

Chemical Durability And Mechanical Properties Of Cementitious Matrices Containing Ashes Obtained After Combustion Of Waste From Moukondo Landfill In Brazzaville, Republic Of Congo.

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Abstract:

The regular burning of solid waste in the open air and on the ground is commonplace in the Republic of Congo. Burning waste produces pollutants and ashes that can be hazardous to the soil and surrounding waters. Inadequate management of the ash generated by the open burning of household waste results in site pollution, particularly heavy metal contamination (Pb, Ni, Cr, Cu, Zn...). The aim of this study is to develop cementitious matrices containing burnt ashes that are sufficiently effective to retain the heavy metals contained in these ashes in their structure. To this end, in order to assess the chemical durability of these cementitious matrices, we carried out static leaching tests at pH=4 and 7 at 25°C in distilled water on the raw ashes firstly, and then on the 24 cementitious matrices synthesized with different ash/cement/lime ratios. The mechanical durability of the cementitious matrices was assessed using flexural and compressive strength tests. The leaching results obtained demonstrated the effective immobilization of heavy metals in cementitious matrices, whose leachates contain very low levels of heavy metals compared with those of raw ash. Flexural and compressive strength tests showed an improvement in strength from 25°C to 60°C. Several cementitious matrices doped with waste ashes show flexural strengths higher than the recommended standard for flexural strength EN1339 (5 MPa) and compressive strength X31-211 (1 MPa) after 28 days curing at 60°C.

Keywords: *Heavy metals, cement, ash, leaching, stabilization, solidification, mechanical strength*

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I. Introduction

In many developing countries, solid and liquid waste management infrastructures are virtually non-existent. Population growth, the diversification of economic activities, new lifestyles and consumption patterns have led to an increase in waste deposits. As a result, we are witnessing the anarchic development of “unregulated” open-air waste landfills in many African countries, due to a lack of regulation and appropriate infrastructure. The proliferation of these unregulated dumps, which have no technical facilities, is seriously damaging to the health of the population and the environment [1]. It has been established that in Congo Brazzaville, 70% of the waste produced is biodegradable (household and similar waste) and the remaining 30% is divided between industrial and hospital waste [2]. This waste is mixed together in uncontrolled dumps. Solid waste in Congo's two main cities, Brazzaville and Pointe-Noire, comes from household refuse, craft activities, hospitals and hotels. In the Congo, solid waste is commonly burned in the open air and on the ground. Open-air burning leaves the operator with virtually no control over the combustion process. This produces pollutants and ashes that can be dangerous, and are likely to have an impact on surrounding soil and water. What's more, food that isn't fully burnt is a major magnet for wildlife.

Unregulated waste landfills are a real risk of air, soil and water pollution: landfill waste ferments and produces biogas, which is mainly rich in CH₄, a greenhouse gas that contributes to global warming [3]. Fermentation juices from these landfills seep into the ground and risk contaminating drinking water resources [4, 5]. The toxic components of this waste, such as heavy metals (mercury, chromium, lead and many others), can leach into the water table and surface waters [6]. Several alternatives can be envisaged for ash management, including solidification/stabilization. Solidification transforms the waste into a solid mass with low porosity and low permeability, thereby minimizing the possibility of dispersal into the environment [7]. Stabilization involves the physical and/or chemical retention of pollutant species in a solid matrix by absorption or ion exchange mechanisms, to make them sparingly soluble and mobilizable. The product of these two processes limits the

dispersion of pollutants in the natural environment. The immobilization of final waste by cement is the most widely used method in the world for the final treatment of hazardous waste, due to its advantages: low economic cost and ease of implementation [8]. Furthermore, all cementitious materials are porous and absorb water into their capillaries to a greater or lesser extent, even though they appear relatively watertight [9]. To check the watertightness of cement-based materials, it is customary to carry out tests to assess water absorption capacity. Determining the intrinsic mechanical characteristics of cementitious materials generally involves experimental tests carried out at laboratory level on specimens meeting standards, of relatively small sizes compared with the actual sizes of the structures in order to lead to an assessment of the behavior of the structures [10]. However, cement-immobilized waste can represent a source of pollution, as it is influenced not only by mechanical loading but also by the environment (freeze-thaw, acid rain, saline and aggressive waters...) [11]. So characterization by leaching tests is needed to predict the immobilization of this ultimate waste and the long-term chemical durability of these materials. In addition, flexural and compressive strength tests on cementitious specimens are often used to assess the mechanical durability of materials. The aim of the present study is to assess the chemical and mechanical durability of materials resulting from the stabilization/solidification by hydraulic and pozzolanic binders of waste ashes from the Moukondo public landfill in Brazzaville. This assessment is based on leaching and mechanical tests inspired by standardized tests applied to porous materials obtained by stabilizing/solidifying ashes.

II. Material And Methods

Study Site

This study was carried out in Brazzaville in Republic of Congo. Located in Central Africa in equatorial forest heart, straddling the equator between latitudes 3°30' North and 5° South and longitudes 11° and 18° East, the Republic of Congo covers an area of 342,000 km². Located on the right bank of the majestic Congo River, the agglomeration of Brazzaville covers an area of nearly 265 km². Brazzaville is located in the southern part of Congo, between 4°6'15" and 4°22'30" southern latitude and between 15°6'0" and 15°19'15" east longitude, bounded to the north by the Djiri River, to the south and east by the Congo River, and to the west by the sub-prefecture of Goma-Tsé-Tsé [12]. The wild landfill chosen for this study was named « Landfill C ». With a latitude of 4°13'13"S and a longitude of 15°15'46"E, it is located in « City of 17 » quarter in district N°7 Mfilou. It has an inclined geomorphology and an approximately depth of 20m. It has been existing for over 20 years. Figure 1 shows a map of Brazzaville city and the localisation of landfill C chosen for this study. Figure 2 shows landfill C picture. Figure 3 shows the jars containing ashes that were stored in laboratory at room temperature.



Figure 1: Map of Brazzaville city locating the wild landfill C ● Wild landfill C



Figure 2: Wild landfill C



Figure 3: Ashes obtained after burning

Landfills Waste Sampling

Household waste collection in landfill C was carried out manually using gloves as well as a mask and garbage bags. Household waste batches were then weighed using a Pocket LBS scale. Ten (10) kilos were taken and transported to a drying place at the Faculty of Sciences and Techniques of Marien Ngouabi University, within the plant chemistry and biohealth unit. Household waste was dried in the open air and at ambient temperature on plastic tablecloths of 2 m² each during two weeks. Household waste was burned in a garden incinerator for at least 1 hour. After burning, the residues obtained (ashes) were sieved using a 2 mm sieve, then ashes obtained

were placed in plastic jars closed by a stopper to avoid any external contamination. It should be noted that these jars were carefully cleaned beforehand, then rinsed with distilled water to avoid any internal contamination. The jars containing ashes that were stored in laboratory at room temperature (Figure 3).

Materials Studied

In the context of our study, the hydraulic binder that we used is Portland limestone cement from the FORSPAK Company in Dolisie in Congo. This Portland cement is of the CEM II/B-M 32.5R type. This cement is composed of (65-79) % clinker, (21-35) % pozzolan and fly ash then (0-5) % secondary constituents. Table I gives the composition by weight of the Dolisie cement used for our study. We used pascual hydrated lime as an admixture, manufactured in Spain and sold in Congo. Cementitious matrices synthesis (Figure 4) was carried out according to the formulations contained in Table II. The ash masses, hydrated cement and quicklime were weighed using a Pioneer-type precision balance. The different mixtures types (ashes + cement + lime + water) were mixed for 5 minutes in a container. The paste obtained is placed in molds to obtain cementitious matrices measuring 2 cm x 2 cm x 2 cm (Figure 5) and 4 cm x 4 cm x 16 cm (Figure 6) cm. After synthesis, the cementitious matrices were dried at ambient temperature (25°C).

Table I: Composition of cement Portland of Dolisie (% weight)

CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	NiO	PbO	Cr ₂ O ₃
64,8	17	6,5	4,6	3,3	2	1,8	/	/	/

Table II : Formulations of cementitious matrices studied

Formulation (%massique)	P0	P1	P2	P3	P4	P5	P6
Cendres	0	50	70	50	50	70	70
Ciment hydraté	100	50	30	40	30	20	10
Chaux vive CaO	0	0	0	10	20	10	20
Eau	150	250	250	270	270	270	270

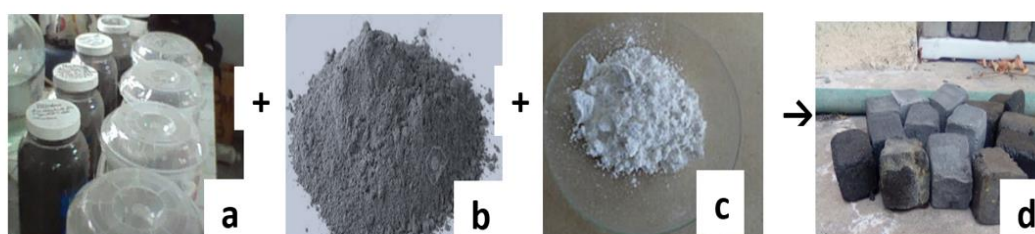


Figure 4 : Cementitious matrices synthesis *a* (ashes) + *b* (cement) + *c* (lime) → *d* (cementitious matrices)



Figure 5: Cementitious matrices measuring 2cm x 2cm x 2cm

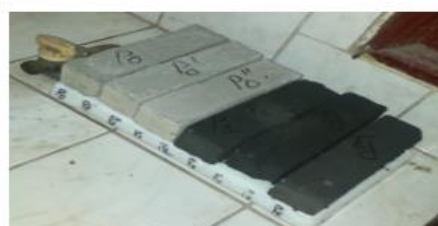


Figure 6: Cementitious matrices measuring 4cm x 4cm x 16cm

Static Leaching Tests Of Cementitious Matrices

All leaching experiments in our study were carried out in static mode on monolith in a non-agitated closed environment. It consists of placing cementitious matrices monoliths in an altering solution in a rigid glass bottle so that all sample surfaces are in contact with solution. These experiments were carried out over short times, far from saturation, to avoid external contamination of solutions. The glass bottles were cleaned before each leaching experiment with 1N hydrochloric acid, then rinsed 5 times with deionized water. After leaching, cementitious matrices samples are then removed from the leaching solution and then dried and weighed. Then, a part of leachate is taken in order to measure pH. A single temperature was chosen for our experiments: 25°C. This temperature was chosen because it avoids evaporation. The ratio surface of matrice / volume of altering solution (S/V) was fixed for the entire leaching duration at 0.1. A low S/V ratio choice makes it possible to move away from saturation conditions and thus to follow pH evolution, masses losses and dissolution rates during alteration. We have selected two (2) solutions with differents pH: a solution of distilled water at pH=7 and a slightly chloride acidic solution HCl at pH=4. The solution at pH=7 was chosen to compare with attack in a slightly corrosive medium and the slightly acidic solution at pH=4 was chosen to simulate acid rain attack. Twenty three (23) leaching times, between 0 and 180 days, were chosen in order to follow the cementitious matrices alteration kinetics.

Leachate analysis methods

The ICP-OES technique was used to analyze the overall chemical composition of leachate by dosing the major and minor the elements. These-analysis were carried out using an inductively coupled plasma optical emission spectrometer (ICP-OES) by the DIN EN ISO 11885 method at the Fresenius Institute laboratory in Germany in collaboration with the SGS-Congo laboratory in Pointe-Noire. The measuring equipment used located in laboratory is Agilent Technologies 5110 ICP-OES type.

Determination of heavy metals contents in raw ashes and cement

In order to determine heavy metal contents in ashes and cement, we carried out leaching tests according to the X31-210 Afnor standard : 5g of ash or cement was placed in contact with 50g of distilled solution (solid/liquid ratio=0.1) with continuous stirring at room temperature (25°C) for 16 hours. After 16 hours of contact, leachate is filtered through filter paper and the solid is recovered and dried in an oven at 100°C to allow residual water evaporation. The filtrate obtained was analyzed by the DIN EN ISO 11885 method at the Fresenius Institute laboratory in Germany in collaboration with the SGS-Congo laboratory using optical emission spectrometry with inductively coupled plasma (ICP-OES).

Détermination of water absorption capacity

The principle is based on placing the treated material in contact with water to determine the material's capacity to store water within the structure. Samples of (2x2x2) cm³ of the material are immersed in distilled water with a liquid/solid mass ratio of 10, for 4 weeks. Determination of the water absorption capacity (WAC)t is based on the difference in mass of the samples before and after contact with water [13]:

$$CAE_t = \frac{m_t + \sum f_i + \sum p_i - m_{os}}{m_{os}}$$

With:

mos : mass of dry starting material

mt : mass of cementitious matrix determined at time t

fi : mass of dry residue determined at each contact sequence i

pi : the dry mass of any remaining particles retained by leachate filtration.

Détermination of flexural strength

The three-point bending test provides a measure of the material's resistance to deformation under shear stress. The test consists in breaking a prismatic specimen of size (4x4x16) cm³ in flexion. This test was carried out at the B.C.B.T.P (EN 196-1 standard) using a three-point bending apparatus. After perfect centering, loading was carried out at a constant rate of load increase [14; 15]. The final value of flexural strength is given using the following formula:

$$R_f = \frac{1,5 \cdot L}{b^3} \cdot F_f$$

With:

Rf : bending strength (MPa)

b : square cross-sectional dimension of the prism (mm) Ff : load applied to the specimen (N)

L : distance between supports (mm)

Détermination of compressive strength

This test was carried out using an electromechanical device called an IGM universal press, with a compression range from 0 to 3000 kN. Specimens of our material (4x4x16) cm³ are tested in compression in accordance with NF EN 196-1 for mortar at intervals defined according to the study objectives. Each specimen is first split into 2 by the bending bench, then the 2 pieces obtained are placed on the compression bench, giving two compressive strength results. Once the specimen has reached crushing age (28 days), it is subjected to an axial force until it breaks. The applied compressive force is displayed directly on the screen of the compression machine. Next, we calculate the compressive strength, which is given by the ratio of the maximum load to the cross-sectional area of the specimen subjected to compression. This resistance is given by the following formula [15]:

$$R_c = \frac{F_c}{S}$$

With:

Rc : compressive strength

Fc : maximum breaking load in KN

S : area of plates or auxiliary plates in contact with the specimen.

III. Results And Discussion

Cementitious matrices were subjected to static leaching tests over 30, 90 and 180 days in acidic (pH=4) and neutral (pH=7) environments. Tab. III and Tab.IV give the concentrations of heavy metals released by the cementitious matrices, at pH=4 and pH=7 respectively.

Metal retention in cementitious matrices

Tables III and IV show the heavy metal contents in raw ash, raw cement and cement matrix leachates P0, P1, P2, P3, P4, P5 and P6 at pH=4 and 7 after 30, 90 and 180 days. When we compare the heavy metal content of the cementitious matrix leachates with that of the raw ash leachates, we see that the heavy metals in the cementitious matrix leachates P0, P1, P2, P3, P4, P5 and P6 have much lower concentrations than those in the raw ash leachates at all pH values and all leaching times. This clearly shows that heavy metals from waste ashes have been retained in the cementitious matrices. Furthermore, all the leachates from the cementitious formulations have leached heavy metal contents below the requirements of the standard applicable to landfill leachate discharge [16]. This demonstrates the effectiveness of the process adopted for the immobilization of heavy metals contained in ash by Portland cement. This proves that, although solidification/stabilization does not necessarily imply stabilization in the strict sense of the term of heavy metals, it does make it possible to considerably reduce their leachability by means of physico-chemical mechanisms responsible for their retention. Indeed, several physico-chemical mechanisms at the solid/liquid interface can trap heavy metals [17; 18; 19]. A metallic element retained on the surface of a material by adsorption, physisorption, complexation, precipitation, chemisorption will be more rapidly brought into solution and therefore present greater toxicity risks than if it is inserted into the cementitious network of the material [20].

Table III : Heavy metals concentrations in leachates from raw cement, raw ashes and P0, P1, P2, P3, P4, P5 and P6 cementitious matrices at pH=4 after 30, 90 and 180 days

pH=4, 30 days										
Parameters	Cement	Ashes	Standard	P0	P1	P2	P3	P4	P5	P6
As (mg/l)	0,005	0,005	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Pb (mg/l)	0,005	21,8	0,5	<0,001	<0,001	<0,001	<0,001	0,007	<0,001	0,005
Cd (mg/l)	<0,001	0,002	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Cr (mg/l)	0,35	6,5	2	0,2	0,071	0,008	0,060	0,15	0,011	0,11
Cu (mg/l)	0,005	1	0,5	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Ni (mg/l)	0,005	9	2	<0,001	<0,001	<0,001	0,008	<0,001	<0,001	<0,001
Zn (mg/l)	<0,001	1,2	2	0,009	0,009	0,009	0,009	0,009	0,009	0,009
pH=4, 90 days										
Parameters	Cement	Ashes	Standard	P0	P1	P2	P3	P4	P5	P6
As (mg/l)	0,005	0,005	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Pb (mg/l)	0,005	21,8	0,5	<0,001	<0,001	<0,001	<0,001	0,13	<0,001	0,005
Cd (mg/l)	<0,001	0,002	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Cr (mg/l)	0,35	6,5	2	0,83	0,093	0,011	0,089	0,11	0,019	0,11
Cu (mg/l)	0,005	1	0,5	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Ni (mg/l)	0,005	9	2	<0,001	<0,001	<0,001	0,008	<0,001	<0,001	<0,001
Zn (mg/l)	<0,001	1,2	2	0,009	0,009	0,009	0,009	0,009	0,009	0,009
pH=4, 180 days										
Parameters	Cement	Ashes	Standard	P0	P1	P2	P3	P4	P5	P6
As (mg/l)	0,005	0,005	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Pb (mg/l)	0,005	21,8	0,5	<0,001	<0,001	<0,001	<0,001	0,007	<0,001	0,005
Cd (mg/l)	<0,001	0,002	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Cr (mg/l)	0,35	6,5	2	0,22	0,12	0,006	0,016	0,032	0,032	0,14
Cu (mg/l)	0,005	1	0,5	<0,001	<0,001	<0,001	0,009	<0,001	<0,001	<0,001
Ni (mg/l)	0,005	9	2	<0,001	<0,001	<0,001	0,009	<0,001	<0,001	<0,001
Zn (mg/l)	<0,001	1,2	2	0,009	0,009	0,009	0,009	0,009	0,009	0,009

Table IV : Heavy metals concentrations in leachates from raw cement, raw ashes and P0, P1, P2, P3, P4, P5 and P6 cementitious matrices at pH=7 after 30, 90 and 180 days

pH=7, 30 days										
Parameters	Cement	Ashes	Standard	P0	P1	P2	P3	P4	P5	P6
As (mg/l)	0,005	0,005	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Pb (mg/l)	0,005	21,8	0,5	<0,001	0,087	0,4	<0,001	0,37	<0,001	<0,001
Cd (mg/l)	<0,001	0,002	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Cr (mg/l)	0,35	6,5	2	0,71	0,15	0,039	0,44	0,16	0,011	0,15
Cu (mg/l)	0,005	1	0,5	<0,001	<0,001	<0,001	0,009	<0,001	<0,001	<0,001
Ni (mg/l)	0,005	9	2	<0,001	0,057	0,3	<0,001	0,26	<0,001	<0,001
Zn (mg/l)	<0,001	1,2	2	0,009	0,009	0,009	0,009	0,009	0,009	0,009
pH=7, 90 days										
Parameters	Cement	Ashes	Standard	P0	P1	P2	P3	P4	P5	P6
As (mg/l)	0,005	0,005	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Pb (mg/l)	0,005	21,8	0,5	<0,001	0,01	0,81	<0,001	<0,001	0,02	<0,001
Cd (mg/l)	<0,001	0,002	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Cr (mg/l)	0,35	6,5	2	0,27	0,12	0,087	0,44	0,23	0,006	0,18
Cu (mg/l)	0,005	1	0,5	<0,001	<0,001	<0,001	<0,001	0,007	<0,001	0,009
Ni (mg/l)	0,005	9	2	<0,001	0,007	0,62	0,22	<0,001	0,022	<0,001
Zn (mg/l)	<0,001	1,2	2	0,009	0,009	0,009	0,009	0,009	0,009	0,009
pH=7, 180 days										
Parameters	Cement	Ashes	Standard	P0	P1	P2	P3	P4	P5	P6
As (mg/l)	0,005	0,005	/	<0,001	<0,001	0,047	0,057	0,007	<0,001	<0,001
Pb (mg/l)	0,005	21,8	0,5	<0,001	<0,001	0,047	0,057	0,007	<0,001	<0,001
Cd (mg/l)	<0,001	0,002	/	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Cr (mg/l)	0,35	6,5	2	0,71	0,15	0,001	0,063	0,024	<0,001	0,16
Cu (mg/l)	0,005	1	0,5	<0,001	<0,001	<0,001	<0,001	<0,001	0,005	<0,001
Ni (mg/l)	0,005	9	2	<0,001	<0,001	<0,001	0,055	0,009	<0,001	<0,001
Zn (mg/l)	<0,001	1,2	2	0,009	0,009	0,009	0,009	0,009	0,009	0,009

Water absorption capacity

Figure 7 and Figure 8 show the evolution of the water absorption capacity (WAC) of cementitious matrices dried at 25°C and 60°C, and subjected to static leaching tests for 90 days in an acid medium (pH=4). It can be seen that all curves show the same trend as a function of time, whatever the type of cementitious matrice. WAC values vary between 0% and 40% at 25°C and between 0% and 30% at 60°C. At 25°C, matrices containing ashes P1, P2, P3, P4, P5 and P6 absorb more water than the reference matrice P0. At 60°C, the opposite is true, as P0 absorbs much more water than matrices containing P1, P2, P3, P4, P5 and P6 ash. The results obtained at pH=7 shown in Figure 9 and Figure 10 are the same as those obtained at pH=4. At pH=7, we also observe that P0

is the cementitious matrix that absorbs the most water at 60°C and the least water at 25°C. In these figures, we can see an increase in water absorption capacity in all matrices at the start of leaching. This is explained by the fact that the outer pores of cementitious matrices become saturated with water through leaching [21]. The water absorption capacity then reaches a plateau, which can be explained by the fact that the inner and outer pores become saturated with water, so the cementitious matrices absorb less and less solution over time. At 25°C, the fact that matrices containing ashes P1, P2, P3, P4, P5 and P6 absorb more water than the reference matrix P0 means that they have more pores than the reference matrix P0 [22].

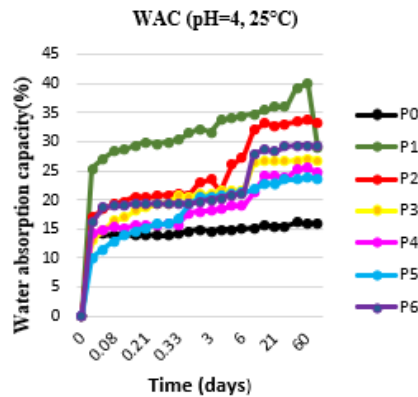


Figure 7: Variation in water absorption capacity of matrices P0, P1, P2, P3, P4, P5, P6 leached at pH=4 and dried at 25°C

At 60°C, cementitious matrices containing the ashes P1, P2, P3, P4, P5 and P6 have constricted pores due to the fact that they have been emptied of water in the presence of heat, which justifies their low water absorption capacity compared with the reference matrix P0 [22].

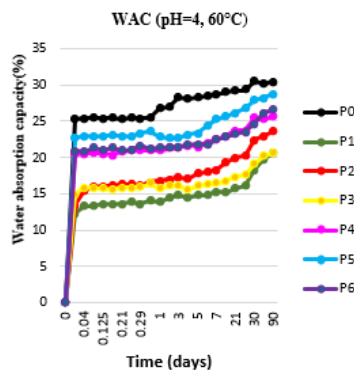


Figure 8: Variation in water absorption capacity of matrices P0, P1, P2, P3, P4, P5, P6 leached at pH=4 and dried at 60°C

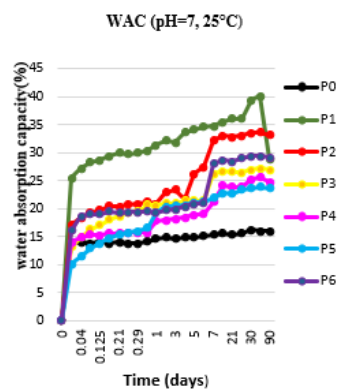


Figure 9: Variation in water absorption capacity of matrices P0, P1, P2, P3, P4, P5, P6 leached at pH=7 and dried at 25°C

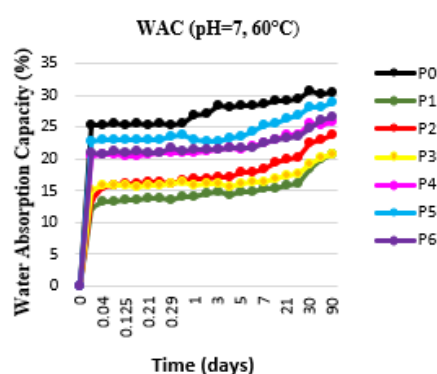


Figure 10: Variation in water absorption capacity of matrices P0, P1, P2, P3, P4, P5, P6 leached at pH=7 and dried at 60° C

Table V and Table VI show the water absorption capacities of matrices P0, P1, P2, P3, P4, P5 and P6 after 90 days of leaching at pH=4 and pH=7, then dried at room temperature of 25°C and at 60°C. For both pH levels, the transition from 25°C to 60°C revealed a significant drop in porosity for cementitious matrices P1, P2, P3 and P6. This means that some of the water is neither chemically nor physically bound to the cement and has settled in the capillary pores, from where it has partially evaporated at 60°C for cement matrices P1, P2, P3 and P6. This formation of capillary pores means that the P1, P2, P3 and P6 cementitious matrices present a mechanical weakening of the cement, as aggressive substances can easily infiltrate the cement via this capillary network, adversely affecting durability [23]. Conversely, the change from 25°C to 60°C showed a slight increase in porosity for P4 and P5, and a large increase in porosity for P0. It is possible that cracks appeared during drying at 60°C and propagated through the matrices, resulting in higher porosity [24]. However, P4 has approximately the same porosity at 25°C and 60°C.

Table V : Water absorption capacity of cementitious matrices at 25°C and 60°C leached at pH=4 for 90 days

	P0	P1	P2	P3	P4	P5	P6
WAC-25°C (%)	15	40	33	27	25	24	29
WAC-60°C (%)	30	20	22	20	26	28	26

Table VI : Water absorption capacity of cementitious matrices at 25°C and 60°C leached at pH=7 for 90 days

	P0	P1	P2	P3	P4	P5	P6
WAC-25°C (%)	15	40	34	26	25	25	30
WAC-60°C (%)	30	20	23	20	26	29	27

Mechanical flexural strength

The flexural strengths of the cementitious matrices were determined at 2 days and 28 days of curing. Figure 11 and Figure 12 show the evolution of the mechanical flexural strength of cementitious matrices as a function of drying temperatures at 25° C and 60° C. It can be seen that materials obtained after a 28-day cure have better flexural strength than those obtained after 2 days, whatever the temperature. Materials obtained after a 28-day curing period and dried at 60° C show better flexural strength than those dried at 25° C. After 2 days' curing and at 25°C, all cementitious matrices show flexural strengths below the recommended EN1339 standard (5 MPa). After 28 days of curing and at 25°C, only P0 (5.2 MPa), P3 (7.8 MPa) and P4 (5.8 MPa) show flexural strengths higher than the recommended EN1339 standard (5 MPa). After 2 days curing and at 60°C, all cementitious matrices show flexural strengths below the recommended EN1339 standard (5 MPa) except P4 (5.2 MPa). After 28 days of curing and at 60°C, only P0 (6 MPa), P2 (8 MPa), P3 (9.5 MPa), P4 (7.5 MPa) and P5 (7.5 MPa) show flexural strengths higher than the recommended EN1339 standard (5 MPa).

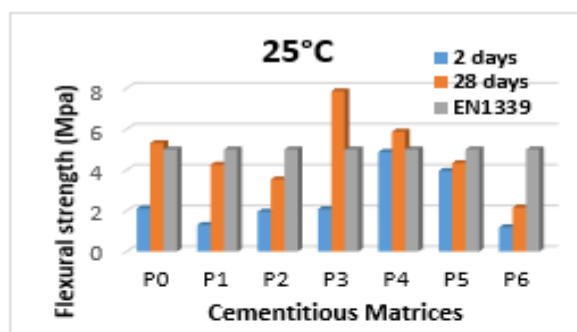


Figure 11: Variation in flexural strength of cementitious matrices P0, P1, P2, P3, P4, P5, P6 dried at 25° C for 2 and 28 days

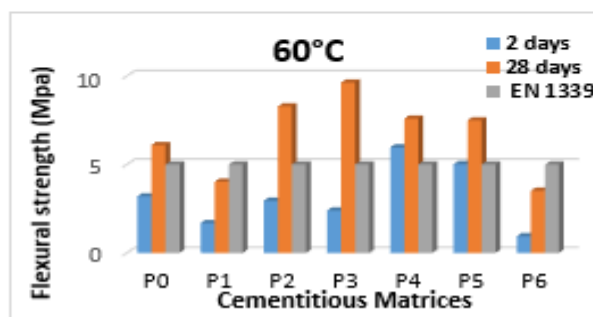


Figure 12: Variation in flexural strength of cementitious matrices P0, P1, P2, P3, P4, P5, P6 dried at 60° C for 2 and 28 days

The results of flexural strength tests indicate an improvement in the residual mechanical properties of cementitious matrices at 60°C after 28 days of curing. This is due to a change in the microstructure of the cementitious matrices brought about by water departure, which reduced porosity and permeability and thus increased flexural strength [25; 26]. Replacing part of the cement with ash and lime (P2, P3, P4 and P5) improves the flexural strength of cementitious matrices after 28 days curing and heated to 60°C compared with the reference cementitious matrix. However, flexural strength increases with the amount of cement for ash-doped matrices. Thus, the P3 cementitious matrices (50% ash, 40% cement, 10% lime) shows the best flexural strength after 28 days curing at both 25°C and 60°C. Whereas the P6 cementitious matrix (70% ash, 10% cement, 20% lime) has the lowest flexural strength after 28 days curing at both 25°C and 60°C. This drop in mechanical flexural strength is due to the excess amount of waste ash in the matrix, which prevents the formation of portlandite and C-S-H hydrated silicate, which confer greater strength to the materials [27].

Mechanical Compressive Strength

The compressive strengths of cementitious matrices were determined at 2 days and 28 days of curing. Figure 13 and Figure 14 show the evolution of the mechanical compressive strength of cementitious matrices as a function of drying temperatures at 25° C and 60° C. It can be seen that materials obtained after a 28-day cure have better flexural strength than those obtained after 2 days, whatever the temperature. Materials obtained after a 28-day curing period and dried at 60° C show a slight improvement in compressive strength compared with those dried at 25° C. It is observed that the reference cementitious matrix P0 has the highest strength (24-25 MPa) irrespective of curing time and temperature. At 2 days and 25°C, only the P0 (24 MPa), P1 (2 MPa) and P2 (2 MPa) cementitious matrices had compressive strengths in excess of the recommended AFNOR X31-211 standard (1 MPa). At 2 days and 60°C, all cementitious matrices have compressive strengths higher than the recommended AFNOR standard X31-211 (1 MPa), except P6 (0.8 MPa). At 28 days of curing, and regardless of temperature, all cementitious matrices have compressive strengths higher than the recommended AFNOR standard X31-211 (1 MPa). This improvement in mechanical compressive strength may be due to the departure of water from the material, which increases the forces of attraction by bringing the CSH sheets closer together [28].

In contrast to flexural strength, the replacement of part of the cement by ash and lime (P1, P2, P3, P4, P5 and P6) leads to a collapse in the compressive strength of waste ash-doped matrices compared to the reference matrix P0. This can be explained by a change in the cement structure that weakens the bonds of the hydrated C-S-H silicates [29]. It should be noted, however, that the compressive strength values of cementitious matrices

doped with waste ash remain well above the recommended AFNOR X31-211 standard (1 MPa) for all at 28 days curing regardless of temperature.

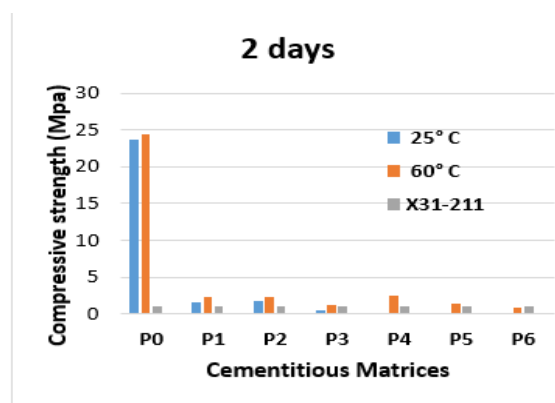


Figure 13: Variation de la résistance à la compression des matrices P0, P1, P2, P3, P4, P5, P6 séchées à 25°C et 60°C pendant 2 jours

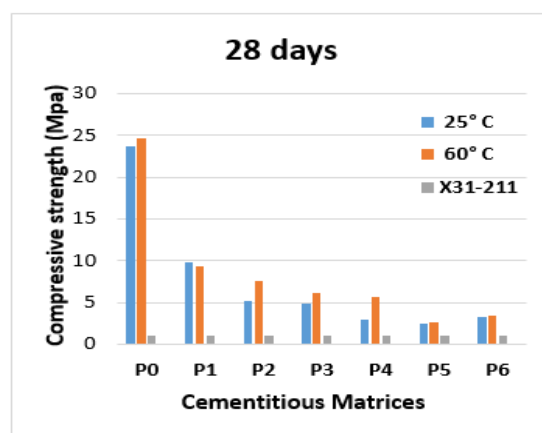


Figure 14: Variation de la résistance à la compression des matrices P0, P1, P2, P3, P4, P5, P6 séchées à 25°C et 60°C pendant 28 jours

IV. Conclusion

In this study, we developed a process for the production of cementitious matrices containing ash from the burning of household waste at 2 and 28 days of curing at temperatures of 25°C and 60°C. Static leaching tests were carried out on these cementitious matrices at room temperature, in acidic and neutral media at different leaching times, as well as mechanical flexural and compressive strength tests. The results of this study highlighted the good chemical durability provided by the stabilization/solidification of ash in cementitious matrices. In fact, all the leachates from the P0, P1, P2, P3, P4, P5 and P6 cementitious matrices had heavy metal contents well below the standard applicable to leachate discharge. Experimental results showed better mechanical strength results for the matrices after 28 days curing. For flexural strength, the results showed that the behavior of cementitious matrices is strongly modified by the rise in temperature from 25°C to 60°C, and that flexural strength increases with the quantity of cement for ash-doped matrices. Cementitious matrices P0, P2, P3, P4 and P5 show flexural strengths higher than the recommended EN1339 standard (5 MPa) after 28 days curing at 60°C. With regard to compressive strength, the replacement of part of the cement by ash results in a collapse in the compressive strength of matrices doped with waste ash compared with the P0 reference matrix. The P0 reference matrix (100% cement) thus has the highest compressive strength, but the compressive strength values of waste ash-doped cementitious matrices remain well above the recommended AFNOR X31-211 standard (1 MPa) after 28 days curing at all temperatures. Of all the cementitious matrices doped with waste ash, P3 (50% ash, 40% cement, 10% lime) offers both good chemical durability and good mechanical strength.

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Competing Interests

Authors have declared that no competing interests.

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