2002) and were considered to be the starting point at 0% APC fly ash. As can be seen, the fragmentation or abrasion resistance defined by the Los Angeles coefficient increased slightly with 5% APC fly ash in the mixture, and more markedly with 10%. This can be explained in two ways. As previously seen, the presence of APC fly ash reduced compressive strength and therefore fragmentation was likely to occur under compaction conditions. Moreover, it seems that part of the APC fly ash remained covering the aggregate's surface, preventing proper bonding with the binder; This indicates that weathered BA might be the main support for fragmentation in the light of the results for solely weathered BA. On the other hand, APC fly ash maximum particle size was around 300µm, which contributed to the fine fraction used to calculate the LA coefficient. In general, the values obtained for the formulations tested revealed certain weakness, and they do not strictly comply the Spanish specifications for road construction (<35% for crushed aggregates under relatively low traffic) (Legislación de carreteras, 1997). Nevertheless, certain structures like embankments are not subjected by such restrictions on mechanical properties and therefore the formulations studied are an excellent choice.

3.2 Leaching behaviour

The same leaching test used to characterize weathered BA and APC fly ash was applied to evaluate the environmental risk of the crushed aggregates obtained from the formulations previously tested, as well as the encapsulation effect of Portland cement on both residues, with special attention to APC fly ash. Evaluation was performed as a function of the Portland cement content (8-10%), maintaining the APC fly ash content at 10% with admixture. Results are presented in Table 5. The leachate pH of all granular samples studied was between 12.3 and 12.5. It was controlled by the solubility of the portlandite –$Ca(OH)_2$– content in the Portland cement binder and/or in the weathered BA and APC fly ash used. As can be seen, the leaching of all heavy metals decreased in the concrete mixtures below the non-hazardous threshold although the increase in cement percentage from 8% to 10% did not have any significant effect. During solidification, the immobilisation of heavy metals is believed to be caused by chemical changes like pozzolanic reactions (characteristic of cementitious materials), incorporation into a solid matrix (vitreous phases in weathered BA) or redox conditions (Sabbas et al., 2003; Todorovic et al., 2003). Special attention should be paid to those metals whose concentration values are limited by the Catalan Government for the reuse of residues (Table 2 and 5) (DOGC 2181). Again, concentrations of all heavy metals are below the limits established for the reuse of the concrete mixture as secondary building material.

Low Arsenic concentration values are as expected as they had been previously reported in other MSWI residues (Sabbas et al., 2003). The addition of an alkali binder like Portland cement did not modify the leaching behaviour of the weathered BA or APC fly ash (Table 2). There is a group of elements like Cd, Cr, Mo, Se and Sb whose concentration values in the leachates are lower than those obtained from the raw materials, weathered BA or APC fly ash. In these cases the effect of the binder reduces the mobility of these heavy metals and metalloids. Even taking into account the percentage of both MSWI residues in the final granular material, the decrease in Cr and Mo release with regard to those obtained from the APC fly ash leachate is noticeable. Some authors have shown that dissolution of some heavy metals and metalloids is controlled by the sorption of amorphous Fe/Al-(hydr)oxides and solubility of calcium bearing minerals, mainly portlandite and ettringite, –$Ca_6Al_2(SO_4)_3(OH)_{12}\cdot26H_2O$– which are actively involved in cement hydration, and their solubility equilibria is highly influenced by the neoformed phases during Portland cement setting (Cornelis et al., 2006; Meima and Comans, 1998). In what respect to Cr, cement itself contains trace amounts of this element and its speciation is dominated by the more mobile Cr (VI) rather than Cr(III) in alkaline conditions (De Windt et al., 2011; Todorovic et al., 2003). However, the results indicate that Cr solubility may be controlled by Cr_2O_3, which suggests that the reduction of Cr(VI) to Cr(III) is also involved in the hydration reaction and the setting of Portland cement.

The release of Cu from granular material shows similar results to those obtained from weathered BA, and significantly lower than the APC fly ash leachates. As other authors have suggested, the Cu leachability from freshly quenched to one year weathered bottom ash may be controlled by the complexation with dissolved organic carbon (DOC) (Åberg et al., 2006; Meima and Comans, 1998). Accordingly, the speciation of Cu contained in weathered BA does not change and only the release of Cu from APC fly ash may be affected by the solidification/stabilization process that takes place when using cement binders.

As demonstrated in a previous study, the release of Ba is related to the quantity of APC fly ash used in the concrete mixture and it seems to be controlled by the solubility of barite –$BaSO_4$–. However, during the hydration of Portland cement, sulphates are strongly involved in the formation of ettringite, thus displacing the solubility equilibrium of barite (Ginés et al., 2009).

The decrease in Zn concentration is assumed to be due to its amphoteric properties, which reduced the solubility of Zn species in a highly alkaline environment (Todorovic et al., 2003). Leaching of Pb is very important, as it is reported exceed the legal limit 20-fold when in contact with water (Quina et al., 2010). However, stables forms of $Pb(OH)_2$ and $Pb_2(OH)_3Cl$ are formed in the pH range of 13-11 and 11-9.5 respectively.

Although additional analysis concerning the leaching of soluble anions such as sulphates and chlorides should have reported more information about leachability it was not considered in this work as they are not restricted by the Catalan Legislation (DOGC 2181; DOGC 5370).

Conclusions

The utilization of a granular material made from a concrete mixture where BA and APC residues are used as aggregates is feasible. An optimum concrete formulation in which economic aspects were taken into account was obtained using 10% APC fly ash. This granular mix showed satisfactory environmental behaviour as all the heavy metal concentration values in the leachates were below the threshold established by the Catalan legislation for the revalorization of waste materials. Other APC fly ash proportions like 15% content were considered to deplete the mechanical properties excessively and 5% was not considered economically viable the process for potential use in industry. Therefore a compromise between economic and performance aspects was considered for environmental evaluation taken into account that the formulations were non-structural intended. Using 10% of APC fly ash in a concrete mixture will allow the total reutilization of the whole APC residues production per year at the facility where the samples were taken. As to mechanical properties, the optimum formulation studied showed a certain tendency to fragmentation, as the abrasion resistance (as specified by the los Angeles coefficient) was too low for use as a road sub-base material. However, this granular material can be used in certain structures like embankments where mechanical properties are not restricted. Nevertheless, in order to increase the resistance under compaction conditions, the granular material can be mixed with weathered BA in different proportions.

On the whole, from an environmental point of view, the formulations casted are suited for use as secondary building material where high mechanical properties are not mandatory and thus can be used as a granular material. However, in order to perform complete evaluation of the heavy-metal behaviour in the leachates, a percolation test in a standard column and an ongoing pilot-scale road will be studied for comparison and correct prediction of the leachates.

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Figure captions

Figure 1. Particle size distribution for BA compared with Fuller Curve.

Figure 2. Unconfined compressive strength vs APC fly ash addition for the specimens obtained without admixture. Solid line represents formulations with 10% cement while the dotted line is for an 8% cement content.

Figure 3. Unconfined compressive strength vs APC fly ash addition for the specimens obtained with admixture: 1.9% of MIRA 43 on the cement used. Solid line represents formulations with 10% cement while the dotted line is for an 8% cement content.

Figure 4. Los Angeles Coefficient (LA) as a function of % APC fly ash. Formulation 10/10, 10/8 and weathered BA without binder.

Oxides	BA (%)	APC fly ash(%)
SiO_2	47.8	6.19
CaO	15.6	38.74
Cl	n.d.	14.78
Fe_2O_3	12.2	0.75
Na_2O	6.47	6.57
Al_2O3	7.79	3.64
MgO	2.02	1.26
K_2O	1.30	5.34
CuO	0.19	-
SO_3	0.37	7.1
ZnO	0.17	1.04
TiO_2	-	0.99
P_2O_5	-	1.06
PbO	-	0.18

Table 1. Average chemical composition of MSWI natural weathered bottom ash (BA) and APC fly ash.

Element	BA	APC fly ash	Limit Values			
			Landfill[2]			Utilization[1]
			Inert	Non-Hazardous	Hazardous	
As	0.003	0.004	0.5	2	25	1
Ba	0.504	43.682	20	100	300	-
Cd	0.043	0.040	0.04	1	5	1
Cr_{total}	0.390	3.643	0.5	10	70	5[3]
Cu	0.989	4.999	2	50	100	20
Hg	<0.01	<0.01	0.01	0.2	2	0.2
Mo	0.401	2.611	0.5	10	30	-
Ni	0.060	1.290	0.4	10	40	5
Pb	0.079	138.284	0.5	10	50	5
Sb	0.460	0.040	0.06	0.7	5	-
Se	0.007	0.092	0.1	0.5	7	-
Zn	0.818	35.083	4	50	200	20

(1) Catalonian Order Number 2181/13.3.1996
(2) Catalonian Order Number 5370/30.4.2009, Decret 69/2009
(3) max. Cr(VI): 1 $mg \cdot kg^{-1}$
LOD: Limit of detection

Table 2. Trace metals concentrations in the leachates for weathered bottom ash (BA) and air pollution control (APC) fly ash using the EN 12457-2 leaching test. Results expressed in $mg \cdot kg^{-1}$.

Without admixture		
APC fly ash (%)	Cement (%)	
	10	8
	Water/Cement	
15	1.16	2.01
10	1.10	1.66
5	1.03	1.29
With admixture		
15	1.08	1.86
10	1.03	1.58
5	0.98	1.16

Table 3. Mixture proportions of APC fly ash and cement used for concrete casting in experimental trial fixing consistence. The rest of material added up to 100% was weathered BA.

	10/10	*10/8*
ρ_a *(Mg/m^3)*	*1.66*	*1.70*
ρ_r	*2.70*	*2.68*
Porosity (%)	*38.55*	*36.75*

Table 4. Apparent density (ρ_a), relative density (ρ_r) and porosity for hardened concrete.

Element	10/10	8/10	Limit Values			
			Landfill[2]			Utilization[1]
			Inert	**Non-hazardous**	**Hazardous**	
As	0.001	0.001	0.5	2	25	1
Ba	15.04	12.89	20	100	300	-
Cd	0.026	0.034	0.04	1	5	1
Cr	0.050	0.057	0.5	10	70	5[3]
Cu	0.938	1.497	2	50	100	20
Hg	<0.010	<0.010	0.01	0.2	2	0.2
Mo	0.117	0.227	0.5	10	30	-
Ni	0.170	0.115	0.4	10	40	5
Pb	2.139	1.996	0.5	10	50	5
Sb	0.079	0.114	0.06	0.7	5	-
Se	<LOD	<LOD	0.1	0.5	7	-
Zn	1.008	1.62	4	50	200	20

[1] Catalonian Order Number 2181/13.3.1996
[2] Catalonian Order Number 5370/30.4.2009, Decret 69/2009
[3] max. Cr(VI): 1 $mg \cdot kg^{-1}$
LOD: Limit of detection

Table 5. Results of the leaching test EN 12457-4 for different concrete mixtures. Results expressed in mg kg^{-1}.

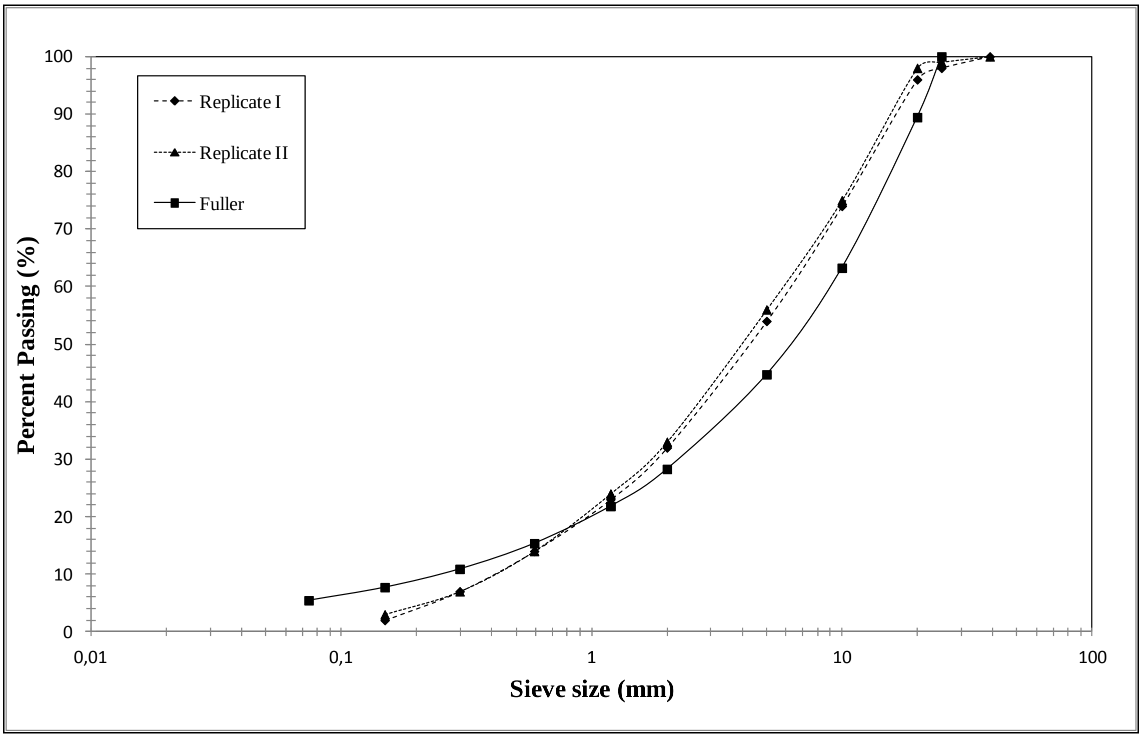

Figure 1

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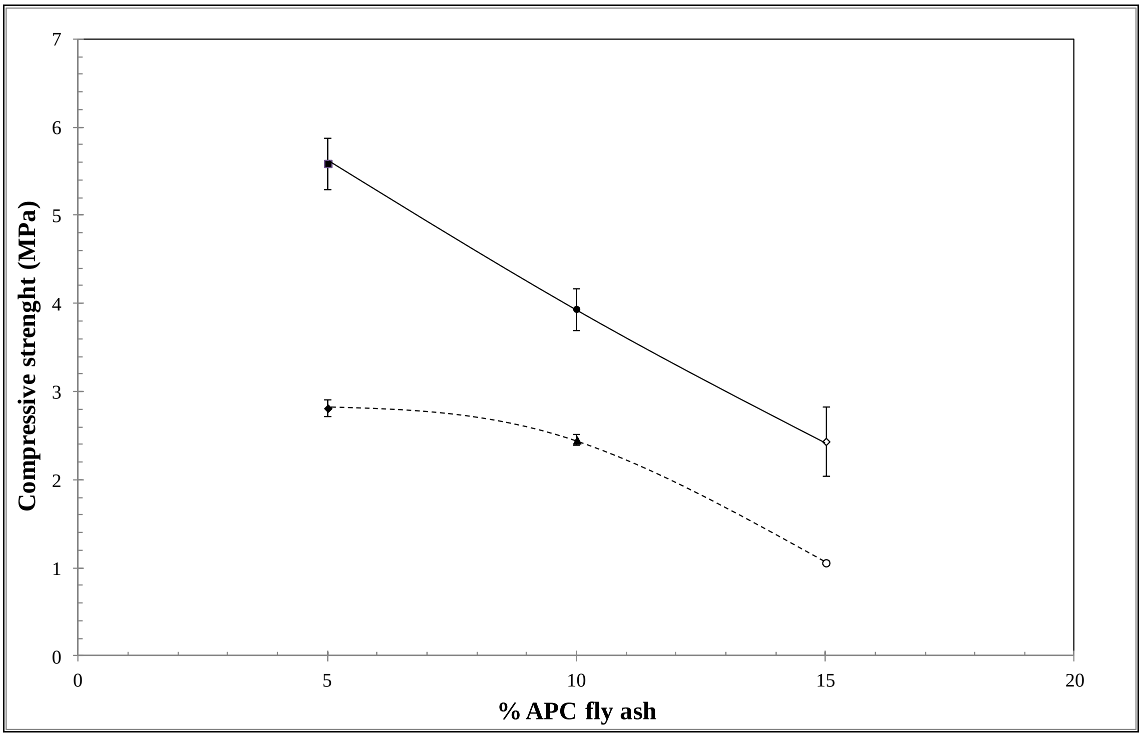

Figure 2

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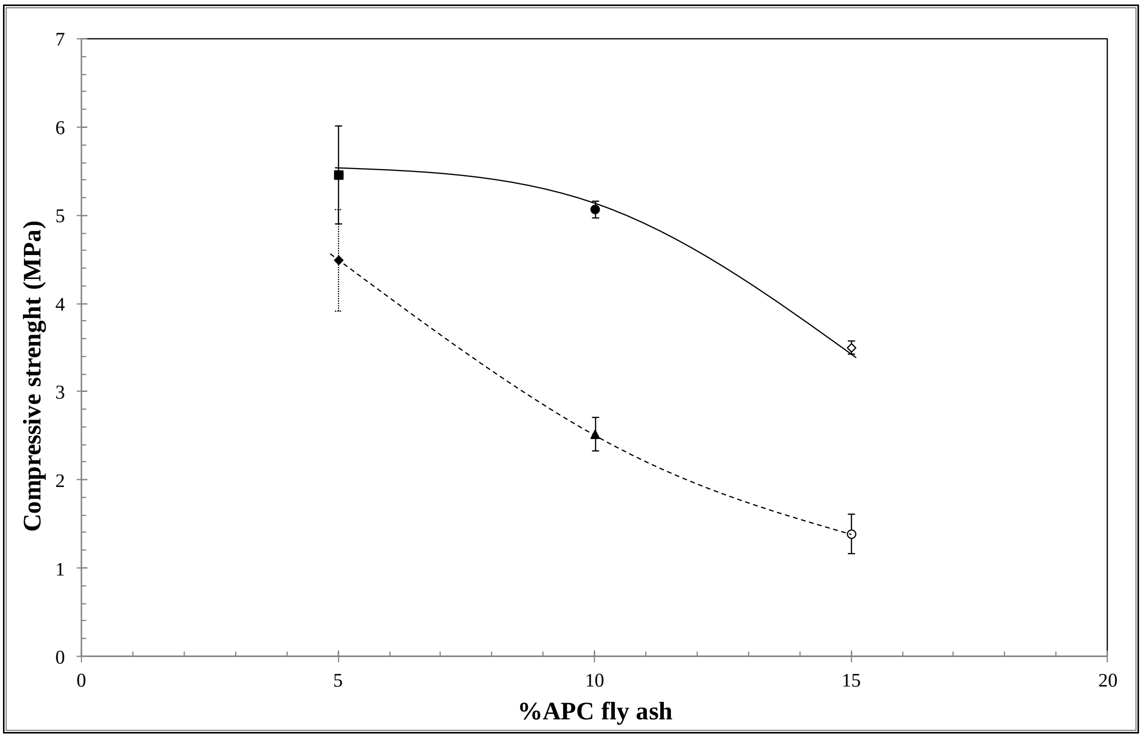

Figure 3

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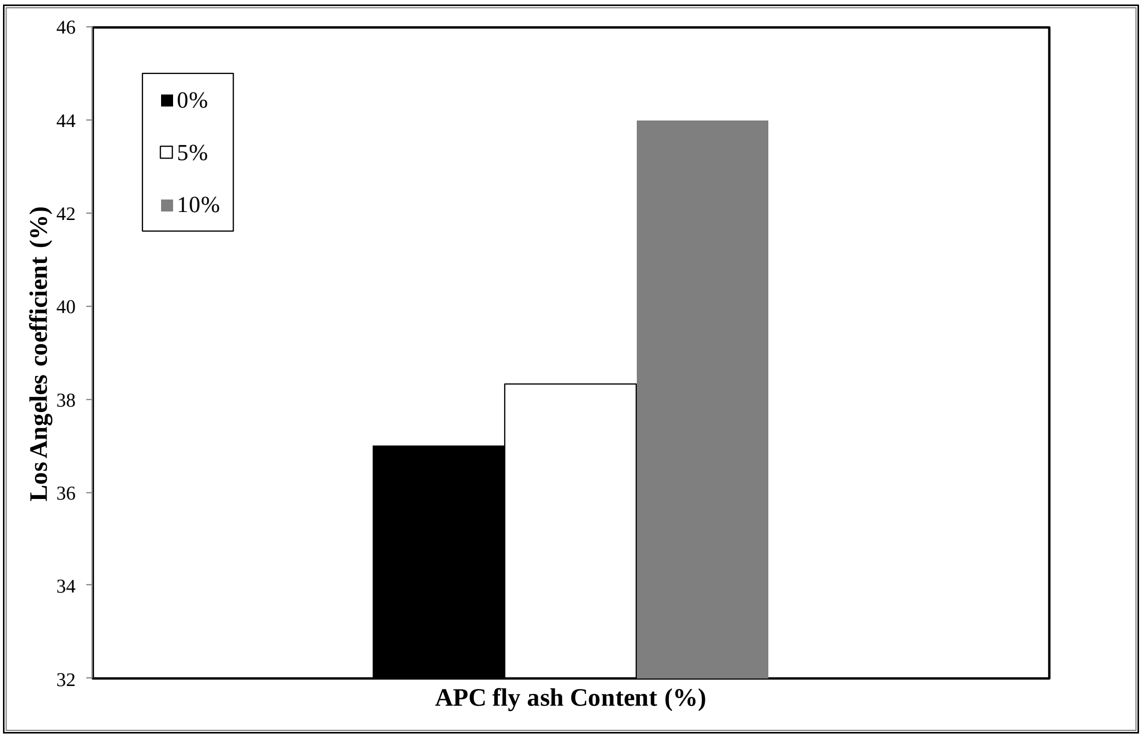

Figure 4

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