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Valorization of Industrial Wastes on Hybrid Low Embodied Carbon Cement Based Mortars

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***Abstract*—**Waste reuse is crucial in a context of circular economy and zero waste sustainable needs. Some wastes deserve further studies by the scientific community not only because they are generated in high amount but also because they have a low reuse rate. This paper reports results of 32 hybrid cement mortars based on fly ash and waste glass. They allow to explore the influence of mix design on the cost and on the embodied carbon of the hybrid cement mortars. The embodied carbon data for all constituents were taken from the database Ecoinvent. This study led to the development of a mixture with just 70 kg CO_{2e}.

***Keywords*—**Waste reuse, fly ash, waste glass, hybrid cements, cost, embodied carbon.

I. INTRODUCTION

WASTE reuse is crucial not only to avoid putting pressure on non-renewable raw materials but also the environmental degradation associated with waste landfill [1]. Some wastes like fly ash (FA) and waste glass deserve an especial attention because they are generated in high amount and have a very low reuse rate [2], [3].

Hybrid cements involve the activation of industrial wastes with alkaline activators, usually composed of hydroxide, silicate, carbonate, or sulfate leading to co-precipitation of two gels (C-S-H + N-A-S-H) but over time a C-A-S-H type gel would be the most thermodynamically stable product [4], [5]. These materials have a particular ability for the reuse of several types of wastes [6], [7]. Thus, the valorization of FA and waste glass in hybrid cement would have obvious environmental benefits. However, several authors [8] state that cost and embodied carbon are crucial, so they can become a real construction material. Therefore, the purpose of this paper is to understand how the composition of hybrid cements based on FA and waste soda lime silicate glass influences its cost and embodied carbon.

II. EXPERIMENTAL PROGRAM

A. Materials and Design

The raw materials used for the preparation of the hybrid cement mortars were FA, calcium hydroxide (CH), fine aggregate, milled glass (MG), and sodium hydroxide solution. The FA was obtained from The PEGO Thermal Power Plant in Portugal and it was classified as class F according to ASTM-C618 standard. The chemical composition of the FA selected for this study is presented in Table I.

TABLE I
CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF FA

Composition	(wt. %)
SiO_2	60.81
Al_2O_3	22.68
Fe_2O_3	7.64
MgO	2.24
Na_2O	1.45
CaO	1.01
TiO_2	1.46
K_2O	2.70
Physical properties	
Specific gravity	2.30
Specific surface (cm^2/g)	3430

The CH used in this study had a commercial name of Lusical H100 and chemical composition of $Ca(OH)_2 \geq 93\%$ and $MgO \leq 3$. Waste soda lime silicate glass was provided by the use of glass bottles that were ground for 1h in a ball mill. The density of the MG was 1.27 g/cm^3. Solid sodium hydroxide which was obtained from commercially available product of ERCROS, S.A., Spain, was used to prepare three solutions with different concentrations (4 M and 12 M). The chemical composition of the sodium hydroxide was composed of 25%Na_2O and 75%H_2O. The NaOH mix was made one day prior to use in order to have a homogenous solution at the time of mortar preparation. A sand/binder ratio of 4 was used. The sand was used as inert filler provided from the MIBAL, Minas de Barqueiros, S.A. Portugal. Two commercial supersplasticizers supplied by BASF and SIKA were used. Its content was 0.1% of the binder weight. The first one is a polycarboxylate-based admixture, and the other one is lignosulfonate-based. Two activator/binder ratios were used (0.4 and 0.5). Table II shows the compositions of the 32 mortars. The materials (Table III) and the embodied carbon data were taken from the database Ecoinvent (Table IV).

III. RESULTS AND DISCUSSION

A. Cost

Fig. 1 shows the cost of the mixtures according to the activator/binder ratio. The results show that a higher sodium hydroxide concentration and a higher activator/binder ratio are associated with a higher cost. The mixtures with 12 M and an activator/binder ratio of 0.5 have a cost around 140 euro/m^3. This is almost independent of the presence of the admixtures and the MG percentage because when one looks at the contribution of each materials, it is possible to see that sodium hydroxide is responsible for more than 40% of the total cost. Sand is responsible for around 30%, while FA represents

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around 10%. The contribution of polycarboxylate and lignosulphonate as admixture is lower than 2% of the total cost. The results also show that the minimum cost was found to be around 100 euro/m^3 for 80% FA, 10% waste glass and 10% CH activated with a 4-M concentration sodium hydroxide solution and an activator/binder of 0.4.

TABLE II
COMPOSITIONS (KG/M^3)

Mix composition	FA	CH	MG	NaOH	Sand
80FA_10CH_10MG_4M_0.5A/B	377	47	47	236	1884
75FA_10CH_15MG_4M_0.5A/B	350	47	70	233	1864
70FA_10CH_20MG_4M_0.5A/B	328	46	92	230	1844
80FA_10CH_10MG_12M_0.5A/B	377	47	47	236	1884
75FA_10CH_15MG_12M_0.5A/B	350	47	70	233	1864
70FA_10CH_20MG_12M_0.5A/B	328	46	92	230	1844
80FA_10CH_10MG_4M_0.5A/B_0.1% Poly.	377	47	47	236	1884
75FA_10CH_15MG_4M_0.5A/B_0.1% Poly.	350	47	70	233	1864
70FA_10CH_20MG_4M_0.5A/B_0.1% Poly.	328	46	92	230	1844
80FA_10CH_10MG_12M_0.5A/B_0.1% Poly.	377	47	47	236	1884
75FA_10CH_15MG_12M_0.5A/B_0.1% Poly.	350	47	70	233	1864
70FA_10CH_20MG_12M_0.5A/B_0.1% Poly.	328	46	92	230	1844
80FA_10CH_10MG_4M_0.5A/B_0.1% Ligno.	377	47	47	236	1884
75FA_10CH_15MG_4M_0.5A/B_0.1% Ligno.	350	47	70	233	1864
70FA_10CH_20MG_4M_0.5A/B_0.1% Ligno.	328	46	92	230	1844
80FA_10CH_10MG_12M_0.5A/B_0.1% Ligno.	377	47	47	236	1884
75FA_10CH_15MG_12M_0.5A/B_0.1% Ligno.	350	47	70	233	1864
70FA_10CH_20MG_12M_0.5A/B_0.1% Ligno.	328	46	92	230	1844
80FA_10CH_10MG_4M_0.4A/B	385	48	48	193	1928
75FA_10CH_15MG_4M_0.4A/B	358	48	72	191	1908
70FA_10CH_20MG_4M_0.4A/B	330	47	94	189	1888
80FA_10CH_10MG_12M_0.4A/B	385	48	48	193	1928
75FA_10CH_15MG_12M_0.4A/B	358	48	72	191	1908
70FA_10CH_20MG_12M_0.4A/B	330	47	94	189	1888
80FA_10CH_10MG_4M_0.4A/B_0.1% Poly.	385	48	48	193	1928
75FA_10CH_15MG_4M_0.4A/B_0.1% Poly.	358	48	72	191	1908
70FA_10CH_20MG_4M_0.4A/B_0.1% Poly.	330	47	94	189	1888
80FA_10CH_10MG_12M_0.4A/B_0.1% Poly.	385	48	48	193	1928
75FA_10CH_15MG_12M_0.4A/B_0.1% Poly.	358	48	72	191	1908
70FA_10CH_20MG_12M_0.4A/B_0.1% Poly.	330	47	94	189	1888
80FA_10CH_10MG_4M_0.4A/B_0.1% Ligno.	385	48	48	193	1928
75FA_10CH_15MG_4M_0.4A/B_0.1% Ligno.	358	48	72	191	1908
70FA_10CH_20MG_4M_0.4A/B_0.1% Ligno.	330	47	94	189	1888
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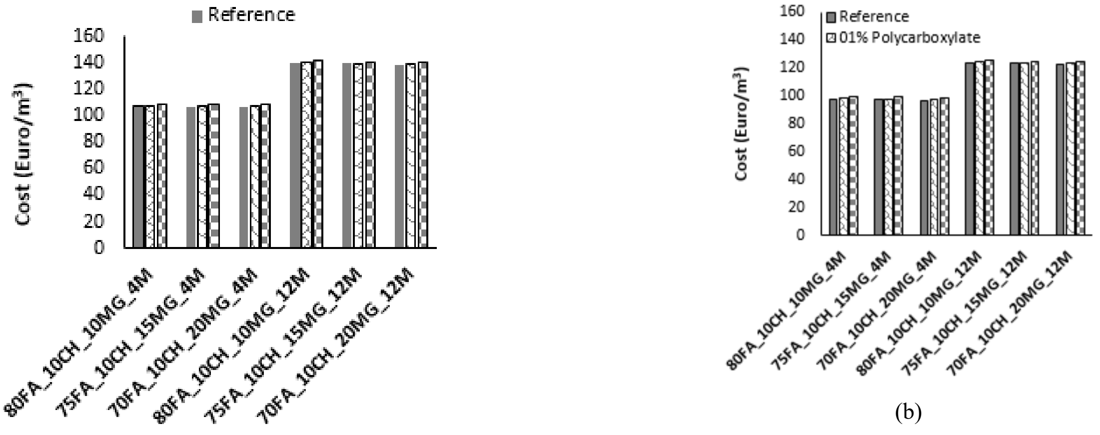

(a)

(b)

Fig. 1 Costs of mix compositions with alkali activator to binder of: (a) 0.5; (b) 0.4

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TABLE III
COST OF THE MATERIALS

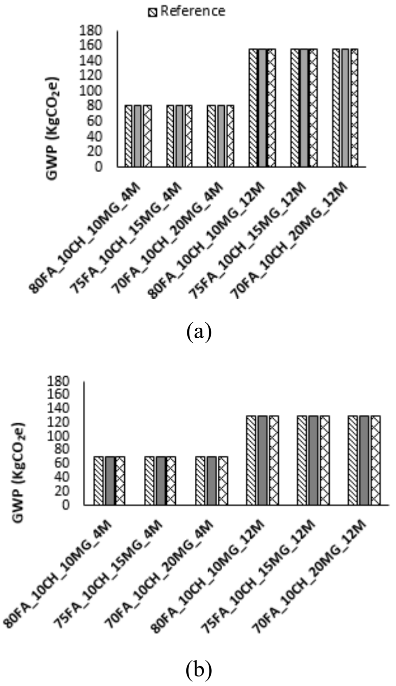
Constituent	Cost (€/kg)
Sand	0.02
MG	0.009
CH	0.3
FA	0.03
Sodium silicate	0.29
Biop. Carrageenan	105
Biop. Xanthan	84

TABLE IV
EMBODIED CARBON

Constituent	GWP (kgCO$_{2eq}$)
Sand	2.40x10^{-3}
MG	5.00x10^{-3}
CH	4.26x10^{-1}
FA	5.26x10^{-3}
Sodium silicate	1.76x10^{0}
Biop. Carrageenan	7.49x10^{-1}
Biop. Xanthan	7.49x10^{-1}

B. Embodied Carbon

Fig. 2 shows the embodied carbon according to the activator/binder ration. The results also show that a mixture of 80% FA, 10% waste glass, and 10% CH activated with a 4 M concentration sodium hydroxide solution has the lower embodied carbon (70 KgCO$_{2e}$). The results also demonstrate that the sodium hydroxide has a major influence on the global embodied carbon performance of the mixtures. Mixtures with a 12-M sodium hydroxide concentration and an activator/binder ratio of 0.5 have around 160 kg CO$_{2e}$. This is because for those mixtures sodium hydroxide represents more than 80% of the global embodied carbon (Fig. 3).



(a)

(b)

Fig. 2 GWP of mix compositions with alkali activator to binder of: a) 0.5; b) 0.4

IV. CONCLUSIONS

The results show that the minimum cost was found to be around 100 euro/m^3 for 80% FA, 10% waste glass, and 10% CH activated with a 4-M concentration sodium hydroxide solution and an activator/binder of 0.4. The results show that the reduction on the sodium hydroxide concentration and the activator/binder ratio led to lower embodied carbon. The mixture of 80% FA, 10% waste glass, and 10% CH activated with a 4-M concentration sodium hydroxide solution has the lower embodied carbon (70 kg CO$_{2e}$).

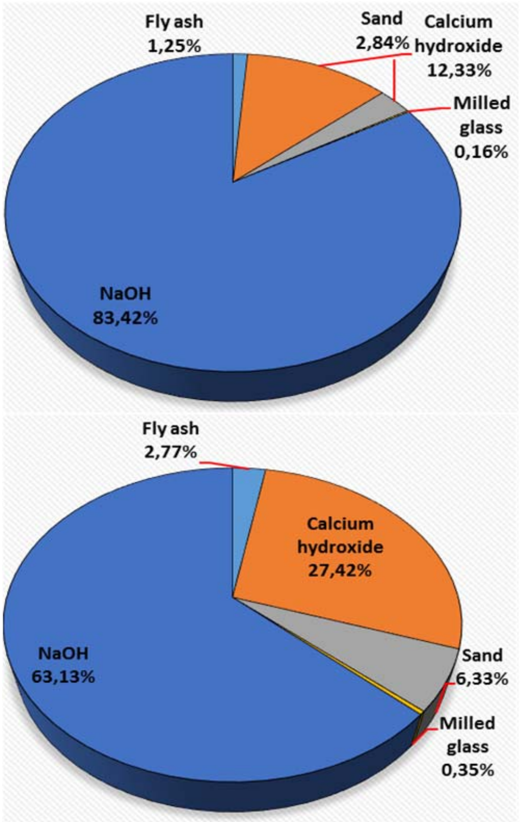


Fig. 3 Embodied carbon according to constituent materials percentage: Above mixture 80FA_10CH_10MG 12M (A/B=0.5). Below mixture 80FA_10CH_10MG 4M (A/B=0.4)

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