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Mechanical behavior of mortars containing sewage sludge ash (SSA) and Portland cements with different tricalcium aluminate content

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Abstract

The influence of sewage sludge ash (SSA) on cement mortars strength has been studied. To evaluate better the increase of strength compared to control mortar, relative compressive strength gain (CSGr) and flexural strength gain (FSGr) were calculated. The experience shows that SSA behaves as an active material, producing an increase of compressive strength compared to control mortar, probably due to pozzolanic properties of SSA. It can be emphasized that high sulfur content of SSA (12.4%) does not seem to have influence on compressive strength of mortars containing SSA. When CSGr of mortars containing different types of cements are compared, no clear correlation is observed between CSGr and C_3A content in cement.

Keywords: Waste management; Mechanical Properties; Pozzolan; $Ca_3Al_2O_6$

Recently, solid waste incinerator systems have become widely used in Europe. Incinerators work on the principle of reducing waste volume and converting solid waste, through a controlled combustion process at high temperatures, to bottom ash, which is collected at the bottom of the furnace chamber, and fly ash, which is collected from the flue gas.

The efficiency of incineration depends on a variety of combustion parameters, including the furnace temperature, amount of air injected into the furnace, degree of turbulence, and time period [1].

As a consequence of water treatment processes, an important amount of sewage sludge is obtained. The properties of sewage sludge depend on the source of wastewater (urban or industrial mainly); for example, their concentration of heavy metals, which have their origin in industrial activities, controls the reuse of sewage sludge in agriculture. The excess of sewage sludge production and, in some cases, undesirable chemical properties have prompted scientists to study other ways to dispose of sewage sludge. The most common sewage sludge disposal alternative is incineration. This method achieves a significant reduction of material volume. The sewage sludge ash (SSA) retained in filters can be deposited in controlled landfills or used in construction, improving some properties of building materials. Incineration residues such as rice husk ash [2,3] and municipal solid waste ash [4–6] have been used successfully in construction. SSA has been used in mortars [7], concrete mixtures [8,9], in brick manufacture [10], as a fine aggregate in mortars [11], and in asphalt paving mixes [12].

The reuse of a waste in concrete production depends on several characteristics of the waste, one of them being chemical composition. Frequently, SSAs are sulfur-rich wastes (% SO_3 >10%). Consequently, concrete degradation processes related to sulfate attack may have to be taken into account. One might expect that there would be a positive correlation between the extent of replacement of cement by SSA and the C_3A content of cements due to the cementitious reactions that form AFm and AFt. The study of the interaction between SSA and cement hydration products can be carried out by strength measurement, and correlation between strength development and chemical evolution of hydrated cement compounds can be established. Because the SSAs contain substantial sulfur compounds, one must check for expansive behavior that would lower the strength of the mortars. In our case, due to the presence of sulfur-rich compounds in the SSA addition, internal sulfate attack could be possible [13]. Cement degradation processes have been observed when gypsum contaminated aggregates [13] or sulfide-bearing aggregates [14,15] are used in concrete.

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1. Experimental

1.1. Materials

SSA was collected from the sewage treatment plant of Pinedo (Valencia, Spain). Original SSA was separated into three fractions using sieves of 80, 40, and 20 μm: the coarsest fraction SSAC (retained on the 80-μm sieve), the medium-sized fraction, SSAM (retained on the 40-μm sieve), and the finest fraction, SSAF (retained on the 20-μm sieve). No significant amount of ash passed through 20-μm sieve. The SSAF fraction was not tested because of the small quantity obtained (2% by weight). Chemical analysis of SSA and their size fractions are summarized in Table 1. It may be noted that original SSA contains 12.4% of SO_3, and the SSAC and SSAM contain 10.7% and 13.1% of SO_3. Portland cements containing increasing percentages of C_3A were used (C1 to C4) to study the influence of sulfur content in SSA on mortar strength. The different cements used were sulfate resistant (C1), two type I cements with different C_3A content (C2 and C3), and a white cement (C4). Chemical analysis and Bogue composition of these cements are summarized in Table 1. Fine aggregate was natural sand with a 2.94 fineness modulus.

1.2. Apparatus and procedures

A digital electromagnetic sifter (CISA) with variable sieving level powers was used to obtain size fractions. Mortar specimens cast in square prismatic mortar molds with internal dimensions of 40 × 40 × 160 mm were used. Preparation of mortars were carried out according to ASTM C-305 [16], mixing 450 g of Portland cement, 1350 g of natural sand, 4.5 g of superplasticizer (commercial sulfonated condensate melamine formaldehyde), and 200 mL of water for the control mortar and the rest of the mortars with variable replacement of Portland cement by SSA or its size fractions (SSAC and SSAM). Mortars were put in a mold and stored in a moisture room (20 ± 1°C) for 24 hours. The specimens were demolded and cured by immersion in a 40 ± 1°C water bath to accelerate the hydration process until testing at 3, 7, 14, and 28 days according to ASTM tests [17–19].

Table 1
Chemical analysis and Bogue composition of cement and SSA

%	C1	C2	C3	C4	SSA	SSAC	SSAM	SSAF
CaO	62.88	64.59	64.93	67.59	31.3	25.9	32.9	32.1
SiO_2	19.65	20.9	20.36	21.91	20.8	30.1	16.2	15.5
Al_2O_3	4.01	4.90	5.80	5.36	14.9	11.9	14.7	14.0
Fe_2O_3	6.83	3.99	2.20	0.29	7.4	7.1	8.2	8.3
MgO	3.39	1.22	1.77	0.88	2.6	2.2	2.4	2.6
K_2O	—	0.94	1.10	0.09	—	—	—	—
Na_2O	—	—	—	—	—	—	—	—
SO_3	2.26	3.27	3.65	3.04	12.4	10.7	13.1	13.7
CaO free	0.69	—	—	1.00	—	—	—	—
C_3S	60.06	56.52	57.1	59.45	—	—	—	—
C_2S	11.04	17.51	15.31	18.01	—	—	—	—
C_3A	—	6.22	10.36	13.71	—	—	—	—
C_4AF	19.03	12.13	7.48	0.88	—	—	—	—
C_2F	0.97	—	—	—	—	—	—	—

2. Results and discussion

Mortars containing SSA were prepared replacing 15% or 30% of cement content in control mortar (1:3 cement-to-sand ratio) and cured at 40°C. Specimens were tested for flexural (Rf) and compressive (Rc) strength for a given curing period (3, 7, 14, and 28 days). These strength values were compared to the control mortar values (Table 2).

Mechanical strengths of mortars containing SSA cured at 40°C were similar to control mortar strengths (even for 3-day curing time), suggesting an active role of SSA in cement paste strength development. Moreover, SSA reactivity at early age (3 days) is higher than that of fly ashes, because SSA-containing mortars cured at 40°C yielded similar or greater compressive strength values than control mortar. However, at 28-day curing time [20], mortars containing fly ashes apparently reached higher Rc values than SSA/cement mortar ones [20,21]. Similar behavior was found for flexural strength, but, in this case, better results for fly ash mortars at 28-day curing time were found.

2.1. Relative CSGr of mortars containing SSAs

Rc values for mortars containing SSA (Rc_i) were similar to control mortar ones (Rc_o) at the same age. For example, Rc_i/Rc_o values for 28-day curing time were in the 0.94 to 1.17 range. A similar range of values was observed in earlier curing times. To evaluate better the increase of strength compared to the control mortar, relative compressive strength gain (CSGr) for SSA-containing mortars were calculated using Eq. (1):

$$\mathrm{CSGr} = \left[\frac{Rc_i}{Rc_o \times w_c/w_c + w_{ssa}} - 1\right] \times 100 \quad (1)$$

where Rc_i is the compressive strength for SSA-containing mortar, Rc_o is the compressive strength of control mortar at the same age, w_c is the weight of cement, and w_{ssa} is the weight of SSA used for preparing mortars. This magnitude

Table 2
Compressive and flexural strength values for control cement mortars

Type of cement	Compressive strength (MPa)				Flexural strength (MPa)			
	Curing time (days)							
	3	7	14	28	3	7	14	28
C1	37.6	41.7	49.3	51.2	4.9	5.2	5.2	5.5
C2	44.7	47.0	53.5	55.3	5.5	5.8	5.9	5.9
C3	33.2	38.8	40.6	45.3	4.8	4.9	5.0	5.8
C4	47.1	49.1	52.7	56.4	4.4	5.3	5.6	5.9

represents the gain of strength produced by the partial replacement of cement by SSA compared to the hypothetical behavior of mortar made with an inert product in the same proportion. Remember that compressive strength of control mortar Rc_o is affected by a coefficient, $w_c/w_c + w_{ssa}$, which only takes into account the amount of cement included in total amount of cementicious mass $w_c/w_c + w_{ssa}$) [22]. For example, if the compressive strength were the same for the control mortar and the SSA-incorporated mortar, the CSGr would be 18% at 15% replacement, and 43% at 30% replacement.

Fig. 1 plots CSGr vs. mortars containing different types of cement (C1 to C4) for 3 to 28 days of curing time at 40°C. Fig. 1a corresponds to 15% and Fig. 1b to 30% cement replacement by SSA. In both sets of experiments, it can be seen that the replacement of cement by SSA produces a positive CSGr, which is more pronounced when 30% of cement is replaced. This experience shows that SSA behaves as an active material, producing an increase of compressive strength compared to the control mortar, probably due to pozzolanic properties of SSA. When we compare CSGr of mortars containing different types of cements, no clear correlation is observed between CSGr and C_3A content in cement. Only white cement (C4) containing the highest C_3A content (13.71%) showed a particularly low CSGr, but no defined tendency is observed for C1 (0% C_3A), C2 (6.22% C_3A), and C3 (10.37% C_3A). SO_3 content in binders ranged from 3.78% to 4.96% for mortars containing 15% of SSA, and ranged from 5.30% to 6.28% for mortars with 30% SSA replacement. Thus, it can be noted that the high sulfur contents due to cement replacement by SSA do not seem to have an influence on compressive strength of mortars containing SSA.

To study the influence of SSA granulometric distribution on compressive and flexural strength of mortars, the original SSA was separated in two size fractions, SSAC and SSAM (see experimental section). Fig. 2 plots 28-day CSGr vs. type of cement for SSAC-, SSA-, and SSAM-containing mortars. This experience was carried out for 15% (Fig. 2a) and 30% (Fig. 2b) cement replacements. A similar tendency

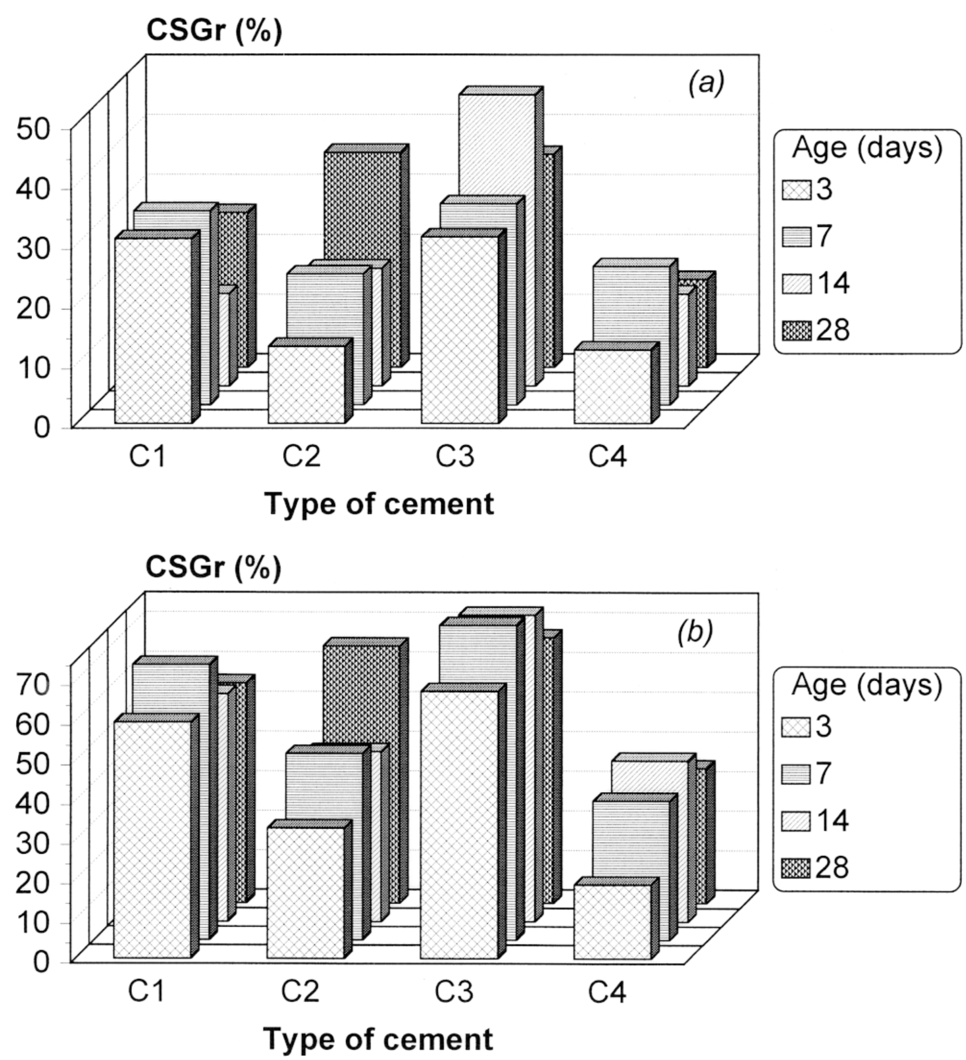
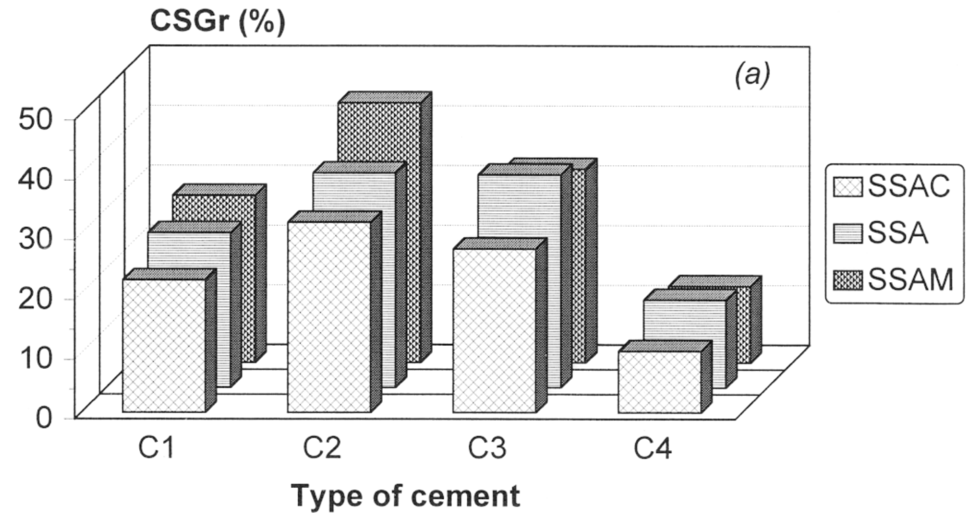


Fig. 1. CSGr of mortars containing SSA and cements with different C_3A content, cured from 3 to 28 days at 40°C: (a) 15% SSA; (b) 30% SSA.



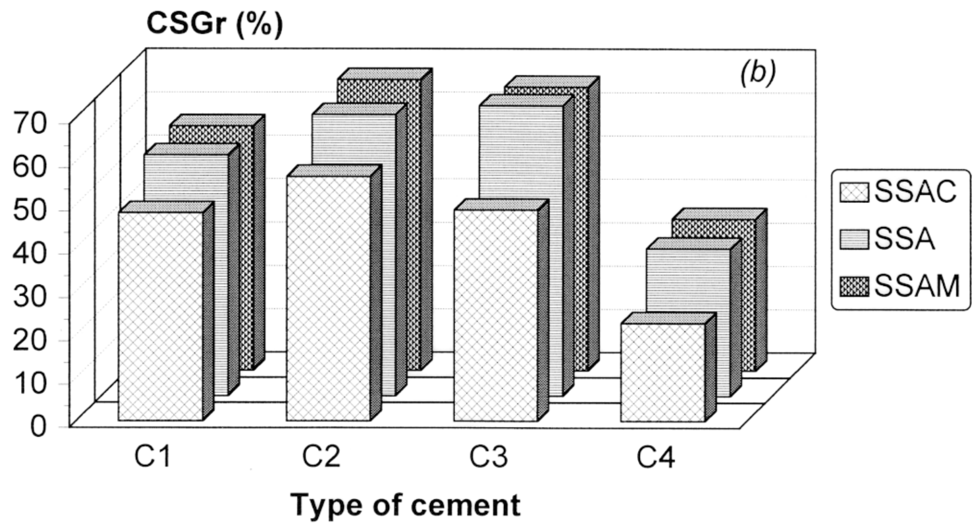


Fig. 2. CSGr of mortars containing SSA and sized fractions (SSAC and SSAM) and cements with different C_3A content, cured for 28 days at 40°C: (a) 15% ash; (b) 30% ash.

is observed in both cases: mortars prepared with C1 and C2 cements showed an increase of CSGr with increasing ash fineness. In the experiments developed using C3 and C4 cements, no significant differences were observed between mortars containing SSA (original ash) and SSAM. It also can be established that there is no direct relation between CSGr and cement C_3A content, only experiments carried out using cement C4 (13.71% of C_3A) showed the lowest CSGr. The coarsest fraction SSAC has lower SO_3 content than SSA and SSAM [7], mortars containing SSAC yielded the lowest CSGr values; on the other hand, SSAC has highest SiO_2 content [7], and it seems that pozzolanic reaction in SSAC-containing mortars is less important than in SSA-in SSAM-containing mortars. Thus, it can be assumed that fineness is the more dominant parameter for chemical reactivity rather than chemical composition.

When Fig. 2a and Fig. 2b are compared, we can conclude that for all the size fractions tested, ash replacement increase produces a significant CSGr increase. This observation is shown more clearly in Fig. 3, when CSGr values for mortars containing 15% and 30% of SSA vs. the type of cement are simultaneously represented. It is important to point out that, in all mortars, when cement replacement by SSA doubles, CSGr also doubles.

2.2. Relative flexural strength gain of mortars containing SSAs

Flexural strength development becomes also a good mechanical property for evaluating sulfate resistance in concrete [23,24]. In our case, Rf values for SSA-containing mortars (Rf_i) were similar to control mortar ones (Rf_o) at the same age. For example, Rf_i/Rf_o values for 28-day curing time were in the 0.92 to 1.28 range. Similar experiments carried out for mortars containing a fly ash, or the finest fraction of it [20], yielded Rf_i/Rf_o values in the 1.25 to 1.50 range, showing that SSA efficiency in flexural strength development is lower than that of fly ash.

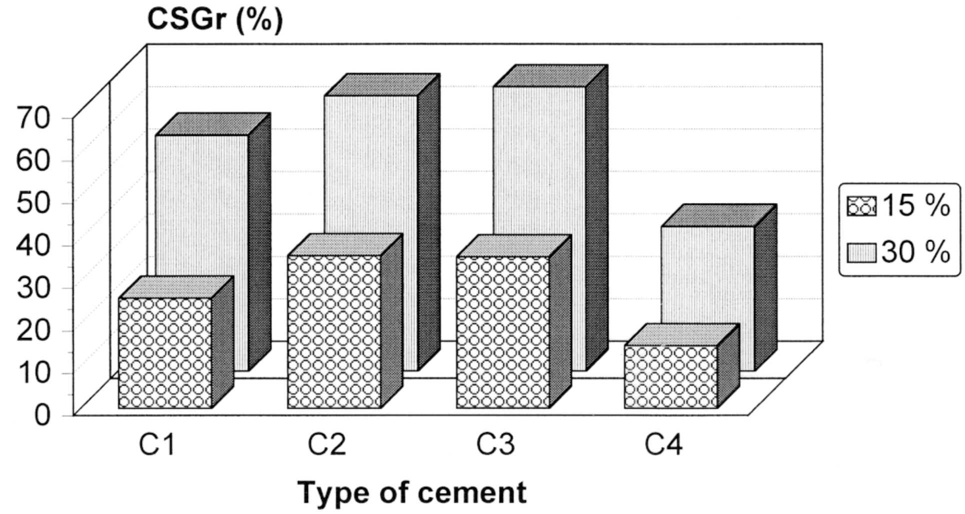


Fig. 3. CSGr comparison between mortars containing 15% and 30% of different types of cements replaced by SSA, cured for 28 days.

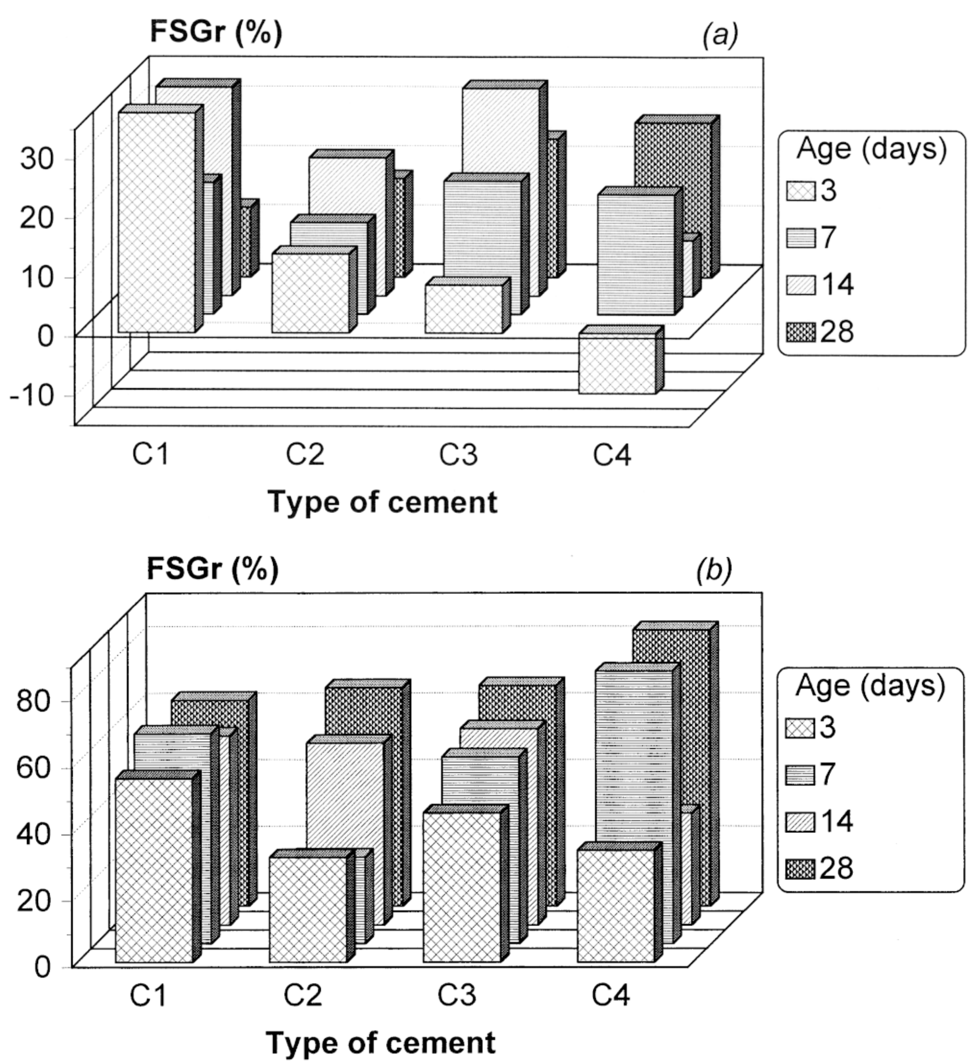


Fig. 4. FSGr of mortars containing SSA and cements with different C_3A content, cured from 3 to 28 days at 40°C: (a) 15% SSA; (b) 30% SSA.

Eq. (2), similar to Eq. (1) established in the preceding section, but including flexural strength instead of compressive strength, was used:

$$FSGr = \left[\frac{Rf_i}{Rf_o \times w_c/w_c + w_{ssa}} - 1\right] \times 100 \quad (2)$$

Fig. 4 represents relative flexural strength gain (FSGr) vs. mortars containing different types of cement (C1 to C4) for 3 to 28 days of curing time at 40°C. Figs. 4a and 4b correspond to 15% and 30% cement replacements by SSA, respectively. Some differences can be discerned between both experiments. In Fig. 4a, for 3 days of curing time, a significant FSGr decrease is observed when C_3A content in cement increases, and a negative value is obtained when C4 cement is tested. For 7 and 14 days of curing time, this trend is not observed. Finally, for 28 days of curing time, the opposite behavior compared to the 3 days of curing time is observed. In this case, an increase of FSGr is produced with an increase in C_3A content. For a 30% replacement percentage, no defined tendency is observed in any curing time (Fig. 4b). From these experiments it can be concluded that the replacement of cement by SSA produces an increase of FSGr in all cases except for C4 cement with 15% replacement and 3 days of curing.

Fig. 5 shows the influence of ash fineness on FSGr of mortars containing 15% and 30% of ash. Fig. 5a corresponds to 15% of cement replaced by ash. In this figure an increase of FSGr is observed when percentage C_3A increases, except for mortars containing SSAM. When ash replacement increases from 15% to 30% (Fig. 5b), only mortars containing SSAC (coarse fraction) showed the same somewhat diminished tendency. Mortars containing SSA and SSAM exhibited no significant differences of FSGr when different cements are used, except when C4 cement is used. Fig. 6, which plots the 15% and 30% replacement experiments for mortars containing the original SSA, shows

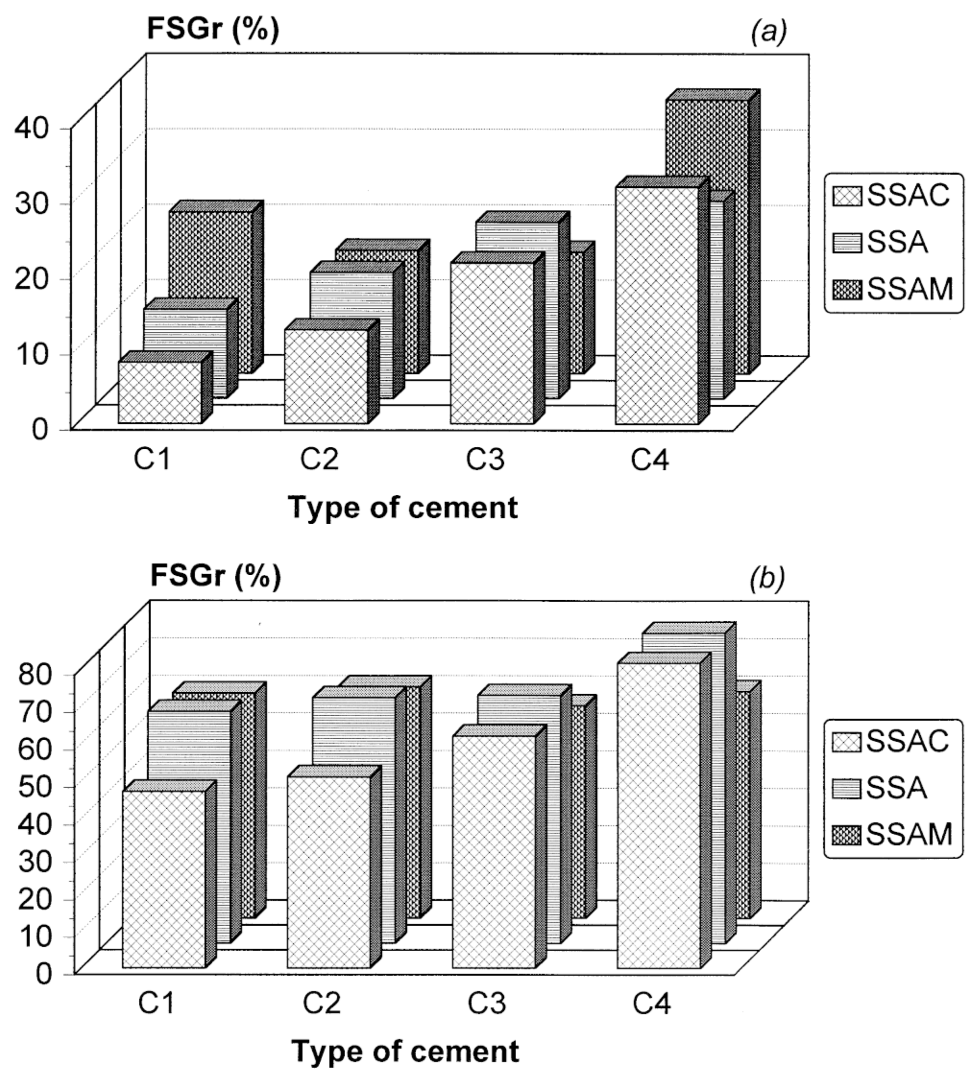


Fig. 5. FSGr of mortars containing SSA and sized fractions (SSAC and SSAM) and cements with different C_3A content, cured for 28 days at 40°C: (a) 15% SSA; (b) 30% SSA.

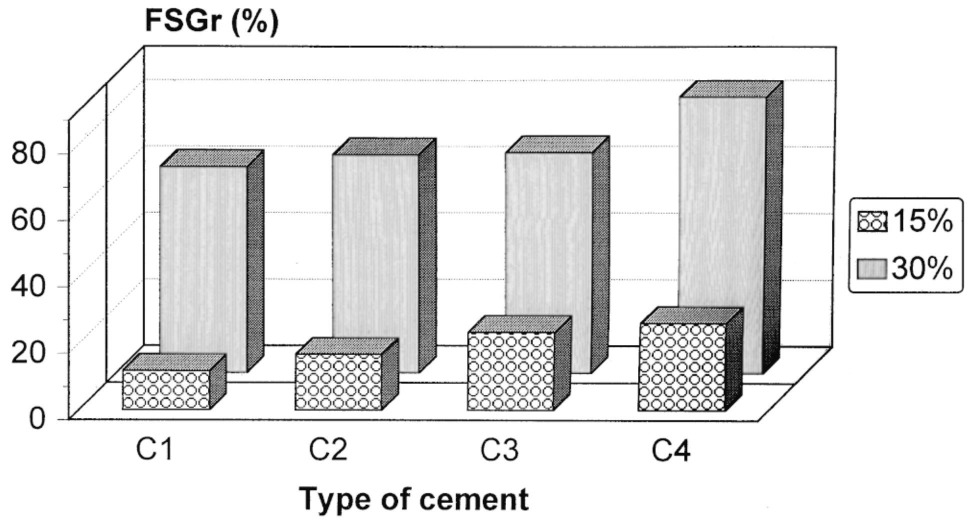


Fig. 6. FSGr comparison between mortars containing 15% and 30% of different types of cement replaced by SSA, cured for 28 days at 40°C.

the enormous increase of 28 days that FSGr produced when percentage of replaced ash doubles.

3. Conclusions

1. Partial substitution (15% or 30% by mass) of cement by SSA does not strongly affect the strength of mortars cured at 40°C for 3- to 28-day curing periods.
2. A positive CSGr took place for all SSA/cement mortars studied, increasing in value with replacing percentage and suggesting an important active role of SSA in compressive strength development.
3. When CSGr of mortars containing different types of cements are compared, no clear correlation between CSGr values and C_3A content in cements is observed.
4. High sulfur content in SSA does not have a decisive influence on strength development.
5. Fineness of SSA is an important parameter for strength development of SSA/cement mortars: the coarsest fraction yields the lowest strength values.
6. For all the size fractions tested, ash replacement increase produces a significant CSGr increase
7. SSA showed a greater or similar contribution to mechanical development than fly ashes at early ages, but they become less efficient for longer term curing.
8. For short curing times, a significant FSGr decrease is observed when the C_3A content in cement increases. This tendency reverses for 28 days of curing times
9. SSA is compatible with cements with high C_3A content as binder in mortars, and no decreases in mechanical properties were observed at 28-day curing time due to degradation of cement/SSA paste. However, for longer curing times, delayed ettringite formation or thaumasite formation, where fine carbonate aggregates are used, could occur, reducing the strength of mortars.
10. In general, CSGr and FSGr increased remarkably with increasing SSA replacement.

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