Pergamon

Cement and Concrete Research 30 (2000) 1671–1678

CEMENT AND CONCRETE RESEARCH

Stabilisation and solidification of sewage sludges with Portland cement

S. Valls*, E. Vàzquez

Department of Construction Engineering, Universitat Politècnica de Catalunya, ETSECCPB, C/Jordi Girona 1-3, E-08034 Barcelona, Spain

Received 17 April 2000; accepted 10 July 2000

Abstract

The objective of this work is to create a binding and stabilising matrix with sludge–cement and sludge–cement–coal fly ash. With this purpose, studies have been made on the effects of various percentages of waste and binder and the behaviour and evolution of sludge in the system of cement and cement–coal fly ash pastes. In these studies, evaluations were made on the setting speed, the hydration products formed and the chemical stability by means of the pH values attained and of the types and concentrations of microorganisms and organic compounds in the system created. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Sewage sludge; Setting process; Portland cement; Stability; Cement paste

1. Introduction

The study consists of including wastewater sewage sludge in a building material bound with Portland cement and guaranteeing the stabilisation and solidification of this waste because the wastewater sewage sludge is a waste product with toxic potential. The sewage sludge used is a biological sludge generated by the anaerobic digestion process that occurs during treatment of the wastewater generated in the area of Manresa, near Barcelona. The anaerobic digestion allows to diminish its bacteriological activity and fermentation.

The principal characteristics of the sludge are reflected in Table 1, they have been obtained by the use of an elemental analyzer [1]. In the characterisation of sewage sludge, the microbiological content and the organic compound content must be taken into account. One of the limitations that can be encountered in the system of stabilisation/solidification of sludge with cement is the nature and concentration of certain constituents in the sewage matrix, such as fats, oils and carbohydrates. These directly affect the setting and hardening process. The microbiological content and the organic compounds analysed are shown in Tables 2 and 3 [1].

* Corresponding author. Tel.: +34-93-401-70-84; fax: +34-93-401-72-62.

E-mail address: susanna.valls@upc.es (S. Valls).

2. Methodology

One of the variables in the preparation process of cement and cement–coal fly ash pastes with the incorporation of waste (sludge) is the water content of the sludge, which alters the mix and the setting speed. The setting time in a system, among other variables, depends on the ratio of water to binder. In order to be able to compare the setting process in cement pastes with different sludge contents, it is necessary to define a point in common in all of them, such as working under conditions of normal consistency [2]. The value obtained is the amount of water necessary for each mix of cement paste and cement–coal fly ash paste with the addition of sludge at a given moisture level of this sludge.

2.1. Mix of the mortars prepared

For the preparation of the corresponding samples, two types of Portland cement were used — I 35/A and I 45/A [3] — of medium and medium–high strength, respectively (European Standard ENV 197-1:92). The I 45/A cement develops the setting process and the mechanical strength with greater speed (Table 4), a fundamental issue in this study, since sewage sludge reduces the setting speed considerably due to its high organic compound and heavy metal content.

The cement pastes were studied with variable additions of waste, 50%, 35% and 25% sludge in the total mixture, partially substituting the Portland cement or Portland

PII: S0008-8846(00)00363-X

Table 1
The main characteristic of the sewage sludge of Manresa

Humidity	68 ± 2%
Loss on ignition (organic matter)	38 ± 4%
pH	7.93 ± 0.36
Nitrogen	2.46 ± 0.003%
Carbon	22.27 ± 0.08%
Hydrogen	3.46 ± 0.02%
Sulphur	0.84 ± 0.02%

Table 2
Organic compounds concentration in the sludge of Manresa, from dry sample

Proteins	12.64 ± 1.25%
Fats	3.07 ± 0.43%
Carbohydrates	33.87 ± 0.105%
Relation C/N	1.12 ± 0.06
Organic nitrogen	0.13 ± 0.015%
Total phosphorus	0.27 ± 0.09%
Fly	50.1 ± 0.6%

cement–fly ash with wet sewage sludge. In the mixing, the added sludge induces a relatively plastic behaviour, and for this reason, the production process consisted of: Firstly, adding the sludge to the mixer and allowing it to homogenise for approximately 5 min in order to eliminate any lumps that may have formed; secondly, adding the cement with the mixing times indicated by the normalised method [2]; and finally, adding the necessary water in the final stage of the mixing. The physical evaluation of the stabilisation/solidification system requires the process of beginning and end of setting, a standardised test EN 196-3 [2]. The beginning of setting is the time interval elapsed between the end of mixing and the moment when the needle penetrates to 4 ± 1 mm from the base. The end of setting is the time interval elapsed between the end of mixing and the moment when the needle only penetrates to 0.5 mm in the cement paste, leaving a slight mark in the sample. The water contents added to the cement pastes with sludge at normal consistency and the determinations of the beginning and end of setting made in these pastes in different mixes are shown in Table 7, where it is observed that the water added to the cement paste of normal consistency decreases as the proportion of sludge added to the mixture increases. The reduction of water added to the cement pastes with greater proportion of sludge is normal, since the waste has a high level of moisture (70–65%). In the production process of the mortar of normal consistency, the mixes with fly ash required more water than in the mixes without ash. The reason was that a batch of sludge of slightly less moisture was used, plus the fact that ‘‘Escucha’’ coal fly ash tends to increase the requirement of water for a given consistency [4,5].

Table 3
Microbiological content in sewage sludge Manresa in dry sample

Aerobes	111 250 ± 26 250 ufc/g
Enterobacteriaceas	190 ± 40 ufc/g
E. coli	< 3 nmp/g
Coliforms	12 ± 3 ufc/g
Fungi	< 10 ufc/g
Clostridium	< 10 ufc/g

Table 4
The setting process in I 45/A and I 35/A cement, by EN UNE 196-3 standard

	Beginning setting	End setting
I 35/A	130 min	210 min
I 45/A	120 min	180 min

Table 5 reflects the nomenclature used for each mix of I 35/A and I 45/A cement paste and the percentage of addition of sludge to the mixture. Table 6 shows the nomenclature of the mixes of the sludge–cement–coal fly ash system. Coal fly ash was added to the mortars by substituting 5%, 10%, 15% and 25% Portland cement with ‘‘Escucha’’ coal fly ash. The hydrated cement paste with added coal fly ash were studied only with Portland I 45/A cement. The systems studied suffer a delay in comparison with the normal setting, and therefore an accelerate-type additive — $CaCl_2$ — was added, at 3% of the cement content and in a 33% solution [6].

The meaning of the initials used for the nomenclature of these study systems is as follows:

- I45/A or I35/A: type of Portland cement.
- 50L, 35L, 25L: the percentage of wet sludge in the mixture.
- 5CV, 10CV, 15CV and 25CV: the percentage of coal fly ash with regard to the weight of binder.
- CL: presence of calcium chloride as an accelerate additive, at 3% of the weight of cement.

3. Results

A total of 25 mixes of hydrated cement paste with wet Manresa sludge were studied (Table 7), and three were used

Table 5
Cement pastes nomenclature and cement and wet sludge percentages, in 500 g of total, with and without $CaCl_2$ additive

Nomenclature	Mixed
I 35/A Portland cement	
25LI35A	25% wet sludge, 75% cement
35LI35A	35% wet sludge, 65% cement
50LI35A	50% wet sludge, 50% cement
I 45/A Portland cement	
25LI45A	25% wet sludge, 75% cement
35LI45A	35% wet sludge, 65% cement
50LI45A	50% wet sludge, 50% cement
25LCLI45A	25% wet sludge, 75% cement, 3% $CaCl_2$
35LCLI45A	35% wet sludge, 65% cement, 3% $CaCl_2$
50LCLI45A	50% wet sludge, 50% cement, 3% $CaCl_2$

Table 6
Nomenclature of mixes of the sludge–cement–coal fly ash system and their percentages, in 500 g of total, with and without $CaCl_2$ additive

Nomenclature	Mixed
25L5CV	25% wet sludge, 75% binder (95% cement and 5% fly ash)
25L10CV	25% wet sludge, 75% binder (90% cement and 10% fly ash)
25L15CV	25% wet sludge, 75% binder (85% cement and 15% fly ash)
25L25CV	25% wet sludge, 75% binder (75% cement and 25% fly ash)
35L5CV	35% wet sludge, 65% binder (95% cement and 5% fly ash)
35L10CV	35% wet sludge, 65% binder (90% cement and10% fly ash)
35L15CV	35% wet sludge, 65% binder (85% cement and 15% fly ash)
35L25CV	35% wet sludge, 65% binder (75% cement and 25% fly ash)
25L5CV-CL	25% wet sludge, 75% binder (95% cement and 5% fly ash), 3% $CaCl_2$
25L10CV-CL	25% wet sludge, 75% binder (90% cement and 10% fly ash), 3% $CaCl_2$
25L15CV-CL	25% wet sludge, 75% binder (85% cement and 15% fly ash), 3% $CaCl_2$
25L25CV-CL	25% wet sludge, 75% binder (75% cement and 25% fly ash), 3% $CaCl_2$
35L5CV-CL	35% wet sludge, 65% binder (95% cement and 5% fly ash), 3% $CaCl_2$
35L10CV-CL	35% wet sludge, 65% binder (90% cement and 10% fly ash), 3% $CaCl_2$
35L15CV-CL	35% wet sludge, 65% binder (85% cement and 15% fly ash), 3% $CaCl_2$
35L25CV-CL	35% wet sludge, 65% binder (75% cement and 25% fly ash), 3% $CaCl_2$

as references, two with Portland I 45/A cement, with and without addition of coal fly ash at 25% of the mixture, and the third with only I 35/A cement (Table 8). During the setting process, the samples are maintained in a humidity chamber at ambient temperature and with a relative humidity $\geq 95\%$ [2].

The results of the setting time (Table 7) show that the greater the quantity of sludge, the greater the delay of the beginning and end of setting, with an improved delay time in the mixes with additions of $CaCl_2$. Obviously, the times of these mixtures do not fulfil the limits established in the UNE 83-454 standard, in which for additions of coal fly ash,

Table 7
Water content in cement pastes with sewage sludge of Manresa, these cement pastes are to normal consistency

	Setting process		
Nomenclature cement pastes	Beginning setting (h)	End setting (h)	Normal consistency H_2O (g)[a]
25LI35A	24.5 ± 1.5	40 ± 0	84.0
35LI35A	44 ± 2	53 ± 1	47.0
50LI35A	80 ± 0	144 ± 0	0.0
25LI45A	15 ± 0	23 ± 2	94.5
35LI45A	20 ± 0	30 ± 0	45.0
50LI45A	80 ± 0	144 ± 0	3.0
25LCLI45A	3.5 ± 0	6.3 ± 0	71.70 g + 22.80 g solution of $CaCl_2$
35LCLI45A	7.75 ± 2.25	23 ± 1	25.20 g + 19.80 g solution of $CaCl_2$
50LCLI45A	40.5 ± 0	50 ± 0	15.20 g in the solution of $CaCl_2$
25L5CV	22 ± 0	30 ± 0	104.0
25L10CV	24.75 ± 0	31 ± 0	105.0
25L15CV	23 ± 0	34 ± 0	102.0
25L25CV	27 ± 0	40 ± 0	95
35L5CV	22 ± 2	50 ± 0	88
35L10CV	34 ± 0	53 ± 0	79
35L15CV	31 ± 2	44 ± 2	106
35L25CV	38 ± 2	47 ± 0	70.0
25L5CV-CL	8 ± 0	12 ± 0	95 g + 21.70 g solution of $CaCl_2$
25L10CV-CL	9 ± 0	13 ± 0	100 g + 20.55 g solution of $CaCl_2$
25L15CV-CL	9.5 ± 0	13 ± 0	80 g + 19.41 g solution of $CaCl_2$
25L25CV-CL	12.20 ± 0	23.20 ± 0	75 g + 17.11 g solution of $CaCl_2$
35L5CV-CL	11 ± 0	19 ± 0	68 g + 18.80 g solution of $CaCl_2$
35L10CV-CL	11.35 ± 0	21 ± 0	68 g + 17.8 g solution of $CaCl_2$
35L15CV-CL	12 ± 0	22 ± 0	76 g + 16.82 g solution of $CaCl_2$
35L25CV-CL	18 ± 2	32 ± 0	65 g + 14.82 g solution of $CaCl_2$

Results of beginning and end of setting process this cement pastes.
[a] The amount of water is the water added to the mix without counting the water contained in the sludge. The sludge humidity was 68%.

Table 8
Water content in cement pastes without sewage sludge of Manresa (cement pastes reference), these cement pastes are to normal consistency

Nomenclature cement pastes	Setting process		Normal consistency H_2O (g)
	Beginning setting(h)	End setting (h)	
I 35/A	2.10	3.30	140
I 45/A	2	3.05	143
I 45/A–25CV	2.30	4	146

Results of beginning and end setting process.

the maximum time of end of setting is 12 h [7]. In none of the mixes tested did a false setting occur.

3.1. Addition of $CaCl_2$

The inclusion of sewage sludge in the cement paste affects the setting speed (Table 7). For this reason, it is recommended, depending on the applications, to add an accelerate additive such as $CaCl_2$. The ideal percentage of this additive is 3% of the weight of cement in a 33% solution [6]. To determine the effectiveness of the additive, tests were performed on various percentages of $CaCl_2$ in the cement pastes at normal consistency with inclusion of sewage sludge at 35% of the mixture. The percentages tested of $CaCl_2$ were 3%, 2% and 1% of the weight of the cement. The three mixes were in a water solution at 33% (see Fig. 1).

Table 9 shows the results of the beginning and end of setting with the various mixes of the additive. Comparing Table 7 with Table 9, it is observed that the hydrated cement paste with 1% $CaCl_2$ has almost the same setting speed, as if it had no additive. As a result, the additive is effective between 3% and 2%, with maximum effectiveness at 3%.

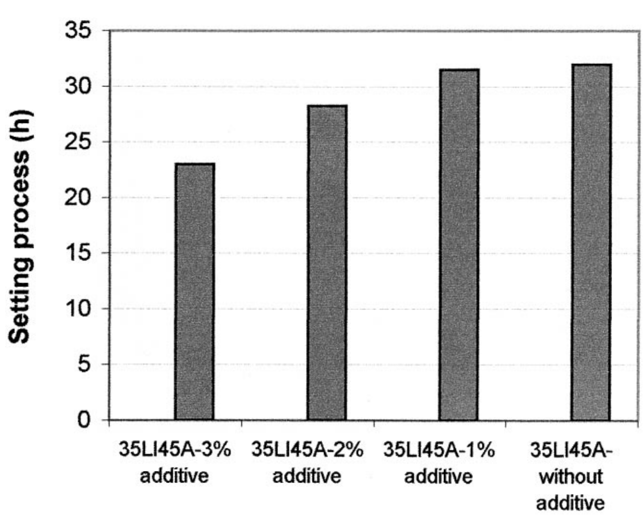


Fig. 1. The percentages tested on $CaCl_2$, 3%, 2% and 1% of the weight of cement, and their setting speed. All cement pastes have 35% of the total weight of sludge.

Table 9
Results of speed setting process with sludge inclusion to 35% and with different percentage of the $CaCl_2$ additive

Nomenclature cement pastes	Setting process	
	Beginning setting (h)	End setting (h)
35LI45A–3% $CaCl_2$	5 ± 0	23 ± 0
35LI45A–2% $CaCl_2$	6 ± 0	28.25 ± 0
35LI45A–1% $CaCl_2$	6 ± 0	31.5 ± 1

3.2. Hydration products

In order to determine the influence of the sludge on the hydration, a study was carried out by diffraction of X-rays on the hydration products formed in the sludge–cement and sludge–cement–coal fly ash systems. The objective of this is to monitor the hydration of the different mortars tested by means of the qualitative observation of the different phases formed during hydration [8].

The samples analysed with the substitutions of cement with sludge are the same as for the study of the cement paste of normal consistency and beginning and end of setting. The hydrated cement pastes were studied at different hydration times, including the final moment of the setting of the paste (which is different in each mix of paste, and that taken as the starting point) and at 3, 5, 7, 14 and 28 days from the end of setting.

The samples, which were not analysed by X-ray diffraction in the corresponding time, were previously submerged in acetone for approximately 45 s and subsequently in ethanol in order to halt the hydration process of the samples.

The phases, which are determined in the different samples tested, are, on the one hand, the anhydrides of the Portland cement (tricalcium silicate, bicalcium silicate, tricalcium aluminate, tetracalcium ferric aluminate and gypsum), the hydrates, including portlandite, ettringite, monosulphoaluminate and a carboaluminate of calcium. On the other hand, the crystal-forming phases of the Manresa sludge (quartz, calcite, dolomite and a small amount of mica in the form of moscovite) and of the coal fly ash in the samples that contain them. The interpretation of the diffractograms is rather complex, taking into account the number of existing phases and the low crystallinity of certain forming compounds of the cement pastes.

The hydration products of the different pastes of normal consistency prepared with sewage sludge in the cement and cement–fly ash systems are the same as those obtained in the standard cement pastes without inclusion of waste. The only difference is the presence of hydrated calcium carboaluminate in the samples containing sludge (see Fig. 2).

3.3. Evaluation of pH in the hydrated cement pastes

To determine the alkalinity of the system created, an evaluation was made on the pH of all of the mixes tested according to standard UNE 83.227-86 [9]. The pH was

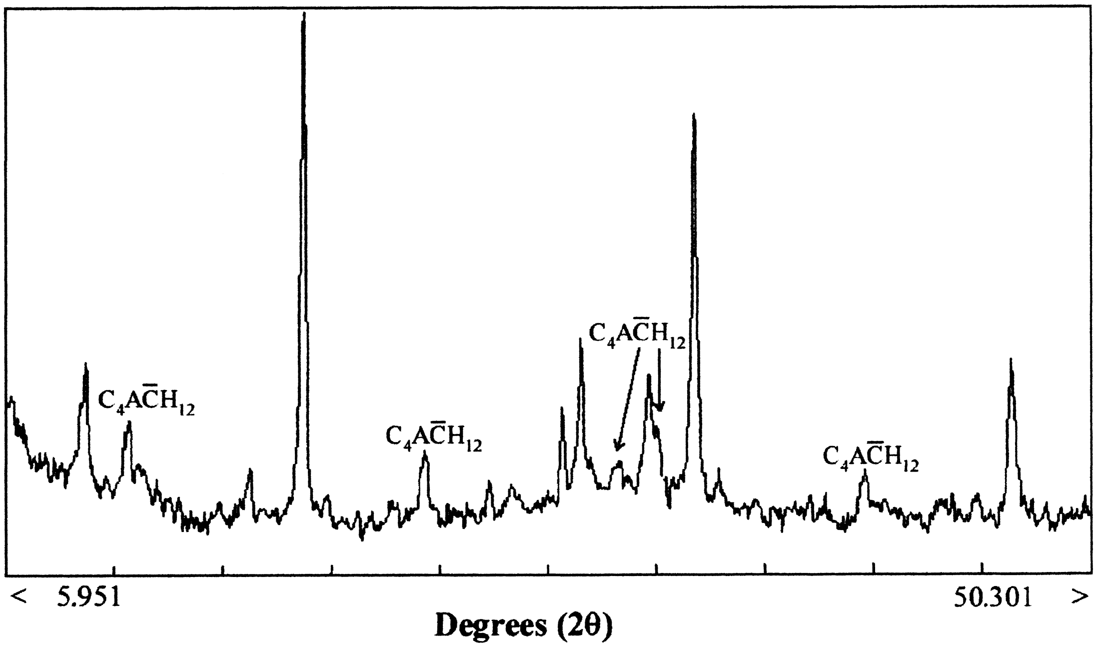


Fig. 2. Result of X-ray diffraction by cement pastes with the inclusion of 35% wet sludge in the mixture, to 28 days.

determined for the 27 mixes of paste of normal consistency at 28 days from the end of setting (Table 10). Table 11 shows the pH values at different hydration times, end of setting, 3, 5, 7, 14 and 28 days, in two cement pastes of normal consistency with 35% sludge in the mixture, but with two types of Portland cements, one with I 35/A and the other with I 45/A. A slight reduction in the pH value was observed in the samples to which calcium chloride was added, as Kurczyk and Schwiete observed in his works [10].

3.4. Microbiological and organic compounds evaluation in the sludge–cement system

Sewage sludge contain microorganisms and a high organic compound content that can affect the setting process and the stabilisation/solidification of the system created: For this reason, it is advisable to evaluate these in the hydrated cement pastes with the addition of this waste.

The study was performed on two types of pastes with Portland cement, one with 35% and the other with 25% sewage sludge in the mixture and at different times, at 28 days and at one-and-a-half years from the end of setting. The results are shown in Tables 12 and 13. A notable decrease is observed in certain organic compounds, and zero microbiological activity as well.

4. Conclusions on the sludge stabilisation/solidification system

(1) The greater the quantity of sludge added to the mixture, the greater the delay of the beginning and end of setting. The hydration speed was improved substantially with the accelerate additive, $CaCl_2$, in all of the mixes

Table 10
Values of pH for normal consistency pastes, to 28 days of the end setting process

Cement pastes	"pH"	Cement pastes	"pH"
I 45/A	12.6 ± 0	25L25CV	12.60 ± 0.09
25LI35A	12 ± 0	35L5CV	12.64 ± 0
35LI35A	12.61 ± 0	35L10CV	12.60 ± 0.15
50LI35A	12.73 ± 0	35L15CV	12.75 ± 0
25LI45A	12.76 ± 0	35L25CV	12.62 ± 0.15
35LI45A	12.77 ± 0.025	25L5CV-CL	12.47 ± 0.015
50LI45A	12.78 ± 0	25L10CV-CL	12.44 ± 0
25LCLI45A	12.56 ± 0.16	25L15CV-CL	12.36 ± 0.04
35LCLI45A	12.69 ± 0.06	25L25CV-CL	12.24 ± 0.14
50LCLI45A	12.56 ± 0.18	35L5CV-CL	12.55 ± 0.02
25L5CV	12.60 ± 0.015	35L10CV-CL	12.48 ± 0.05
25L10CV	12.63 ± 0.03	35L15CV-CL	12.40 ± 0.09
25L15CV	12.52 ± 0	35L25CV-CL	12.40 ± 0.10

Table 11
Comparative values of pH between two cement pastes to normal consistency, with a 35% of sludge and cement Portland I 35/A and I 45/A, in different times of setting process

Values of "pH"		
Time	Sample — 35LI45A	Sample — 35LI35A
End setting	13.03	12.90
3 Days	12.86	12.88
5 Days	12.91	12.80
7 Days	12.80	12.78
14 Days	12.70	12.73
28 Days	12.60	12.61

Table 12
Organic compounds concentration in the sludge of Manresa, from dry sample and in cement pastes with inclusion of sludge, to 28 days and one-and-half years old

		Cement pastes with inclusion of sludge			
		35% Sludge		25% Sludge	
Organic compounds	In sludge	28 Days	1 1/2 Years	28 Days	1 1/2 Years
Proteins	12.64 ± 1.25%	0.37%	0.76%	0.38%	0.92%
Fats	3.07 ± 0.43%	0.49%	0.61%	0.44%	0.70%
Carbohydrates	33.87 ± 0.105%	28.86%	28.37%	29.73%	22.64%
Relation C/N	1.12 ± 0.06	2.01	2.02	1.94	1.80
Organic nitrogen	0.13 ± 0.015%	0.01%	0.01%	0.01%	0.01%
Phosphates	0.26 ± 0.09	0.33%	0.34%	0.31%	0.37%
Fly	50.1 ± 0.6	70.06%	69.95%	69.39%	75.29%

tested. The maximum and optimal mix of additive, $CaCl_2$, is 3% of the weight of cement at 33% of the solution added. Two percent of $CaCl_2$ accelerates the process but with less effectiveness, and 1% $CaCl_2$ does not improve the setting process.

(2) The 25 mixes tested all attain setting in time, with no false setting occurring in any case.

(3) There is a notable improvement in the setting speed in the mixes with Portland cement I 45/A (medium–high strength) in comparison with that of the Portland cement I 35/A (medium strength).

(4) In the sludge–cement system, the percentages of sludge added to the total mixture were 50%, 35% and 25%. Fifty percent sludge without additive shows excessively high setting times, 144 h (6 days), for some applications of the material, for example, in civil engineering. The cement paste with 50% sludge with accelerate additive and Portland cement I45/A, referred to here as 50LCLI45A, presents an acceptable setting time of the order of 50 h. It depends on the possible application in construction. The setting speed of this system improves substantially with the addition of $CaCl_2$.

(5) The addition of coal fly ash in substitution of the Portland cement in the pastes increases the setting time, which in turn increases proportionally with the percentage of addition added. The time improves substantially if the accelerate additive $CaCl_2$ is added to these cement pastes. The increase in the setting speed with the addition of $CaCl_2$ is inversely proportional to the percentage of ash in the mixture.

(6) The cement pastes with 25% sludge in the mixture and 5%, 10%, 15% and 25% "Escucha" coal fly ash without $CaCl_2$ also present acceptable setting times. In contrast, in the cement pastes with 35% sludge and also with 5%, 10%, 15% and 25% coal fly ash, the setting time increases considerably.

(7) The hydrates formed in all of the cement pastes with sludge are the same as those formed in pastes without it, with the exception of the formation of hydrated calcium carboaluminate due to the carbonation of calcium monosulphoaluminate in a porous system. In the mixes of cement pastes with greater mass of sludge, the calcium carboaluminate appears earlier, due to its higher proportion of pores in the system.

(8) The hydrates of the Portland cement formed, particularly the calcium hydroxide, guarantee a high alkalinity of the system, creating a buffer effect. No variation of pH is observed between the cement pastes with and without addition of coal fly ash: they are totally alkaline systems. A slight reduction is observed in the pH value in the samples with the additive $CaCl_2$.

(9) The alkalinity of the medium favours the neutralisation and decomposition of the microorganisms and organic compounds contained in sewage sludge, guaranteeing the stability and solidification of the system. The proteins, fats and organic nitrogen decompose; in contrast, the carbohydrates decrease slightly. The microorganisms content also decreases appreciably, particularly aerobes, Enterobacteriaceae and coliforms.

(10) Therefore, we can conclude that Porltand cement is a good agent for sewage sludge solidification.

5. Discussion

The physical inerting of sewage sludge in a cement matrix of Portland cement is possible. The mixture produces a hard and resistant system due to the formation of the hydration products of the cement. The delay of the process is offset by the addition of an accelerator such as calcium

Table 13
Microbiological content in sludge of Manresa, from dry sample and in cement pastes with inclusion of sludge, to 28 days and one-and-half years old

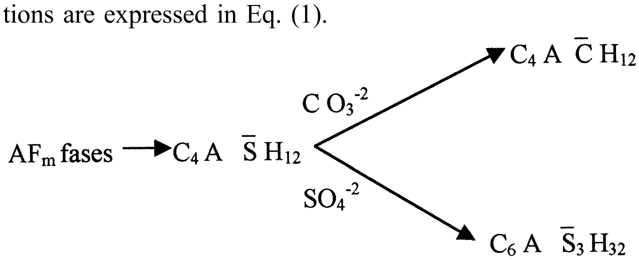
		Cement pastes with inclusion of sludge			
		35% Sludge		25% Sludge	
Microbiological	In sludge	28 Days	1 1/2 Years	28 Days	1 1/2 Years
Aerobios	111 250 ± 26 250 ufc/g	100 ufc/g	< 10 ufc/g	< 10 ufc/g	< 10 ufc/g
Enterobacteriaceas	190 ± 40 ufc/g	< 10 ufc/g	< 10 ufc/g	< 10 ufc/g	< 10 ufc/g
E. coli	< 3 nmp/g	< 3 nmp/g	< 3 nmp/g	< 3 nmp/g	< 3 nmp/g
Coliforms	12 ± 3 ufc/g	< 3 ufc/g	< 3 ufc/g	< 3 ufc/g	< 3 ufc/g
Fungi	< 10 ufc/g	< 10 ufc/g	< 10 ufc/g	< 10 ufc/g	< 10 ufc/g
Clostridium	< 10 ufc/g	< 10 ufc/g	< 10 ufc/g	< 10 ufc/g	< 10 ufc/g

chloride. This additive favours the hydration reaction, increasing the surface area and altering the morphological characteristics of the hydrates formed [11].

The substitution of cement for coal fly ash in the solidification/stabilisation system reduces the setting speed and the hardening in the short term, but its usefulness resides in its providing more economic inerting.

The differences between the cement pastes made with I 35/A cement and I 45/A cement lie not in the composition but in the reaction speed and the concentration of the hydrates formed. The Portland I 45/A cement, due to having a smaller grain size (greater specific surface area), presents a larger amount of anhydride for reaction, which in turn entails a greater reaction speed, with a larger amount of ettringite and portlandite forming in the first days of hydration. Consequently, the monosulphoaluminate and hydrated calcium carboaluminate are formed earlier. This aspect is particularly accentuated in the first seven days from the end of setting. The hydrated calcium carboaluminate is formed in both the sludge–Portland I 35/A cement paste and the sludge–Portland I 45/A cement paste. Another difference between the two types of cement is that the gypsum takes longer to react in cement pastes with I 35/A cement, the reason being the larger grain size of the anhydrides in this cement, with which the C_3A reacts more slowly to form ettringite.

The formation of the hydrated calcium carboaluminate in the pastes with the inclusion of wet sludge is due, according to Taylor [12], to the fact that in the first phases of the hydration in a porous system, the calcium monosulphoaluminate, $C_4A\bar{S}H_{12}$, reacts with the environmental $CO_3{}^{-2}$ to form hydrated calcium carboaluminate, $C_4A\bar{C}H_{12}$. If, instead of reacting with the calcium monosulphoaluminate, the environmental $CO_3{}^{-2}$ reacts with the calcium hydroxide, it is transformed into ettringite, $C_6A\bar{S}_3H_{32}$. The reactions are expressed in Eq. (1).



(1)

The pH values show a high degree of alkalinity of the material prepared in all of the mixes tested with and without coal fly ash, guaranteeing chemical, microbiological and organic stability. The pH has a clear influence on the leachable potential of the forming constituents [1,13], controlling the solubility of the different chemical species [14–16] and destroying, in turn, certain organic components and bacteriological activity. There are no great differences in the pH value between the different mixes of cement pastes with sludge–cement and sludge–cement–fly ash tested in time, nor with the two types of Portland cements, I45/A and I35/A. The hydrated cement paste is a highly alkaline system that exerts a buffer effect due to the formation of calcium hydroxide [1].

In the stabilisation/solidification system with Portland cement, the majority of the organic compounds show a clear tendency to disappear. The alkalinity of the medium neutralises and decomposes proteins, fats and organic nitrogen. The alkalinity of the inerting system not only favours the neutralisation and decrease of the organic compounds, but it also appreciably neutralises the microorganism content (aerobes, Enterobacteriaceae and coliforms).

Acknowledgments

The authors wish to thank the support of Junta de Sanejament of the Dpt. de Medi Ambient of the Generalitat de Catalunya and UBENA, BBS (Barcelona, Spain).

References

[1] S. Valls, Estabilización física y química de los lodos de depuradora de aguas residuales y de material de demolición para su utilización en ingeniería civil, Doctoral thesis, July 1999.
[2] EN 196-3, Methods of Testing Cement: Determination of setting time and soundness, European standard, CEN, Brussels, 1997.
[3] UNE 80-302 (AENOR), Asociación española de normalización y certificación, Cementos. Especificaciones Químicas para sus constituyentes, Madrid 1985.
[4] P.K. Mehta, Standard specifications for mineral admixtures, An Overview. Second International Conference on the Use of Fly Ash, Silica Fume, Slag and the Natural Pozzolans in Concret, Madrid, 1986.
[5] N. Alba, Estabilització/solidificació de residus d'incineració de RSU en matrius de ciment. Valoració ambiental, Doctoral thesis, March, 1998.
[6] V.S. Ramachandran, Calcium Chloride in Concrete, Science and Technology, Applied Science Publishers, London, 1976.
[7] UNE 83-450 (AENOR), Asociación española de normalización y certificación, Adiciones al Hormigón. Cenizas volantes. Determinación del principio y fin de fraguado del cemento portland conteniendo ceniza volante, Madrid 1987.
[8] Powder Diffraction File Search Manual, Joint Commitee on Powder Diffraction Standards, International Centre for Diffraction Data, 1601 Park Lane, Swarthmore, PA 19081, USA, 1980.
[9] UNE 83.227-86 (AENOR), Asociación española de normalización y certificación, Aditivos para hormigones. Morteros y pastas determinación del Ph, Madrid 1986.
[10] H.G. Kurczyk, H.E. Schwiete, Electron microscopic and thermochemical investigations on the hydration of the calcium silicates $3CaO{\cdot}SiO_2$ and the effects of calcium chloride and gypsum on the process of hydration, Tonind-Ztg 84 (1960) 585–598.
[11] I. Teoreanu and M. Muntean, The Kenetics of the hydration process of the silicate constituents of portland cement clinker under the influence of electrolytes, Silicates Ind., 39 (1974) 49–54.
[12] H.F.W. Taylor, Cement Chemistry, Academic Press, New York, 1990.

[13] H.A. Van der Sloot, L. Heesman, Ph. Quevauviller, Harmonization of Leaching Extraction test, Studies in Environmental Science, Elsevier Amsterdam, 1997.
[14] J.J.J.M. Goumans, H.A. Van der Sloot, Th.G. Albers (Eds.), WASCON 1991, Waste Materials in Construction, Elsevier, Amsterdam, 1991.
[15] J.J.J.M. Goumans, H.A. Van der Sloot, Th.G. Albers (Eds.), WASCON 1994, Environmental Aspects of Construction with Waste Materials, Elsevier, Amsterdam, 1994.
[16] H.A. Van der Sloot, D. Hoede, R.N.J. Comans, The influence of reducing properties on leaching of elements from waste materials, in: J.J.J.M. Goumans, H.A. Van der Sloot, Th.G. Albers (Eds.), WASCON 1994, Environmental Aspects of Construction with Waste Materials. Elsevier, Amsterdam, 1994, pp. 483–490.