

WASTE STABILIZATION/SOLIDIFICATION (S/S) USING FLY ASH-BASED GEOPOLYMERS. INFLUENCE OF CARBONATION ON THE S/S OF AN EAF DUST

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Abstract

The effect of the curing in a carbonated ambient of the solids obtained after the stabilization/solidification (S/S) of metallurgical waste using geopolymerization technology is described in this paper. The electric arc furnace (EAF) dust used to stabilize contains hazardous metals such as Pb, Cd, Cr or Zn. Different geopolymeric agents as potassium hydroxide, potassium silicate, metakaolin and blast furnace slag have been used. Mixtures of EAF waste with these kinds of geopolymeric materials and class F fly ash have been processed. Samples were submitted to an accelerated carbonation test. Compressive strength tests and different leaching tests for determining the efficiency of heavy metal immobilisation have been carried out. Comparison of fly ash-based geopolymer systems with classical Portland cement (OPC) stabilization methods has also been accomplished. Compressive strength values far better than those achieved by hydraulic S/S methods were easily obtained by geopolymer solids at 28 days. Carbonation produced a great increment of compressive strength in samples containing a higher K₂O proportion. Regarding leachability, the geopolymer S/S solids also manifested better behaviour in general, showing very promising results. Carbonation effects on pH and on Zn and Pb leachabilities are more marked for OPC than for geopolymer S/S solids.

1. Introduction

EAF dust is generally classified as hazardous waste by many regulations because of its heavy metal content. Stabilization/solidification (S/S) technique has been used worldwide to treat this and other similar residues. Although EAF dust constitutes a waste product that is difficult to stabilize, the use of different S/S systems containing Type F coal fly ash, lime, dolomitic lime, Type I Portland cement, lime, blast furnace

slag, silica fume, sodium silicate, low-grade MgO or combinations of them may be found in the literature¹⁻⁵.

Geopolymer technology has recently received attention in waste stabilization/solidification (S/S) systems of heavy metal containing wastes. In the immobilization of toxic metals geopolymer systems function similarly to cement binders in terms of encapsulation. They have, however, improved chemical and physical properties, such as structural integrity, low permeability, high compressive strength and durability⁶⁻⁸. Some authors have studied the potential use of geopolymer systems as S/S agents of an EAF dust, waste that presents a challenge for both recovery, as many elements are difficult to separate, or disposal, because many of the elements are hazardous^{9, 10}. In a previous paper of the authors of this article¹⁰, cured conditions have been studied in order to establish better conditions in a landfill. In general, the best results for 28 days-cured S/S solids were obtained when samples were cured at room temperature. But, it is necessary to study the evolution with time of properties such as compressive strength or leachability, when the S/S solids are landfilled. In the long term many processes that could affect the S/S solid properties such as the carbonation are produced.

Much research relating to carbonation has been performed on cementitious forms. Carbonation occurs when Portlandite and other calcium bearing phases in the waste form react with CO₂ to form calcite (CaCO₃). It has been reported that carbonation may directly alter the chemical and physical properties of solidified waste forms¹¹, but contradictory results regarding metal leachability have been published. According to Lange et al.^{12, 13}, the effects of carbonation appear to be beneficial on the leachate production of cement-solidified hazardous wastes, showing a significant reduction in leachable metals extracted. However, other studies show that carbonation produces the opposite effect. Thus, in a study carried out to evaluate the role of carbon dioxide on the long-term performance of cementitious waste forms, carbonation increased the release of Cd, Pb, and Co¹⁴. In another paper concerning the S/S of municipal solid waste incineration residues, the pastes were exposed to an accelerated carbonation procedure. In contrast with other studies, the authors mention that the carbonation process increased the leachability of heavy metals such as Zn and Cr¹⁵. In this paper and to the best of our knowledge, a carbonation accelerated process has been carried out for the first time in fly ash based geopolymer S/S solids, with the aim of studying its influence in mechanical and leaching properties.

2. Experimental

2.1. Materials

Low calcium fly ash (ASTM class F) from the combustion of high quality pulverized coal in one of the biggest coal power plants in the south of Spain, Los Barrios (550 MW) was used as the main silicoaluminate agent. Blast furnace slag (BFS) as a lime and silicon source and kaolinite as a secondary silicoaluminate source were also used. Ordinary Portland Cement (OPC, type II) was used in order to compare

geopolymer stabilization/solidification (S/S) process with conventional S/S process. The main elements of the four S/S agents are detailed in Table 1.

Table 1.

Main elements of Fly ash (FA), Kaolinite, Slag (BFS), OPC and Electric arc furnace (EAF)

	Moisture 105 °C	LOI 750 °C	Main Elements (wt %)						
			Fe ₂ O ₃	CaO	MgO	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O
FA	0.05	3.32	5.86	3.94	1.84	63.91	21.51	0.68	1.67
Kaolinite	1.16	12.17	0.51	<0.03	0.17	65.23	31.97	0.05	1.28
BFS	0.24	0.31	0.41	43.49	7.6	41.08	10.7	0.26	0.32
OPC	0.15	-	2.15	61.7	2.76	21.2	5	0.13	0.16
EAF	0.42	12.77	36.32	8.60	3.05	6.21	2.00	1.13	0.48

The potassium silicate solution used to prepare the samples was named KSil 0,65 (K₂O/SiO₂ weight ratio = 0.649), and was supplied by Industrias Químicas del Ebro (Zaragoza, Spain). The product specifications are listed in Table 2.

Table 2.

Specifications of potassium silicate solutions

	SiO ₂ , wt %	K ₂ O, wt %	Density 25 °C, g·cm ⁻³
KSil 0,65	23	14.9	1.38
KSil 0,46	23.1	10.6	1.31

The main elements content of EAF dust is shown in Table 1 and the heavy metals content of the waste is shown in Table 3.

Table 3.

Heavy metal content in Electric Arc Furnace (EAF) dust

	Metal content g·kg ⁻¹			
	Zn	Cd	Cr	Pb
EAF	342.9	0.29	2.108	2.29

2.2. Preparation of S/S solids

Three kinds of geopolymer samples were prepared maintaining constant the fly ash and EAF dust proportions and adding potassium silicate, KOH, BFS and metakaolin (MK) using the same methodology of previous studies¹⁶. These three compositions were chosen by their good physical and chemical properties obtained in previous investigations¹⁷: KSil 0.8 BFS 0.3, KSil 0.8 KOH BFS 0.3 and KSil 0.8 MK 0.3. Distilled water was used throughout. The water content was adjusted to achieve the

same workability in all the mixtures. With the mass obtained, cylindrical plastic moulds (30 mm diameter and 41 mm height) were filled and compacted. Finally, samples were vibrated for 5 minutes in order to release bubbles. On the other hand, hydraulic binders such as, ordinary Portland cement (OPC) and lime have also been used in order to compare geopolymer S/S solids with conventional S/S solids. Compositions of geopolymeric matrices are shown in Table 4. Compositions of hydraulic binder matrices are shown in Table 5.

Table 4.

Composition of S/S matrices using geopolymers

		(wt %)							
		EAf	FA	KSil	KOH	MK	BFS	MS	Water
KSil (0,65)	0.8 BFS 0.3	0.5	1.4	0.8			0.3		0.308
KSil (0,65)	0.8 KOH BFS 0.3	0.5	1.4	0.8	0.42		0.3		0
KSil (0,65)	0.8 MK 0.3	0.5	1.4	0.8		0.22			0.3

Table 5.

Composition of S/S matrices using hydraulic binders

		(wt %)			
		EAf	FA	CaO	OPC
OPC CaO		1	1.4	0.2	0.2

2.3. Carbonation test

Seven days after the preparation, the samples were demoulded and placed in a plastic tray, and then were introduced into a thermally sealed impermeable plastic bag. CO₂ was introduced into the bag through a valve connected to a CO₂ bottle. A vacuum pump was used to release air from the bag while CO₂ entered the bag using another valve. A moist ambient is necessary to promote the carbonation reaction, so trays were filled with 40 mL of water to maintain constant the ambient moisture content during the process. The CO₂ content was maintained constant during the process at a 99 % by volume approximately. A general view is shown in Figure 1.

The effect of the carbonation exposing time has been studied by removing samples from two different bags at 28 or 84 days. Three monolith samples of each composition have been used. When the time ended, monoliths were taken out of the bag and were subjected to the compressive strength test and different leaching tests.

2.4. Compressive strength

Compressive strength test was performed as per ASTM D-1633-84 using two cylinders of each sample and averaging the experimental values obtained. All

samples were tested after 28 days. A Suzpecar, MEM-102 / 50 t, compressive strength testing apparatus was used.

2.5. Leaching tests

The stabilization/solidification efficacy was assessed from the chemical point of view using four leaching tests: UNE-EN 12457¹⁸, USEPA TCLP¹⁹, NEN 7341²⁰ and NEN 7345 test²¹. The US Environmental Protection Agency (EPA) TCLP (Toxicity Characteristic Leaching Procedure) Method No. 1311 test consists of stirring the granular material (< 9 mm), using an acetic acid solution at pH = 2.88 ± 0.02 or an acetic acid plus NaOH solution at pH = 4.93 ± 0.02 with a liquid/solid ratio (L/S) of 20 for 18 h. The UNE-EN 12457-4 is an extraction method similar to the TCLP, but the extraction fluid is distilled water, in a liquid to solid ratio of 10 for 24 h. The availability test described in NEN 7341 is aimed to indicate the maximum amount of contaminant which can be leached from the material under extreme conditions, in other words, the fraction of the total contaminant potentially available for leaching. The test is performed on finely ground material (< 125 µm) at a high dilution (L/S = 100) by controlling the pH at 7 for 3 hours and subsequently at pH 4 for another 3 hours using 1M HNO₃. The NEN 7345 test (tank leaching test) is a monolith-type leaching test that can be used to assess the leaching potential of stabilized/solidified wastes over the long term. The leaching agent is distilled water acidified at pH 4 with nitric acid. The liquid to solid ratio is between 2 and 5 and the extraction fluid is renewed in 8 extractions at 0.25, 1, 2.25, 4, 9, 16, 36 and 64 days from the test start. After each stage, pH and conductivity is determined in the leachates.

After the tests, samples were filtered through Whatman membrane filters (pore size 0.45 µm). When the procedures were completed, the metal contents in the solution were determined using Atomic Absorption Spectrometry.

The aim of S/S technology is to obtain solids that reduce the overall environmental impact of waste disposal. To achieve this goal, the USEPA criteria, the landfill leachate regulations (European Landfill Directive, EULFD)²² and the Dutch Building Materials Decree (DBMD)²³ were followed to establish quality criteria on metal concentrations limits in leachate from S/S solids after the usual curing time (28 days). The quality criteria applied to the metal leachate concentrations are shown in Table 6.

Table 6.
Quality criteria

Parameter	Range/Value			
pH	2 – 12.5			
USEPA metal concentrations in TCLP leachate (mg·L ⁻¹)	Cd 0.5	Cr total 5	Pb 5	Zn 300
Inert Waste (mg·kg ⁻¹)				
EULFD	0.04	0.5	0.5	4
Non Hazardous Waste	1	10	10	50

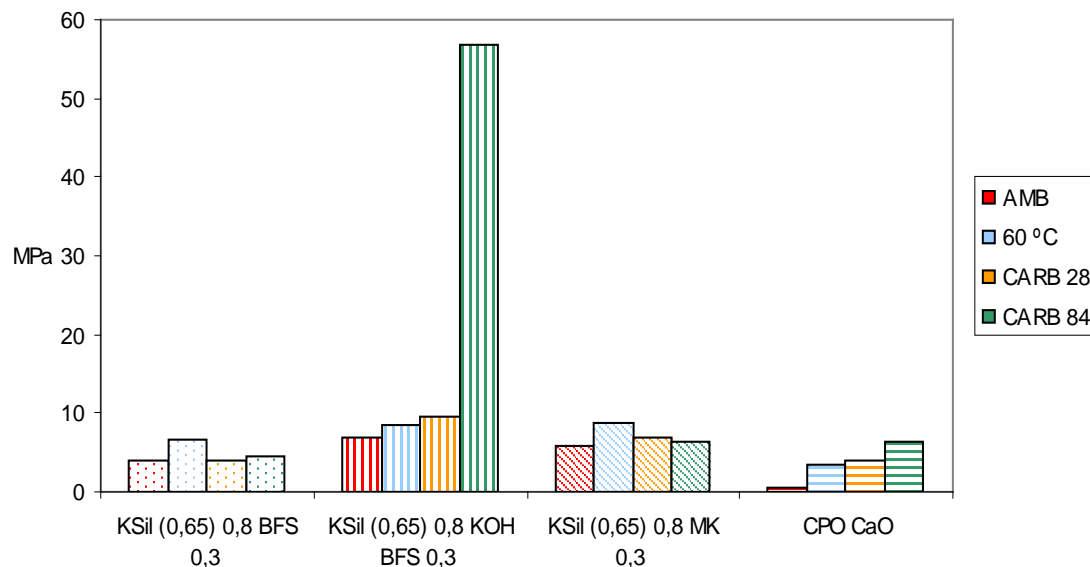
(mg·kg ⁻¹) EULFD Hazardous Waste (mg·kg ⁻¹) EULFD	5	70	50	200
U1 (mg·m ⁻²) DBMD	1	150	100	200

3. Results and discussion

3.1. Compressive strength (CS)

Figure 1 shows the influence of carbonation on the CS measurements carried out in the samples studied.

Figure 1.
Compressive strength at 28 days.



As can be seen in Figure 1, the variations of the compressive strength of carbonated samples cannot be explained easily, since samples with KSil+slag (BFS)+KOH and OPC samples showed the highest values in carbonated conditions, while KSil+metakaolin+KOH samples, showed the highest resistances at high temperatures and carbonation slightly worsens the CS. Samples with KSil and BFS showed a different behaviour, since carbonation time improved the CS. Therefore, it is difficult to find a tendency or regularity to explain this behaviour.

The high CS of KSil (0,65) 0,8 KOH BFS 0,3 at 84 days of carbonation can be emphasized. This fact could be due to some crystal formation since all samples appear covered with a white layer similar to the crystals formed by the oversaturation of an inorganic salt solution (NaCl, K₂CO₃...).

Besides, all the samples kept in the carbonation chamber (bag) showed a water layer on their surface. This phenomenon was probably produced in the course of the CO₂ filling process, when the expanding process from CO₂ (l) to CO₂ (g), led to a

temperature reduction (Joule-Thomson effect) that caused the water condensation on the samples as the atmosphere in the bag was moisture saturated. So, carbonation samples had higher water content than samples cured at ambient or at 60 °C. To conclude, it is possible that the high quantity of moisture in carbonated samples has counteracted the CS increment potentially produced by the carbonation process. To avoid this phenomenon, a CO₂ expanding chamber to heat the gas to be used in the carbonation chamber could be an option.

3.2. Leaching tests

3.2.1. UNE-EN 12457-4 leaching test

Table 7 shows the pH and Zn, Pb, Cr and Cd concentrations of the EN 12457-4 leachates.

Table 7.

pH and metal concentrations in UNE-EN 12457-4 leachates at 28 days and EULFD limits

	pH	Metal concentration (mg·kg ⁻¹)			
		Zn	Pb	Cr	Cd
KSil (0,65) 0.8 BFS 0.3 AMB	11.43	0.9	<2	3.6	≤0.2
KSil (0,65) 0.8 BFS 0.3 60 °C	11.23	5.7	8	6.5	≤0.2
KSil (0,65) 0.8 BFS 0.3 CARB 28	9.57	0.8	5.4	≤0.5	≤0.2
KSil (0,65) 0.8 BFS 0.3 CARB 84	9.85	1.3	3.7	1	≤0.2
KSil (0,65) 0.8 KOH BFS 0.3 AMB	12.68	17.5	17	8	≤0.2
KSil (0,65)0.8 KOH BFS 0.3 60 °C	12.8	41.2	16.1	6.4	≤0.2
KSil (0,65) 0.8 KOH BFS 0.3 CARB 28	10.73	0.7	15.2	1.6	0.2
KSil (0,65) 0.8 KOH BFS 0.3 CARB 84	10.37	4.1	48	2.9	≤0.2
KSil (0,65) 0.8 MK 0.3 AMB	10.9	1.4	2.1	15.2	≤0.2
KSil (0,65) 0.8 MK 0.3 60 °C	11	5.5	8	8.3	0.2
KSil (0,65) 0.8 MK 0.3 CARB 28	9.41	1.2	8.6	2.1	≤0.2
KSil (0,65) 0.8 MK 0.3 CARB 84	9.53	3.5	7.6	1	≤0.2
OPC CaO AMB	12.21	12.6	3760	≤0.5	≤0.2
OPC CaO 60 °C	12.17	14.7	950	2	≤0.2
OPC CaO CARB 28	8.36	2.3	2.2	2.2	≤0.2
OPC CaO CARB 84	8.55	5.7	<2	1.2	≤0.2
Inert waste		4	0,5	0,5	0,04
Non hazardous waste		50	10	10	1
Hazardous waste		200	50	70	5

Both for OPC and lime and for geopolymer systems, the pH values in EN 12457-4 leachates at 28 days were between 11 and 13. Carbonation lowers the leachate pHs

considerably to 8.4-9.6, values improving the leaching behaviour of all samples, especially the OPC samples.

In general, the lowest leached amounts for the metals studied were obtained for EAF stabilized with geopolymeric activators. Large amounts of Pb (and Cr in some instances) were leached from samples prepared with OPC and lime, probably because of a high leachate pH (12.2-12.3). But apart from this, there must be another phenomenon that releases Pb because the pH differences with KSil (0,65) 0.8 BFS 0.3 are not so high. Therefore, the low Pb leachabilities found in geopolymer samples at the same (high) pHs evidence a higher degree of Pb immobilization in geopolymer matrices and must be emphasized.

The lowest leached amounts were found for samples prepared with KSil 0,65 and slag at room temperature. In general, lower S/S solid leachabilities are observed at room temperature instead of 60°C, except for Cr that almost always has lower concentrations in the 60°C-cured samples.

Regarding the carbonation time, pH slightly increased with time, except for KSil (0,65) 0.8 KOH BFS 0.3 which showed the lower pH at 84 days. Besides, in this case, lead concentration increased with the carbonation time from 15.2 at 28 days to 48 mg/kg after 84 days of carbonation, probably as a consequence of the lower pH. Zn leachability increases slightly with the carbonation time in all the samples.

3.2.2. TCLP leaching test

Table 8 shows the pH and the metals concentrations in the TCLP leachates.

Table 8.
pH and metal concentrations in TCLP leachates at 28 days and USEPA limits

	pH	Metal concentration (mg·L ⁻¹)			
		Zn	Pb	Cr	Cd
KSil (0,65) 0.8 BFS 0.3 AMB	6.5	362	4.15	<0.05	1.22
KSil (0,65) 0.8 BFS 0.3 60 °C	6.27	553	14.6	<0.05	1.63
KSil (0,65) 0.8 BFS 0.3 CARB 28	6.36	417	2.99	<0.05	1.41
KSil (0,65) 0.8 BFS 0.3 CARB 84	6.42	426	0.15	≤0.05	1.21
KSil (0,65) 0.8 KOH BFS 0.3 AMB	8.49	137	<0.2	<0.05	0.03
KSil (0,65) 0.8 KOH BFS 0.3 60 °C	5.84	105	0.99	<0.05	0.22
KSil (0,65) 0.8 KOH BFS 0.3 CARB 28	7.25	135	0.29	<0.05	0.56
KSil (0,65) 0.8 KOH BFS 0.3 CARB 84	7.11	18	0.14	0.07	0.54
KSil (0,65) 0.8 MK 0.3 AMB	2.94	1544	3.38	2.24	4.51
KSil (0,65) 0.8 MK 0.3 60 °C	3.07	1640	3.69	2	4.58
KSil (0,65) 0.8 MK 0.3 CARB 28	6.79	804	7.61	<0.05	2.44
KSil (0,65) 0.8 MK 0.3 CARB 84	6.3	782	4.21	≤0.05	2.04
OPC CaO AMB	10.97	0.05	0.9	0.31	<0.2
OPC CaO 60 °C	11.24	0.09	0.3	0.48	<0.2
OPC CaO CARB 28	6.5	415	1.47	0.06	1.6
OPC CaO CARB 84	6.72	364	0.43	≤0.05	1.74

After 28 days of curing at room temperature and at 60 °C, the leachates of all the samples prepared with OPC and lime were alkaline, with pH values around 11. However, samples prepared with geopolymeric activators showed a neutral or slightly acidic pH. With respect to the carbonation process a clear neutralization effect can be observed, especially for OPC samples that showed a pH drop from 11 to 6.6. However, in KSil (0,65) 0.8 MK 0.3 samples, a pH increment is produced due to the low pH of samples at ambient and 60 °C (2.94 and 3.07, respectively) possibly caused by some contamination. For the rest of samples, no significant differences exist in pH with the curing conditions.

In OPC samples carbonation reduces pH and consequently Zn, Pb and Cd leachabilities worsen. For samples prepared with geopolymer agents, in general carbonation improves Zn, Pb and Cd leachabilities. Carbonation time also produces a decrease in metal concentrations. The best values are obtained for KSil (0,65) 0.8 KOH BFS 0.3 samples independently of the curing condition.

3.2.3. NEN 7341 leaching test

The calculated leached fractions, that is, the percentage ratio between the measured leached metal concentration and the total concentration of the same metal in EAF dust for samples cured at room temperature, at 60 °C and in a carbonated atmosphere are depicted in Table 9.

Table 9.

Leached fractions in availability test leachates (NEN 7341)

	Leached fraction (%)			
	Zn	Pb	Cr	Cd
KSil (0,65) 0.8 BFS 0.3 AMB	7.89	10.2	0.25	24.4
KSil (0,65) 0.8 BFS 0.3 60 °C	8.56	18.78	0.25	25
KSil (0,65) 0.8 BFS 0.3 CARB 28	6.85	1.03	0.28	23.1
KSil (0,65) 0.8 KOH BFS 0.3 AMB	0.47	0.98	0.59	5.8
KSil (0,65) 0.8 KOH BFS 0.3 60 °C	1.3	0.94	0.26	4.8
KSil (0,65) 0.8 KOH BFS 0.3 CARB 28	0.16	1	0.27	5.1
KSil (0,65) 0.8 MK 0.3 AMB	7.11	0.91	0.74	28.4
KSil (0,65) 0.8 MK 0.3 60 °C	8.94	0.9	0.39	35.1
KSil (0,65) 0.8 MK 0.3 CARB 28	6.86	1.01	0.27	32.3
OPC CaO AMB	9.79	100	0.25	43.7

OPC CaO 60 °C	15.46	100	0.25	64.1
OPC CaO CARB 28	13.73	37.47	0.27	53.7

Low extraction percentages were found for Zn and Cr, so these two metals were quite well immobilized in almost all mixtures. Practically, almost 100 % of Cr is immobilized using both geopolymeric and hydraulic binders. Conversely, Pb and Cd showed the highest availabilities in all samples, being always better immobilized using geopolymeric agents (KSil (0,65) 0.8 KOH BFS 0.3). Samples stabilized by hydraulic binders cured at ambient temperature and at 60 °C produced a Pb leached fraction of nearly 100 %. Carbonation in OPC samples reduced the lead leachability considerably (leached fractions from 100 to 37.5 %) as well as KSil (0,65) 0.8 BFS 0.3 samples (from 18.8 to 1 %). Carbonation led to a pH reduction, and therefore, in general, metal retention is increased.

3.2.4. NEN 7345 leaching test

The leachate pH remained constant throughout the test time in all the (sub)-samples. In all the cases carbonation reduced the leachate pH. In OPC samples the carbonation produced pH drops of around 4 units while in geopolymeric samples the pH dropped 1.5-2 units.

Conversely, the leachate conductivity dropped with time in all the (sub)-samples. Carbonation reduces leachate conductivity for KSil+ KOH+BFS and OPC samples, but in the other cases there are no relevant differences between carbonated and non carbonated samples.

Table 10 shows the cumulative concentrations at 64 days of tank leaching test leachates.

Table 10.

Results of the NEN 7345 tank leaching test in S/S solids at 64 days and U1 limits according to Dutch Building Materials Decree (DBMD)

	Cumulative concentration (mg·m ⁻²)			
	Zn	Pb	Cr	Cd
KSil (0,65) 0.8 BFS 0.3 AMB	11.54	36.92	33	<3.69
KSil (0,65) 0.8 BFS 0.3 60 °C	18.27	39.94	55.87	<3.4
KSil (0,65) 0.8 BFS 0.3 CARB 28	34.04	73.6	10.17	<3.54
KSil (0,65) 0.8 BFS 0.3 CARB 64	45.81	72.15	8.85	<3.54
KSil (0,65) 0.8 KOH BFS 0.3 60 °C	49.5	82.54	72.87	<3.77
KSil (0,65) 0.8 KOH BFS 0.3 CARB 28	37.21	39.02	11.28	<3.61
KSil (0,65) 0.8 KOH BFS 0.3 CARB 64	56.22	98.08	9.03	<3.28
KSil (0,65) 0.8 MK 0.3 AMB	49.85	73.26	143	<3.47
KSil (0,65) 0.8 MK 0.3 60 °C	26.32	41.94	70.39	<3.42
KSil (0,65) 0.8 MK 0.3 CARB 28	74.99	143.27	30.56	<3.47

KSil (0,65) 0.8 MK 0.3 CARB 64	48.08	183.7	8.22	<3.29
OPC CaO AMB	109	15503	8.98	<3.59
OPC CaO 60 °C	85.18	3970	17.35	<3.56
OPC CaO CARB 28	122	33.46	38.91	<3.5
OPC CaO CARB 84	245	38.91	14.4	<4.72
DBMD U ₁	200	100	150	1

When non carbonated geopolymer and OPC S/S solids are compared, in general the leaching benefit of geopolymeric techniques is clear, especially for Pb and Zn, while Cr concentrations are lower using conventional methods. Cd concentrations are under the detection limits in all samples, so it is impossible to draw any conclusion. Carbonation reduces pH. This reduction makes the Zn and Pb retention of KSil BFS samples and KSil MK samples worsen. Besides, Zn is increased in OPC samples. However, the pH drop produced a Pb concentration reduction in OPC samples, improving its leachability. Regarding Cr, carbonation caused a clear reduction of the metal concentration for geopolymeric samples, but the effect in OPC samples is the opposite.

All non carbonated samples showed leachate concentrations for Zn, Cr and Pb under the DBMD U1 limits, except OPC samples in the case of Pb. In relation to Cd concentrations, the high Cd detection limit, does not strictly allow the drawing of any conclusions on the accomplishment of the U1 limit, as commented before. Carbonation increases the Pb release of KSil MK samples.

4. Conclusions

Although the variations of the compressive strength of carbonated samples cannot be explained easily, it is clear that this mechanical property is slightly better in carbonated samples than in samples cured at room temperature.

In general, in almost all the leaching tests, the carbonation effect is more noticeable in OPC samples than in geopolymer samples. Carbonation considerably reduces the pH and worsens leachability. In the TCLP test, curing the S/S solids at 60°C during geopolymer preparation lowers the pH and worsens leachability in practically all the cases. In many cases heating (without carbonation) lowers the pH of TCLP leachates even more than carbonation. When all the cases were compared, the best metal immobilization results were obtained with the KSil KOH BFS geopolymeric mixture.

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