Table 1 – Composition and properties of fresh mortars

Fresh properties	Mixture					
	S0	S2	S4	S8	S16	S32
GGBFS [kg/m^3] *(lb/ft^3)*	475 *(29.65)*	475 *(29.65)*	475 *(29.65)*	485 *(30.28)*	480 *(29.96)*	475 *(29.65)*
ACTIVATOR [kg/m^3] *(lb/ft^3)*	0 *(0.00)*	10 *(0.62)*	20 *(1.25)*	40 *(2.50)*	80 *(4.99)*	160 *(9.99)*
% VS GGBFS	0	2	4	8	16	32
Fine aggregate [kg/m^3] *(lb/ft^3)*	1420 *(88.65)*	1420 *(88.65)*	1420 *(88.65)*	1460 *(91.14)*	1445 *(90.21)*	1430 *(89.27)*
Water [kg/m^3] *(lb/ft^3)*	280 *(17.48)*	280 *(17.48)*	280 *(17.48)*	240 *(14.98)*	240 *(14.98)*	205 *(12.80)*
w/cm	0.59	0.59	0.59	0.50	0.50	0.43
Flow [mm] *(in.)*	155 *(6.1)*	160 *(6.3)*	170 *(6.7)*	150 *(5.9)*	165 *(6.5)*	170 *(6.7)*
Fresh Density [kg/m^3] *(lb/ft^3)*	2170 *(135.47)*	2185 (136.41)	2185 *(136.41)*	2220 *(138.59)*	2240 *(139.84)*	2280 *(142.34)*
Pot-life [min]	>360 **	60	60	45	45	30
pH activator solution	7.00	13.26	13.43	13.61	13.70	13.84
Note: ** Pot-life time is longer than 360 minutes						

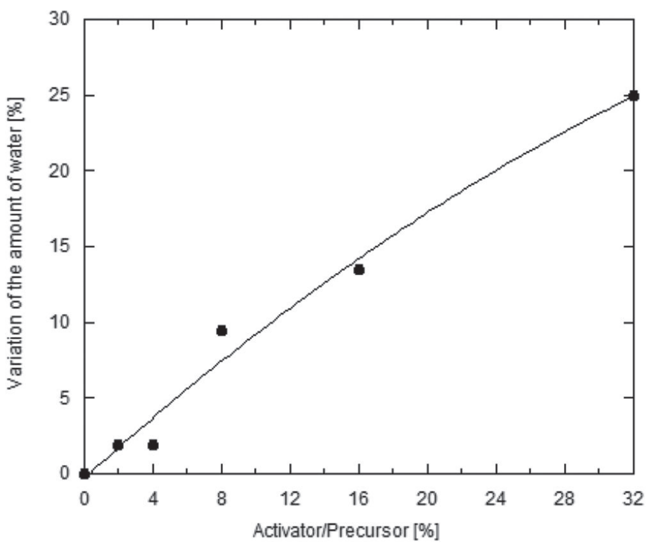

Figure 1 - Variation of the amount of water depending of the percentage of the activator, at equal workability

behavior could be ascribed to the higher amount of water that can evaporate in reference mixture without activator and in mortars manufactured with 2 and 4% of the activator.

Hardened mixtures

Compressive and flexural strength tests were carried out on prismatic specimens according to EN 1015-11. Table 2 and Fig. 5 show compressive and flexural strength at 1, 7 and 28 days. After 24 hours, mortars activated with a dosage lower than 8% were not strong enough to measure mechanical properties. Flexural (Tab. 2) and compressive (Tab. 2 and

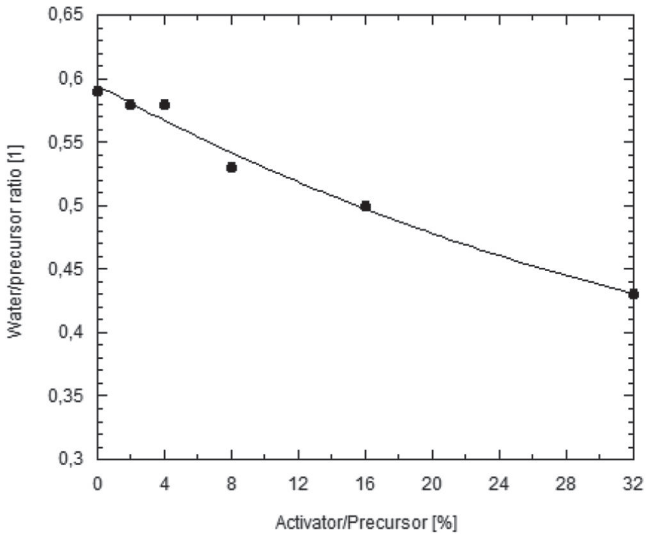

Figure 2 - Variation of the water/precursor depending of the percentage of the activator, at equal workability

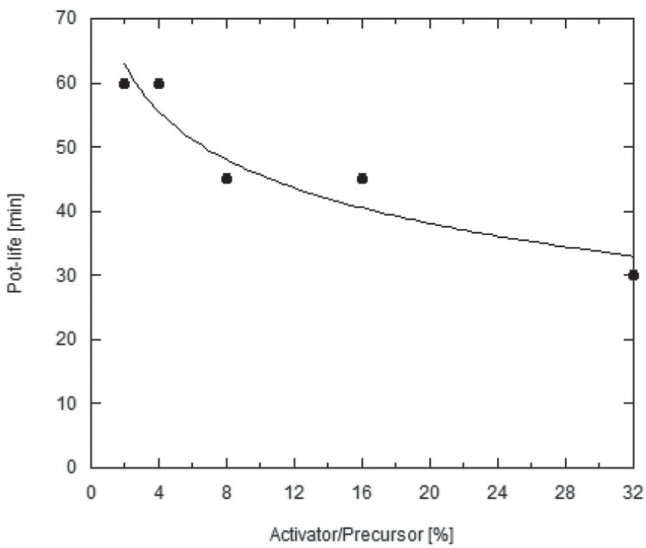

Figure 3 - Pot – life depending of the activator/precursor

Figure 5) strength are strictly related to the dosage of the activator. Independently of the age (1, 7, and 28 days), the higher the activator dosage the stronger mechanically is the mortar. Compressive strength at 28 days was 6.7 MPa (971.8 psi) and 63.7 MPa (9238.9 psi) for the reference mortar and the mixture containing 32% of activator, respectively. This effect is ascribed to the higher amount of silica dissolved as the activator dosage increases. This

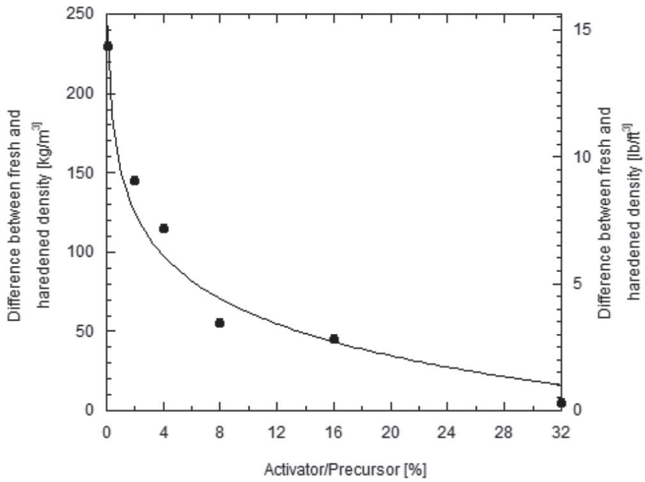

Figure 4 - Difference between fresh and hardened density as a function of activator/precursor

Table 2 – Mechanical properties of hardened mortars

Hardened properties	Mixture					
	S0	**S2**	**S4**	**S8**	**S16**	**S32**
w/cm	0.59	0.59	0.59	0.50	0.50	0.43
Density at hardened state [kg/m^3] *(lb/ft^3)*	1940 *(121.1)*	2040 *(127.4)*	2070 *(129.2)*	2165 *(135.2)*	2195 *(137.0)*	2275 *(142.0)*
	Flexural Strength					
R_f at 24 h [MPa] (psi)	**	**	**	1.2 (174)	2.9 (421)	4.7 (682)
R_f at 7 d [MPa] (psi)	1.1 (160)	3.2 (464)	4.0 (580)	4.0 (580)	6.3 (914)	6.6 (957)
R_f at 28 d [MPa] (psi)	1.2 (174)	3.5 (508)	4.0 (580)	4.4 (638)	6.5 (943)	6.7 (972)
	Compressive Strength					
R_c at 24 h [MPa] (psi)	**	**	**	4.4 (638)	13.8 (2002)	27.9 (4047)
R_c at 7 d [MPa] (psi)	3.7 (537)	13.3 (1929)	18.1 (2625)	34.2 (4960)	49.7 (7208)	55.8 (8093)
R_c at 28 d [MPa] (psi)	6.7 (972)	19.2 (2785)	26.4 (3829)	46.2 (6701)	62.8 (9108)	63.7 (9239)
Note: ** The mixture is not hardened enough to de demolded						

assumption is confirmed by the good correlation between pH of the alkaline activator solution, dissolved silica and 28-day compressive strength of the mortars (Fig. 6) according to Pachego-Torgal.[45] It is therefore possible to "tailor" the compressive strength of alkali-activated material through the dosage of activator. Specifically, reference mortar (no-activated) can be used for plasters and renders (28-day compressive strength: 6.7 MPa (971.8 psi)). Weakly alkali-activated (2 - 4%) slag cement mortars exhibit compressive strength values specified for seismic retrofitting of masonry buildings (28-day compressive strength equal to 19.2 MPa (2784.7 psi) and 26.4 MPa (3829 psi), respectively). Dosages of the activator higher than 8% allows producing mixtures devoted to structural and/or "cosmetic" repairs of existing reinforced concrete elements (Fig. 7). Moreover, it is possible to observe how

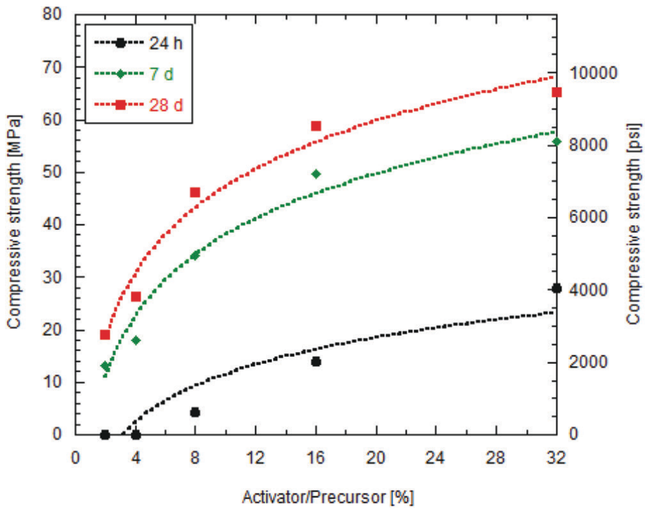

Figure 5 - Compressive strength of mortars

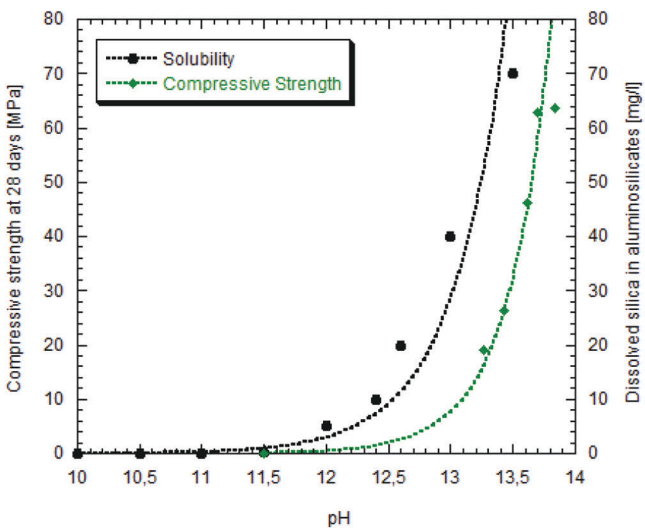

Figure 6 - Variation of compressive strength of mortars at 28 days vs pH and amount of dissolved silica in aluminosilicate vs pH

the strength of the activated slag cement mortars at dosage of 16% and 32% by mass are similar. It can therefore be concluded that there is not any advantage in producing mixtures with activator/precursor equal to 32%.

Shrinkage tests were performed up to 150 days on prismatic specimens at 20 °C (68 °F) and R.H. 60%. Figure 8 shows high free shrinkage of AAMs compared with mixtures manufactured with traditional binders.[46] In addition, it is possible to note that shrinkage is

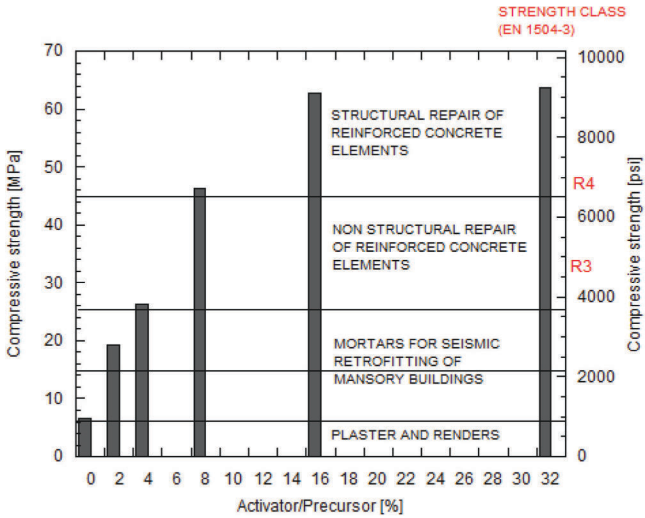

Figure 7 - Compressive strength of slag cement-based mortars at different activator/precursor dosage

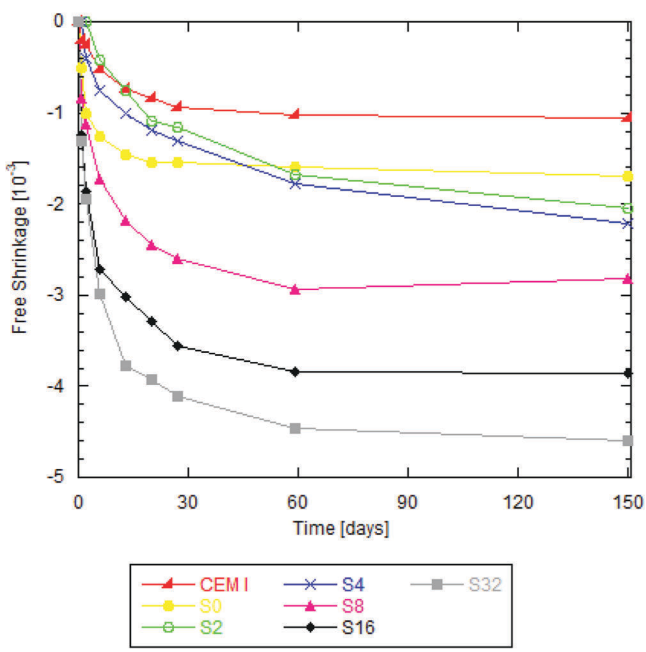

Figure 8 - Free shrinkage of mortars

also influenced by the percentage of alkaline activator. Mortar with 2% activator shows free shrinkage equal to 2000 x 10^{-6} at 150 days from casting, while the mixture with 16% of acti-

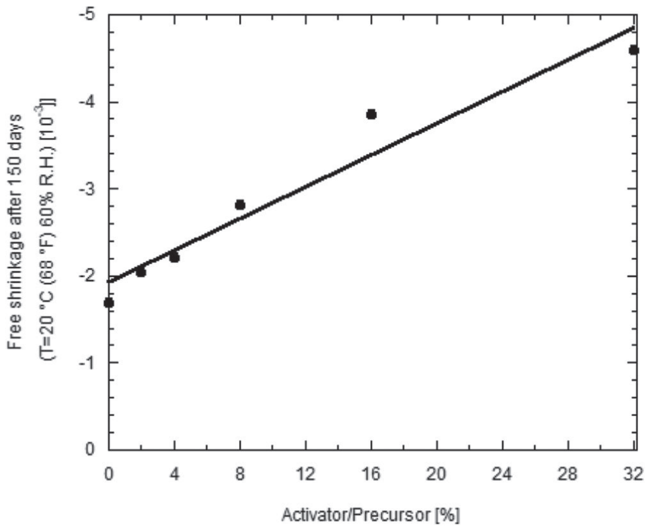

Figure 9 - Free shrinkage of mortars vs activator/precursor

Table 3 – Parameters GER and GWP of raw materials (source Ecoinvent 3.0 database)

	GWP		GER	
	[$kgCO_2/kg$]	(lb CO2/lb)	[MJ/kg]	(kWh/lb)
CEM I 52.5 R	$9.8 \cdot 10^{-1}$	$9.8 \cdot 10^{-1}$	5.50	0.69
GGBFS	$1.7 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$	0.31	0.04
Aggregates	$2.4 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$	0.13	0.02
Sodium metasilicate pentahydrate	1.24	1.24	10.58	1.33
Potassium hydroxide	1.94	1.94	20.50	2.58
Sodium carbonate	2.20	2.20	7.23	0.91

vators experienced a contraction equal to 4200 x 10^{-6} at 150 days. Figure 9 shows a linear relationship between the long-term free shrinkage and the dosage of activator. This effect is probably due to the greater amount of silica dissolved with increasing activator dosage.[46]

As far as elastic modulus, results indicated that the stiffness of AAMs is significantly lower compared with ordinary portland cement mortars, at equal strength class. In particular, low activator/precursor ratios result in Young's modulus ranging from 10 GPa (1.4 x 10^6 psi) and 15 GPa (2.1 x 10^6 psi), while higher activator dosages cause an increase in stiffness and, consequently, elastic modulus grows up to 20 GPa (2.9 x 10^6 psi). Because the elastic modulus is significantly lower than that of a portland cement-based mortar, tensile stress as induced by restrained shrinkage would be low, preventing the AAM from cracking and debonding.

GER AND GWP PARAMETERS

The use of alkali-activated binders gives enormous benefits from the environmental and ecological point of view. For this reason, two fundamental parameters are analyzed: GWP

Table 4 – Parameters GER and GWP of mortars at the same 28-day strength class

28-day compressive strength	Mixture	GER [MJ/m^3]	GER [% vs REF]	GWP [kg CO_2/m^3]	GWP [% vs REF]
25 MPa	OPC	2374	--	395	--
	S4	541	23%	38	10%
45 MPa	OPC	3314	--	566	--
	S8	774	23%	66	12%
65 MPa	OPC	3906	--	674	--
	S16	1242	32%	120	18%

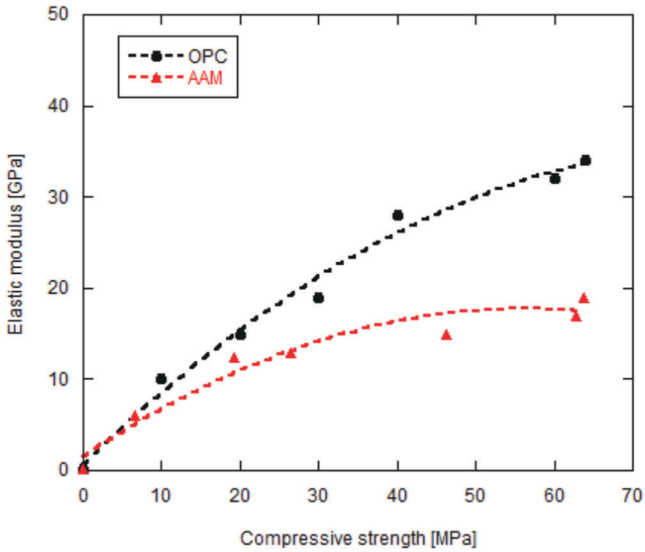

Figure 10 - Elastic modulus as a function of compressive strength (1 MPa = 145 psi)

(Global Warming Potential) and GER (Gross Energy Requirement). In particular, the environmental impact of slag-based mortars was calculated on the basis of the data shown in Table 3 and compared to that of OPC mortars at equal 28-day strength class (Table 4). It is possible to observe how, at the same compressive strength, 80 – 90% and 70 – 80% reduction in greenhouse gas emission and energy production, respectively, can be achieved compared with mortars produced with portland cement (Figure 11).

CONCLUSIONS

In this paper, the performance of mortars made with an alkali-activated binder based on slag cement were evaluated in terms of rheological and physical properties. Experimental results indicated that the key parameter that regulates most of the properties of alkali-activated compounds is the precursor/activator. In particular, slag cement without activator results in compressive strength required for plasters and renders. When the dosage of the

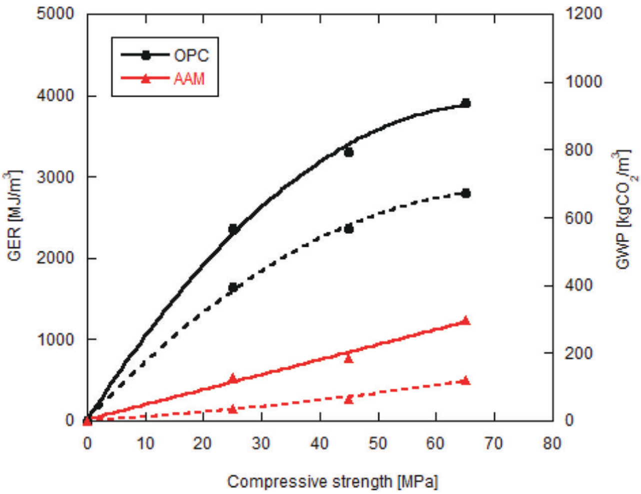

Figure 11 - Variation of GER and GWP of portland cement mortars and slag cement mortars as a function of compressive strength (1 MPa = 145 psi)

activator is in the range 2-4% by precursor mass, mortars exhibit compressive strength values specified for seismic retrofitting of masonry buildings. Activator dosage higher than 8% (vs precursor mass) allows for mixtures that can be used for structural and/or "cosmetic" repair of existing reinforced concrete elements. No significant benefits are observed in increasing the percentage of activator above 16%.

Shrinkage values for AAMs are significantly higher (2000 – 4000 x 10^{-6}) compared with a Portland cement-based mortars at the same compressive strength. However, although shrinkage is very high, the modulus of elasticity is about 40% lower than that of a Portland cement mortar (at the same strength level). This means that tensile stress as induced by restrained shrinkage could still be low, preventing the AAM from cracking and debonding.

At the same compressive strength, AAMs evidence 80 – 90% and 70 – 80% reduction in greenhouse gas emission and energy consumption, respectively, compared to mortars produced with portland cement.

In conclusion, from the analysis of the strengths and weaknesses of alkali-activated slag cement, it turns out that alkali-activated mortars and concretes can be reasonable alternatives to natural hydraulic lime-based and/or traditional portland cement-based mixtures for rehabilitation or restoration of ancient masonry buildings and existing concretes structures.

Further experimentations are needed to measure the adhesion properties, tensile strength and capillary absorption of these eco-friendly slag binders. In addition, durability issues of mortars have to be investigated, especially in chloride and sulfate – rich environments or subjected to freeze and thaw cycles.

AUTHOR BIOS

Luigi Coppola, *engineer, is professor of Structural and Repair Materials for Concrete Construction at University of Bergamo (Italy), Department of Engineering and Applied*

Sciences. He has authored more than one hundred and seventy papers and eighteen books on concrete properties, durability, admixtures, and self-compacting concretes. He was recipient of the CANMET/ACI award for the outstanding and sustained contribution to concrete durability.

Denny Coffetti*, engineer, is a PhD student at University of Bergamo (Italy), Department of Engineering and Applied Sciences. His research topics are related to sustainability and durability of concrete structures.*

Elena Crotti*, engineer, is a research fellow at University of Bergamo (Italy), Department of Engineering and Applied Sciences. Her research is mainly devoted to study alternative binders to portland cement.*

REFERENCES

1. Coppola, L.; Coffetti, D.; and Lorenzi, S., "Cement-Based Renders Manufactured with Phase-Change Materials: Applications and Feasibility," *Advances in Materials Science and Engineering*, V. •••, 2016, p. 2016

2. Coppola, L.; Coffetti, D.; and Crotti, E., "Plain and ultrafine fly ashes mortars for environmentally friendly construction materials," *Sustainability (Switzerland)*, V. 10, 2018, doi: 10.3390/su10030874

3. L. Coppola, S. Lorenzi, S. Pellegrini, Rheological and mechanical performances of concrete manufactured by using washing water of concrete mixing transport trucks, ACI SPECIAL PUBLICATIONS. (2016) 32.1-32.12.

4. Coppola, L.; Cerulli, T.; and Salvioni, D., Sustainable development and durability of self-compacting concretes, in: 11th Int. Conf. Fract. 2005, ICF11, 2005.

5. L. Coppola, S. Lorenzi, P. Marcassoli, G. Marchese, Concrete production by using cast iron industry by-products | Impiego di sottoprodotti dell'industria siderurgica nel confezionamento di calcestruzzo per opere in c.a. e c.a.p, Industria Italiana Del Cemento. 77 (2007).

6. Rashad, A. M., and Sadek, D. M., "An investigation on Portland cement replaced by high-volume GGBS pastes modified with micro-sized metakaolin subjected to elevated temperatures," *International Journal of Sustainable Built Environment.*, V. 6, No. 1, 2017, pp. 91-101. doi: 10.1016/j.ijsbe.2016.10.002

7. Elchalakani, M.; Aly, T.; and Abu-Aisheh, E., "Sustainable concrete with high volume GGBFS to build Masdar City in the UAE," *Case Studies in Construction Materials.*, V. 1, 2014, pp. 10-24. doi: 10.1016/j.cscm.2013.11.001

8. Tsiliyannis, C. A., "Cement manufacturing using alternative fuels: Enhanced productivity and environmental compliance via oxygen enrichment," *Energy*, V. 113, 2016, pp. 1202-1218. doi: 10.1016/j.energy.2016.07.082

9. Aranda Usón, A.; López-Sabirón, A. M.; Ferreira, G.; and Llera Sastresa, E., "Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options," *Renewable & Sustainable Energy Reviews*, V. 23, 2013, pp. 242-260. doi: 10.1016/j.rser.2013.02.024

10. Rahman, A.; Rasul, M. G.; Khan, M. M. K.; and Sharma, S., "Recent development on the uses of alternative fuels in cement manufacturing process," *Fuel*, V. 145, 2015, pp. 84-99. doi: 10.1016/j.fuel.2014.12.029

11. Monosi, S.; Troli, R.; Coppola, L.; and Collepardi, M., "Water reducers for the high alumina cement-silica fume system," *Materials and Structures*, V. 29, No. 10, 1996, pp. 639-644. doi: 10.1007/BF02485972

12. Coppola, L.; Belz, G.; Dinelli, G.; and Collepardi, M., "Prefabricated building elements based on FGD gypsum and ashes from coal-fired electric generating plants," *Materials and Structures*, V. 29, No. 5, 1996, pp. 305-311. doi: 10.1007/BF02486365

13. Thomas, M., "The effect of supplementary cementing materials on alkali-silica reaction: A review," *Cement and Concrete Research*, V. 41, No. 12, 2011, pp. 1224-1231. doi: 10.1016/j.cemconres.2010.11.003

14. Lothenbach, B.; Scrivener, K.; and Hooton, R. D., "Supplementary cementitious materials," *Cement and Concrete Research*, V. 41, No. 12, 2011, pp. 1244-1256. doi: 10.1016/j.cemconres.2010.12.001

15. Krajči, Ľ.; Mojumdar, S. C.; Janotka, I.; Puertas, F.; Palacios, M.; and Kuliffayová, M., "ʼudovít Krajči, S.C. Mojumdar, I. Janotka, F. Puertas, M. Palacios, M. Kuliffayová, Performance of composites with metakaolin-blended cements," *Journal of Thermal Analysis and Calorimetry*, V. 119, No. 2, 2015, pp. 851-863. doi: 10.1007/s10973-014-4119-2

16. Rashad, A. M., "Metakaolin as cementitious material: History, scours, production and composition-A comprehensive overview," *Construction & Building Materials*, V. 41, 2013, pp. 303-318. doi: 10.1016/j.conbuildmat.2012.12.001

17. Coppola, L.; Bellezze, T.; Belli, A.; Bignozzi M.C.; Bolzoni, F.; Brenna, A.; Cabrini, M.; Candamano, S.; Cappai, M.; Caputo, D.; Carsana, M.; Casnedi, L.; Cioffi, R.; Cocco, O.; Coffetti, D.; Colangelo, F.; Coppola, B.; Corinaldesi, V.; Crea, F.; Crotti, E.; Daniele V.; De Gisi, S.; Delogu, F.; Diamanti, M.V.; Di Maio, L.; Di Mundo, R.; Di Palma, L.; Donnini, J.; Farina, I.; Ferone, C.; Frontera, P.; Gastaldi, M.; Giosuè, C.; Incarnato, L.; Liguori, B.; Lollini, F.; Lorenzi, S.; Manzi, S.; Marino, O.; Marroccoli, M.; Mascolo, M.C.; Mavilia, L.; Mazzoli, A.; Medici, F.; Meloni, P.; Merlonetti, G.; Mobili, A.; Notarnicola , M.; Ormellese, M.; Pastore, T.; Pedeferri, M.P.; Petrella, A.; Pia, G.; Redaelli, E.; Roviello, G.; Scarfato, P.; Scoccia, G.; Taglieri, G.; Telesca, A.; Tittarelli, F.; Todaro, F.; Vilardi, G.; Yang, F., "Binders Alternative to Portland Cement and Waste Management for Sustainable Construction-Part 1," *Journal of Applied Biomaterials and Functional Materials*, 16(3), pp 186-202, 2018.

18. Telesca, A.; Marroccoli, M.; Pace, M. L.; Tomasulo, M.; Valenti, G. L.; and Monteiro, P. J. M., "A hydration study of various calcium sulfoaluminate cements," *Cement and Concrete Composites*, V. 53, 2014, pp. 224-232. doi: 10.1016/j.cemconcomp.2014.07.002

19. Coppola, L; Coffett, D; Crotti, E; Pastore, T.; "CSA-Based Portland-Free Binders to Manufacture Sustainable Concretes for Jointless Slabs on Ground," *Construction and Building Materials*, 187, pp. 691-698, 2018.

20. Coppola, L.; Buoso, A.; Coffetti, D.; Kara, P.; and Lorenzi, S., "Electric arc furnace granulated slag for sustainable concrete," *Construction & Building Materials*, V. 123, 2016, pp. 115-119. doi: 10.1016/j.conbuildmat.2016.06.142