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Valuation of sewage sludge ash as a component of precast concrete

F. Baeza Brotons[1], P. Garcés Terradillos[1], J. Payá Bernabeu[2], O. Galao Malo[1]

[1]Department of Civil Engineering, University of Alicante, Spain.
[2]Institute of Science and Technology of Concrete (ICITECH), Polytechnic University of Valencia, Spain.

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ABSTRACT

This paper proposes binary and ternary combinations of sewage sludge ash (SSA) with fly ash, marble dust and rice hull ash, as partial replacement or addition relative to Portland cement in concretes with a similar dosage to that used in the manufacture of precast blocks, with very dry consistency given its manufacturing process in plant. Several physical-mechanical tests were carried out on concrete and mortar specimens with curing ages of 28 and 90 days: density, water absorption and compressive strength. It is proved that replacing cement by SSA involves a decrease in density and compressive strength compared to the reference sample, however, the combinations of residues significantly improve the characteristics of the cementitious materials. The addition of SSA provided densities and resistances similar to the control sample and significantly reduces the water absorption.

Keywords: sustainability; industrial products; mineral additions.

RESUMEN

Se plantea la combinación binaria y ternaria de cenizas de lodo de depuradora (CLD) con ceniza volante, polvo de mármol y ceniza de cáscara de arroz, como sustitución parcial o como adición respecto al cemento Portland en hormigones, con una dosificación similar a la utilizada en la prefabricación de bloques (consistencia muy seca). Se llevaron a cabo ensayos físico-mecánicos sobre probetas de mortero y hormigón con edades de curado de 28 y 90 días: densidad, absorción y resistencia a compresión. Se comprueba que la sustitución de cemento por CLD supone una disminución de la densidad y de la resistencia respecto a la muestra patrón, sin embargo, las combinaciones con otros residuos mejoran notablemente las características de los materiales cementantes. La adición de CLD proporcionó densidades y resistencias similares a la muestra de control y reduce significativamente la absorción de agua.

Palabras claves: sostenibilidad; subproductos industriales; adiciones minerales.

RESUMO

Impõe-se a combinação binária e ternária de cinzas de lodo de esgoto com cinza volante, pó de mármore e cinzas de casca de arroz, tal como uma substituição parcial ou adição em relação ao cimento Portland em concretos. Com esses materiais foram produzidos argamassas e concretos com consistência similar à utilizada na pré-fabricação de blocos (consistência muito seca). Nas argamassas e concretos, com idades de 28dias e 90dias, foram realizados os seguintes ensaios físico-mecânicos: densidade, resistência à compressão e absorção. Verificou-se que a substituição de cimento por cinza de lodo de esgoto acarretou uma diminuição na densidade e na resistência em comparação com a amostra padrão. Por outro lado, as combinações com outros resíduos melhoraram significativamente as características das argamassas e concretos. A adição de cinza de lodo de esgoto proporcionou densidades e resistências similares à amostra padrão e reduziu significativamente a absorção de água.

Palavras-chave: sustentabilidade; produtos industriais; aditivos minerais.

Corresponding author: Francisco Baeza (fbaeza.brotons@ua.es)

INTRODUCTION

The generation and management of waste is a serious environmental problem in modern societies. Neglect or inadequate management of waste produce significant impacts on the receiving sites and can cause pollution in water, soil and air, contributing to climate change and affecting ecosystems and human health. However, when properly managed, waste become a resource that contribute to raw materials' saving, natural resources and climate conservation and sustainable development (PNIR, 2008).

Some residues can be used in concrete and mineral additives, which are defined as inorganic materials, pozzolanic materials or latent hydraulicity materials. Finely divided they can be added to Portland cement concrete and mortar, in order to improve some properties or confer special characteristics (Hewlett, 1998).

In this paper, besides sewage sludge ash (SSA), three waste materials generated in various industrial processes were used: a) fly ash from coal power plant (FA); b) marble dust (MD); d) rice husk ash (RHA). Locally in Spain, SSA and MD residues pose a serious problem due to the high quantity of sewage sludge, which was approximately 1.06 million tonnes of dry matter (European Commission, 2010). SSA is used as fertilizer (65-80%), deposit in landfills (8-20%) or incineration to reduce its volume. Approximately 4-10% of the total amount of sludge is incinerated, but the trend is to increase this amount to 20-25%, which is the average in Europe (European Commission, 2010; Ministry of Agriculture, Food and Environment, 2013; Cyr et al, 2007). The problem with these residues after incineration is the presence of heavy metals in its composition, which makes it a potential polluter and justifies an intense search for alternatives to landfill. Regarding MD, although it is not a hazardous waste according to European Waste List (Ministry of Environment, 2002) as its composition is 98% calcium carbonate, the uncontrolled dumping is an historical local problem, as it may cause environmental damages, like visual impact and pollution of water. Currently the province of Alicante (Spain) produces and exports 70% of the national marble, being Spain the second largest producer in Europe and the world's seventh. 500,000 tonnes per year of sludge are generated in Spain as a result of cutting and polishing of natural stone (Alicante Marble Association, 2013).

The effect of these residues individually or in combination, the latter to a lesser extent, as substitutes of conventional binders in cement composites has been thoroughly studied:

- Concrete specimens with SSA as partial replacement of 10% of cement, or 2% substitution of sand, showed similar compression strength as control specimens. Regarding leaching, results indicated that the mixture of SSA with cement and sand in mortars or concretes induced stabilization of Molybdenum and Selenium, being a good treatment of the ashes (Chen et al., 2013). Other studies have shown that mortars containing SSA have good mechanical properties (Monzó et al., 1996; Alcocel et al., 2006). The observed improvement is due to the SSA pozzolanic activity (Payá et al., 2002).
- FA has been used for decades as addition, being its most relevant characteristics: particles sphericity, high contents of vitreous SiO_2 and Al_2O_3, and medium and long term pozzolanic activity. The addition of the FA in Portland cement mortars and concretes increased workability and consistency (Peris et al., 1993).
- In cement / SSA / FA ternary system to fabricate binders, SSA showed high pozzolanic activity, increasing the mechanical strength of mortar at 7 and 28 days. Likewise, fluidity of mortars is reduced by SSA and increased by FA (Monzó et al., 1999; Borrachero et al., 2002).
- Studies showed that adding MD in cement composites is effective to enhance the cohesion of the mix, to replace up to 10% of sand without affecting the compressive strength with improved

mechanical behaviour with respect to mixes containing limestone filler, and also to provide lower water permeability (Corinaldesi et al, 2010;. Binici et al., 2007).

- RHA used as 25% partial replacement of cement in concrete showed the same or better results compared to conventional concrete (Khana et al., 2012). Replacement up to 30% showed improvements in durability and homogeneity, not increasing the compressive strength at early ages but improving compressive strength at older ages (Madandoust et al., 2011).

The main objective of this study was to extend the knowledge about the synergies generated in fresh and hardened concrete for precast blocks (with special characteristics due to the manufacture process) with partial substitutions of Portland cement or addition of waste materials (individually or in binary or ternary combinations). Special attention to SSA has been given. This study is partially based on previous work related to: replacement of cement pastes and mortars by binary and ternary combinations of waste materials (Baeza et al, 2014a) and SSA addition to cement concrete for blocks manufacture (Baeza-Brotons et al., 2014b). New data provided are in accordance to doctoral thesis on the use of SSA in this field (Baeza-Brotons, 2012). These studies about the use of SSA were initiated in a precast concrete blocks research (Perez-Carrion et al., 2014), in which the addition of SSA showed improved mechanical response up to 25%.

Results obtained in this study with cubic concrete specimens would not be directly comparable to the results obtained with plant manufactured concrete blocks, as they differ in size, configuration and manufacturing process. However since there is agreement on the dosage, this work could be a first stage in the plant manufacture of blocks with those additions and the best laboratory results.

1. EXPERIMENTAL

2.1. Materials.

Mineral additions used in this work have the following origins: a) Sewage sludge ash (SSA) has been supplied in bulk by the incinerator of the wastewater treatment plant of Pinedo, in Valencia (Spain), where it was obtained from the discharge electrostatic precipitator of a fluidized bed incinerator at a maximum temperature of 800º C, b) Fly ash (FA) from the coal power plant of Andorra-Teruel (Spain), also in bulk; c) Marble dust (MD) was obtained from a landfill located in the town of Novelda, province of Alicante (Spain) that collects the waste produced by numerous local industries; d) Rice husk ash (RHA) from DACSA (Valencia, Spain) from an energy cogeneration plant which uses rice husks as fuel.

Portland cement used in mortars was CEM II / BL-32.5R type, supplied in bags of 25 kg. Sand for control mortars (CEN, EN 196-1) was supplied in bags with the required quantity of 1350 g. Portland cement used in concretes was CEM II (S-LL)-42,5R, the same type as the one used in the local plant for manufacturing concrete blocks. It is therefore a mixed cement, strength class 42.5 N/mm2 and high initial strength, with the following composition in percentage by mass: 65-79% clinker, 21-35% blast furnace slag plus limestone and 0-5% other minor components, according to Spanish Standard for Cement Receipt (RC-08). Aggregates, crushed limestone type, were supplied by the aforesaid blocks manufacturing plant and corresponded to the size fractions designated according to Spanish Instruction on Structural Concrete (EHE-08) as F1:0/4-T-C and F2:2/8-T-C.

Figure 1. Mineral additives used (left to right): sewage sludge ash (SSA); fly ash (FA); marble dust (MD); rice husk ash (RHA).

2.2. Dosage and designation of mixes.

Mortar used as control (C) was fabricated in accordance to UNE-EN 196-1 (AENOR, 2005): one part cement, three parts sand and half water, keeping constant in all mixes the water to binder ratio, or in other words the water/(cement + mineral additions) ratio equal to 0.5.

The concrete used as control was similar dosage to the one fabricated by a local precast block manufacturer, with dry consistency (Abrams cone of 0 mm). Such consistency is essential in the process of developing these precast concrete blocks, as concrete is poured into moulds which are immediately removed. The dosage in kg per m3 was: 125.6 kg cement, 85.6 kg water, 1227 kg of aggregate size 0-4mm and 571 kg of aggregate size 4-8 mm. Water/binder ratio in all mixes was set to 0.68. Water and cement dosages are lower than conventional concrete. This fact together with a high quantity of fine aggregates (F-0/4), which implies higher water absorption, result in a fresh concrete with a very dry consistency.

In addition to the control specimens, 18 different dosages with waste materials were fabricated, which can be divided in four groups:

a) 10% cement substitution with respect to control, with each one of the mineral residues. Thus, in mixture named S10 (S), 10% of cement was replaced by SSA; in S10 (R) by RHA; in S10 (M) MD; and in S10 (F) by FA.

b) 20% cement substitution. In S20 (S), 20% of cement was replaced by SSA. Also binary combinations (10 + 10%) of two residues in specimens S20 (SF), S20 (SM), S20 (MF) and S20 (SR) were fabricated.

c) 30% cement substitution. In S30 (S), 30% of cement was replaced by SSA. In S30 (SFR) a ternary substitution of cement with 10% of each residue was fabricated. In S30 (SR) 20% SSA and 10% RHA were used.

d) Other dosages with 5, 10, 15 and 20% addition of SSA with respect to cement were used in A5 (S), A10 (S), A15 (S) and A20 (S), respectively. Also 15% addition of MD with respect to cement was fabricated in A15 (M), and finally 10% substitution of sand by SSA was fabricated in Sa10 (S).

2.3. Experimental program and procedure.

Prior to the fabrication of specimens, in order to provide information about the chemical composition of the four residues used in this work as mineral additions, the X-ray fluorescence technique (XRF) was applied. The equipment used to carry out the technique was a sequential X-ray spectrometer (Philips Magix Pro) equipped with rhodium tube and beryllium window. The compressive strength of mortars cured at 28 and 90 days was stablished with three specimens according to Spanish Standard UNE-EN 196-1 (AENOR, 2005) by means of a Suzpecar MEM-101-10A press.

Six cubic concrete specimens of 150 mm sides were fabricated (Figure 2). Three of them were used for physical tests and three for mechanical tests at 28 days curing time.

Figure 2. Concrete specimens fabrication procedure (from left to right): cubic specimens 150 mm sides; premixing of dry components; mixing of concrete; preservation of the specimens in controlled humidity chamber.

As shown in Figure 3, the tests performed on the former specimens were: dry mass density (Dmd), water absorption (Abs) and compressive strength (Cs), in accordance with European Standard EN 771-3 (AENOR, 2011), initial tests for precast concrete blocks. Also Standards UNE-EN 12390-2 (AENOR, 2001), EN 12390-3 (AENOR, 2003) and UNE-EN 12390-7 (AENOR, 2009) were used.

Figure 3. Concrete specimens tests procedure (left to right): Specimens submerged to saturation; density and absorption; compressive strength.

2. RESULTS AND DISCUSSION

3.1. Previous tests.

3.1.1. X-ray fluorescence on additions.

Table 1 shows the results of oxide percentages of the four mineral additions used, obtained by means of XRF.

It can be observed that the SSA has a high content of SiO_2 (17.27%) and Al_2O_3 (9.64%), showing good prospects for its application as active mineral addition on Portland cement composites. Also CaO, SO_3, P_2O_5 and Fe_2O_3 contents should be highlighted. FA shows high silica content (36.70%)

and alumina content (25.57%), much higher than SSA, and therefore it could be classified as FA pozzolanic mineral addition type F (according to ASTM C618). Also its Fe_2O_3 content could be highlights. MD main content is CaO (64.25%) and so it is expected to act as an inert mineral residue. Finally, CEC primarily component is SiO_2 (81.57%), with also high expectations of acting as a pozzolanic addition.

Table 1. Additions' oxide concentration (% by weight) - Analysis by X-ray fluorescence.

SSA			FA			MD			RHA		
Analyte	**Form.**	**Conc.**	**Analyte**	**Form.**	**Conc.**	**Analyte**	**Form.**	**Conc.**	**Analyte**	**Form.**	**Conc.**
Na	Na_2O	0.94	Na	Na_2O	0.17	Na	Na_2O	0.39	Na	Na_2O	0.09
Mg	MgO	3.22	Mg	MgO	1.06	Mg	MgO	6.90	Mg	MgO	0.67
Al	Al_2O_3	9.64	Al	Al_2O_3	25.57	Al	Al_2O_3	1.39	Al	Al_2O_3	0.44
Si	SiO_2	17.27	Si	SiO_2	36.70	Si	SiO_2	3.77	Si	SiO_2	81.57
P	P_2O_5	14.25	P	P_2O_5	0.65	P	P_2O_5	0.09	P	P_2O_5	0.95
S	SO_3	8.95	S	SO_3	1.53	S	SO_3	1.27	S	SO_3	0.33
K	K_2O	1.28	K	K_2O	1.28	K	K_2O	0.30	K	K_2O	3.51
Ca	CaO	30.24	Ca	CaO	5.56	Ca	CaO	64.25	Ca	CaO	1.23
Ti	TiO_2	0.92	Ti	TiO_2	0.90	Fe	Fe_2O_3	0.35	Ti	TiO_2	0.02
Cr	Cr_2O_3	0.17	Cr	Cr_2O_3	0.03	Sr	SrO	0.04	Mn	MnO	0.16
Mn	MnO	0.07	Mn	MnO	0.04	Cl	Cl	0.13	Fe	Fe_2O_3	0.16
Fe	Fe_2O_3	8.52	Fe	Fe_2O_3	15.72				Zn	ZnO	0.01
Ni	NiO	0.03	Ni	NiO	0.02				Sr	SrO	0.01
Cu	CuO	0.18	Zn	ZnO	0.03				Cl	Cl	0.28
Zn	ZnO	0.32	As	As_2O_3	0.01				Br	Br	0.00
As	As_2O_3	0.00	Rb	Rb_2O	0.01						
Rb	Rb_2O	0.01	Sr	SrO	0.11						
Sr	SrO	0.25	Y	Y_2O_3	0.01						
Sn	SnO_2	0.03	Zr	ZrO_2	0.02						
Ba	BaO	0.14	Ba	BaO	0.10						
Pb	PbO	0.04	Pb	PbO	0.01						
Cl	Cl	0.15									

3.1.2. Compressive strength of mortars.

Based on data collected in Table 2 and Figure 4, which show the compressive strength average values of specimens at 28 and 90 days curing times, the following considerations can be drawn:

- As expected, the compressive strength increases with curing time in all mixes.
- Generally compressive strength does not reach control specimen (C) values for both curing times studied except for two mixes at 90 days curing time, i.e. "S10 (R)", with 10% RHA replacement of cement and "S30 (SFR)" with 30% SSA-FA-RHA replacement of cement, which compressive strengths are higher than control. However, most additions at 28 days curing time show similar or higher compressive strength values than the cement strength type used (32.5 MPa) what can be set as a very positive fact.
- Regarding reference series formed by the different substitutions and addition of only SSA, the higher content of such material the less compressive strength, with a decrease of almost 40% compared to control specimen for "S30 (S)" specimens (30% substitution of cement by SSA). However, specimens "Sa10 (S)", with the higher quantity of SSA (as fabricated with 10% sand substitution), shows a very interesting result with a relative value of 88%.

Table 2. Compressive strength (Cs) in MPa of mortar specimens with curing age (D) of 28 and 90 days (rel: relative value in% compared to control).

D	Type	Cs	rel	Type	Cs	rel	Type	Cs	rel	Type	Cs	rel
28	C	38.0	100	S20(S)	31.9	84	S30(S)	23.5	62	A5(S)	32.4	85
90	C	41.1	100	S20(S)	32.3	79	S30(S)	24.4	59	A5(S)	36.9	90
28	S10(S)	33.5	88	S20(SF)	31.8	84	S30(SFR)	33.6	88	A10(S)	34.1	90
90	S10(S)	35.0	85	S20(SF)	34.8	85	S30(SFR)	45.0	109	A10(S)	35.8	87
28	S10(R)	37.5	99	S20(SM)	30.1	79	S30(SR)	34.0	89	A15(S)	34.0	89
90	S10(R)	44.4	108	S20(SM)	31.2	76	S30(SR)	38.2	93	A15(S)	34.9	85
28	S10(M))	27.9	73	S20(MF)	28.8	76				A20(S)	32.1	84
90	S10(M)	28.5	69	S20(MF)	31.3	76				A20(S)	33.3	81
28	S10(F)	33.5	88	S20(SR)	34.2	90				A15(M)	28.6	75
90	S10(F)	37.8	92	S20(SR)	37.5	91				A15(M)	29.2	71
28										Sa10(S)	32.4	85
90										Sa10(S)	36.3	88

- It is also observed that specimens containing MD (inert material), individually or in combination, show lower compressive strength values, which could be associated with the pozzolanic contribution to the compressive strength of other additions.
- The good results obtained with RHA and FA individually (specimens "S10 (R)" and "S10 (F)") are reflected in binary or ternary combinations with SSA and MD.

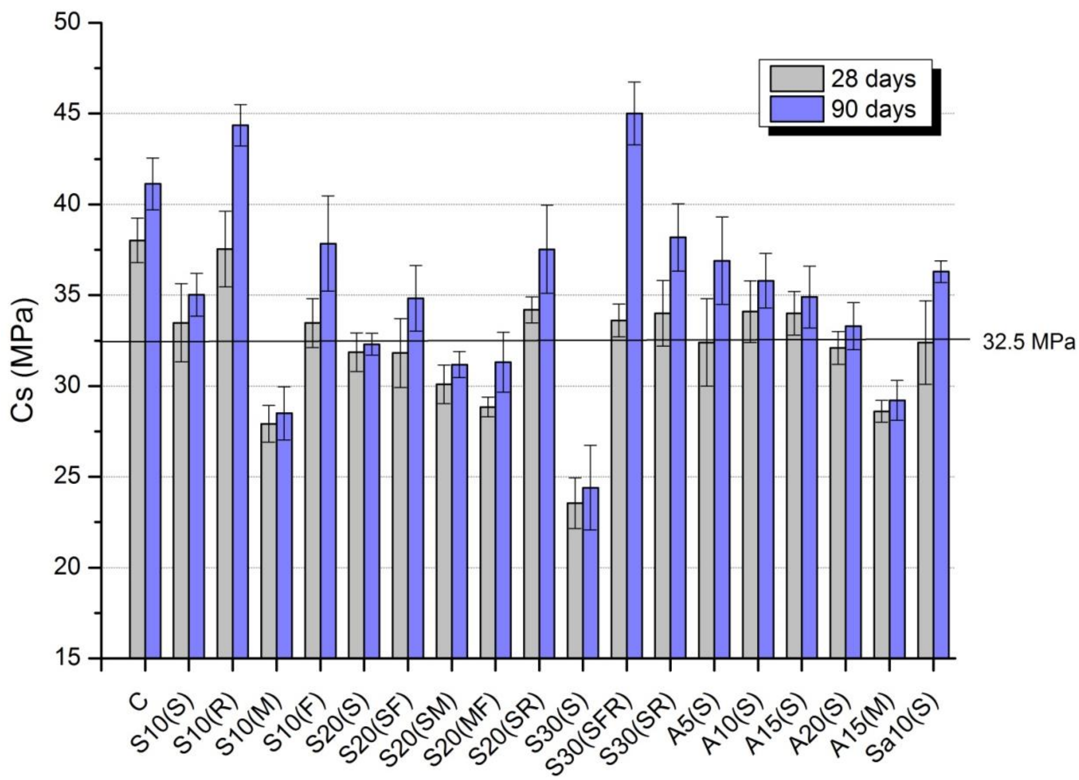

Figure 4. Mean absolute values of compressive strength (Cs) of mortars at 28 and 90 days curing time.

3.2. Concrete results.

3.2.1. Density.

Table 3 and Figure 5 show the mean values of dry mass density of concrete specimens at 28 days curing time. No significant differences in density among relative values are observed, being similar or even higher than control specimens. However, two different behaviours can be observed in specimens with only SSA (shaded in different colour in Figure 5):

a) When SSA substitutes cement, the higher content of SSA, the lower density, which may be due to the lower hydration products as cement content is diminished.

b) When SSA is added, the behaviour is contrary to the former, i.e. higher density as higher quantity of SSA. This is probably due to small particles occupying holes between coarse aggregate, which compensates its low relative specific gravity. The higher values are once more obtained with "Sa10 (S)", the ones with the higher quantity of SSA.

In this so porous cement matrix the pore refinement seems to be more important than the pozzolanic activity of additions, even if they are inert additions as MD.

Ternary mixes show density values slightly higher than the "S30 (S)" (SSA only) ones.

Table 3. Dry mass density (Dmd) in kg/m^3 of concrete specimens at 28 days curing time (rel: relative value in% compared to control specimens).

Type	Dmd	rel	Type	Dmd	rel	Type	Dmd	rel	Type	Dmd	rel
C	2058	100	S20(S)	2085	101	S30(S)	2010	98	A5(S)	2059	100
S10(S)	2131	104	S20(SF)	2056	100	S30(SFR)	2039	99	A10(S)	2087	101
S10(R)	2138	104	S20(SM)	2047	99	S30(SR)	2025	98	A15(S)	2096	102
S10(M)	2091	102	S20(MF)	2074	101				A20(S)	2101	102
S10(F)	2101	102	S20(SR)	2104	102				A15(M)	2103	102
									Sa10(S)	2204	107

3.2.2. Absorption.

Table 4 and Figure 5 show the mean values of water absorption of concrete specimens at 28 days curing time. In this case, as formerly discussed regarding density, there are no major differences between the relative values of the different mixes. However, it can also be observed that decreasing the quantity of cement (replaced by SSA) the absorption values are higher. Moreover, the addition of SSA implies a decrease in absorption values.

Table 4. Water absorption (Abs) in%, of concrete specimens at 28 days curing time (rel: relative value in% compared to control specimens).

Type	Abs	rel	Type	Abs	rel	Type	Abs	rel	Type	Abs	rel
C	8.7	100	S20(S)	7.7	89	S30(S)	9.7	111	A5(S)	8.9	102
S10(S)	6.9	79	S20(SF)	8.3	95	S30(SFR)	8.7	100	A10(S)	7.9	91
S10(R)	6.6	76	S20(SM)	8.8	101	S30(SR)	9.2	106	A15(S)	7.3	84
S10(M)	7.7	89	S20(MF)	8.1	93				A20(S)	7.3	84
S10(F)	7.4	85	S20(SR)	7.4	85				A15(M)	8.1	93
									Sa10(S)	6.0	69

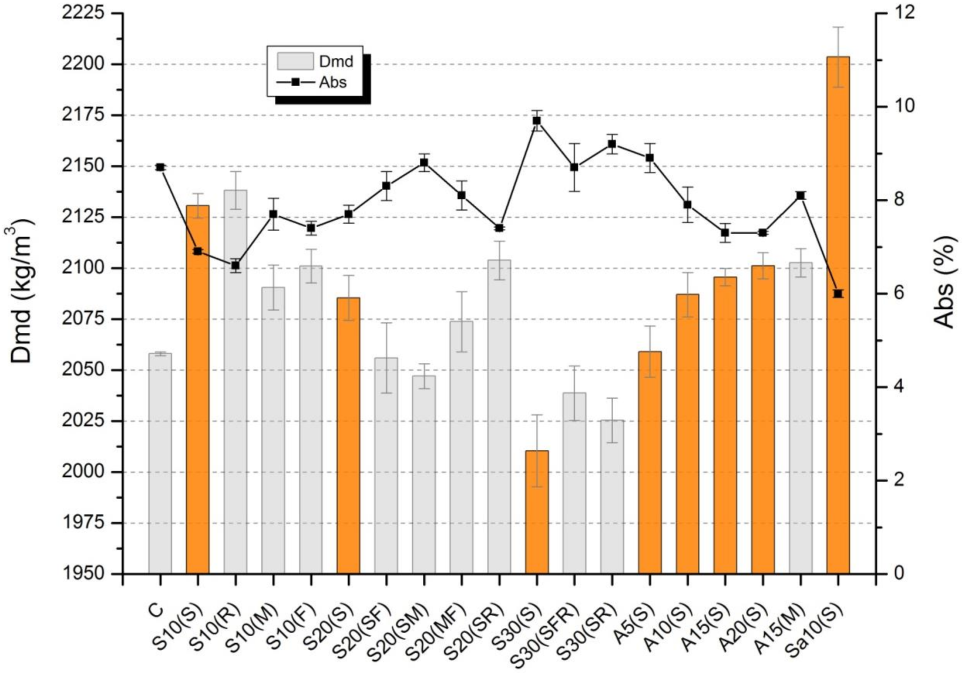

Figure 5. Dry mass density (Dmd) and water absorption (Abs) of concrete specimens at 28 days curing time.

According to density and absorption values obtained, a quasi-linear relation between both of them can be drawn based on statistical analysis (correlation coefficient -0.92), as shown in Figure 6.

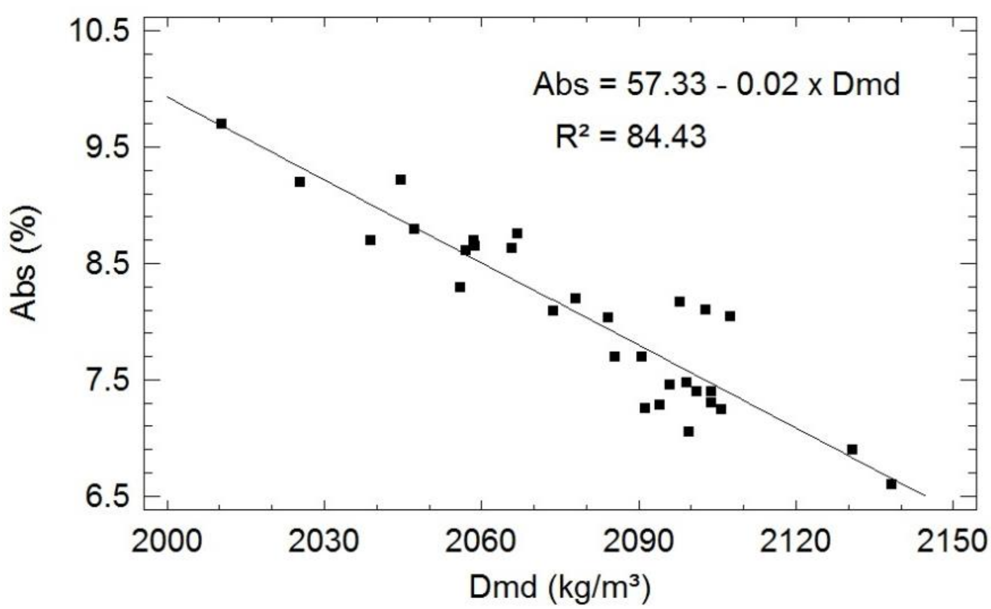

Figure 6. Dry mass density (Dmd) and water absorption (Abs) adjusted model relationship of concrete specimens at 28 days curing time.

3.2.3. Compressive strength.

Table 5 shows the mean values of compressive strength of concrete specimens at 28 days curing time. The values obtained are low due to the high porosity of this type of concrete for precast blocks, e.g. 7 MPa obtained for control specimens.

Table 5. Compression strength (Cs) in MPa of concrete specimens at 28 days curing time (rel: relative value in% of the control specimen).

Type	**Cs**	**rel**	**Type**	**Cs**	**rel**	**Type**	**Cs**	**rel**	**Type**	**Cs**	**rel**
C	7.0	100	S20(S)	5.2	74	S30(S)	4.6	66	A5(S)	7.1	101
S10(S)	6.4	91	S20(SF)	6.6	94	S30(SFR)	6.2	89	A10(S)	6.8	97
S10(R)	7.4	106	S20(SM)	7.1	101	S30(SR)	7.0	100	A15(S)	6.5	93
S10(M)	7.6	109	S20(MF)	6.2	89				A20(S)	5.5	79
S10(F)	7.2	103	S20(SR)	7.5	107				A15(M)	4.0	57
									Sa10(S)	14.4	206

As shown in Figure 7, differently shaded, mixes with substitution of cement or only SSA addition stand out. All of these showed a decrease in compression strength with respect to control, even much sharper in substitutions than in additions, e.g. S30 (S) specimens below 66% of control values.

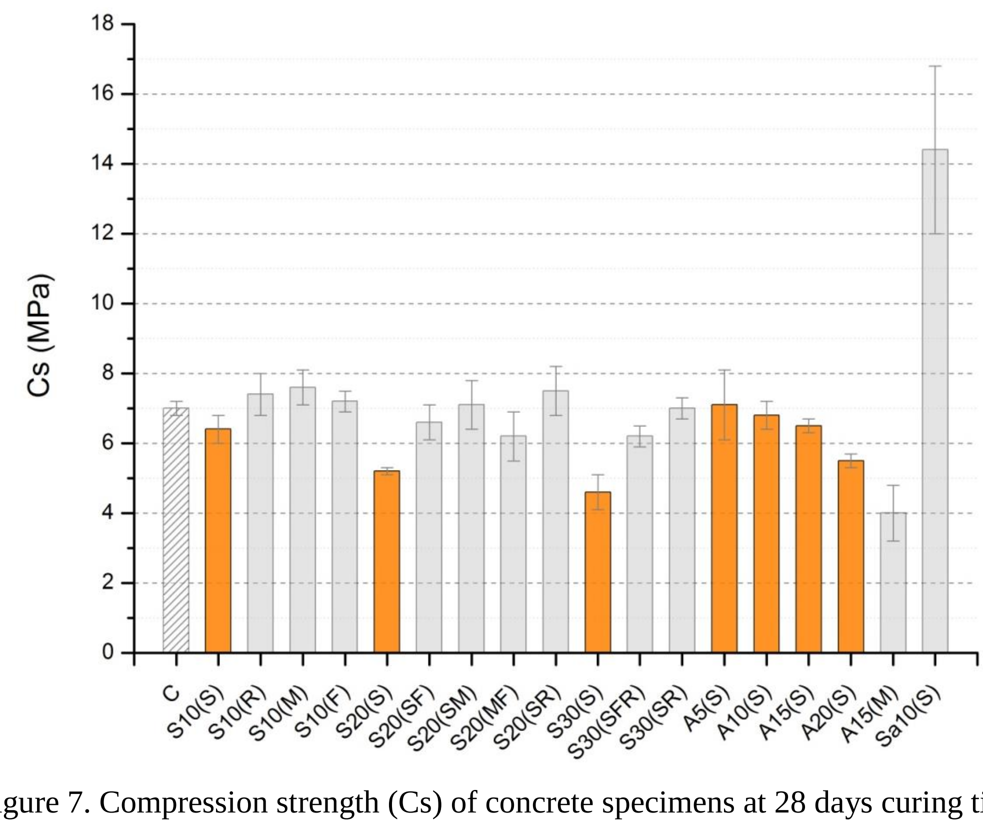

Figure 7. Compression strength (Cs) of concrete specimens at 28 days curing time.

Combinations of waste materials improve the results obtained with only SSA in all cases, with values close or equal to control in several mixes: "S20 (SM)”, "S20 (SR)" or "S30 (SR) ". “S30 (SR)” mix could be highlighted as it was fabricated with a high substitution of cement (30%) with 20% SSA and 10% RHA, and even so its compression strength is similar to control, i.e. 7 MPa.

Therefore, a significant reduction of Portland cement is achieved with excellent mechanical response.
In mixes with additions, although it may appear that SSA has no influence on the development of strength, this is not so, since comparing specimens "A15 (S)" and "A15 (M)" with an addition of 15 % SSA in the first case and of 15% MD in the second, it can be clearly identify a difference in behaviour: the first with 6.5 MPa compared to the second one with 4.0 MPa.
It is worth mentioning the behaviour of "Sa10 (S)" mix, with substitution of sand. Consistent with the density and absorption values observed, the mechanical behaviour shows much higher values than control specimens, as the increase in fine particles implies a denser matrix with fewer voids.

3. CONCLUSIONS

The following conclusions can be drawn from this study:
1. The pozzolanic effect of the mineral additions used has been identified and quantified.
2. The substitution of cement with SSA for the manufacture of precast concrete blocks implies a decrease of density and compressive strength, with respect to control specimens. However, the replacement of cement by binary or ternary combinations of waste materials, significantly improved the physical-mechanical properties, i.e. increase of density and increase of compressive strength, with results close or equal to control specimens in various mixes.
3. The addition of SSA in concrete implies similar results of density and compressive strength than control mixes, whereas water absorption is significantly lower. The behaviour of mixes with 10% sand substitution with SSA can be highlighted, as they showed the best results in density and absorption (as voids are filled with fine particles) and, moreover, their mechanical results are much higher than control mix.

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