

# Analysis of Carbonation in Mortars made with Solid Waste as a Substitute for Cement

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**Abstract**—This research evaluates the behaviour of Portland cement-based mortars with additives that act as cementing materials. These additions are silica rich materials used as substitutes for PC (Portland cement type IV ASTM) in the preparation of mortars, as an alternative to reduce the amount of cement, reusing agribusiness waste. The results indicate that the use of some additions in the percentages specified herein is not convenient to mitigate the phenomenon of carbonation, since as the degree of substitution increases, the speed also increases carbonation. On the other hand, if the emission of polluting particles into the environment is mitigated, the amount of cement used in the mortar decreases.

**Keywords**—solid waste substitute; mortars cement; carbonation

## I. INTRODUCTION

In nature, the CO<sub>2</sub> present in the atmosphere and the lithosphere (soil and water), when combined with water produces H<sub>2</sub>CO<sub>3</sub>, which generates a pH reduction. This is deleterious to sedimentary rocks (limestone), as it promotes its dissolution, forming bicarbonate ions (HCO<sub>3</sub><sup>-</sup>) [3].

One of the main environmental concerns since the late twentieth century is global warming, which is the temperature increase on the planet. As a result, climate change is predicted to affect the stability of existing ecosystems and thus the species that inhabit them are threatened. The gases that are targeted to cause this phenomenon are methane (CH<sub>4</sub>), nitrous

oxides (N<sub>x</sub>O<sub>y</sub>) and CO<sub>2</sub>, among others.

The construction building material used in the greatest quantities is currently concrete. This is because of its versatility in terms of the geometric shape that it can adopt and its application either on site or prefabricated. It is composed of cement, coarse aggregate (gravel), fine aggregate (sand) [1, 2], water and sometimes additives and additions that encourage the hardening material to form a compact appearance; also, cement-based mortar is the most commonly used material, and so is the focus in this paper.

Cement is the binder component in the concrete/mortar, so the specific final properties depend largely on its quality and dosage. This material is obtained by calcining limestone with clay in a kiln. In this process, the limestone releases CO<sub>2</sub> into the atmosphere. Furthermore, the CO<sub>2</sub> produced by the combustion of hydrocarbons to reach the calcination temperature leads to the generation of close to one ton of CO<sub>2</sub> per ton of cement. By mixing the cement with water, compounds are produced that provide rigidity and coalesce with other components into a solid mass. As reaction products, calcium hydroxide (Ca(OH)<sub>2</sub>), sodium hydroxide (NaOH) and potassium hydroxide (KOH) are generated, giving it an alkaline pH close to 12.5 [3].

The preparation of mortar requires a dosage of water for the cement compounds to react fully. Excess water is trapped in the rigid paste, causing pores to fill with water. The solution in

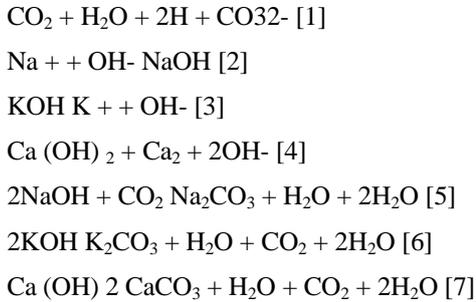
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the pores acquires an alkaline pH by dissolving the hydroxides produced from the reaction of cement with water [2].

*A. Carbonation Process*

The water contained in the pores of the concrete is able to dissolve the CO<sub>2</sub> in the atmosphere forming H<sub>2</sub>CO<sub>3</sub>, an acid which is combined with alkali in a neutralization reaction by reducing the pH of the solution [5].



As the compound formed at the end is CaCO<sub>3</sub>, it is called the carbonation process.

Due to the porosity of the concrete and relative humidity conditions in the exposure environment, the pores may encounter different filling conditions. In the case of saturation of the pore, the transportation of carbon dioxide (CO<sub>2</sub>) occurs by diffusion, being a very a slow progress in the order of 8–10cm<sup>2</sup>/s, causing no deterioration risk to the concrete by carbonation. When the relative humidity is very low, as in arid and semi-arid areas, the amount of water retained in the pores is not sufficient for carbonation to occur. The most favourable conditions for the progress of the carbonation occurs when the relative humidity of the medium is in the range 60 to 75%. Thus, it is seen that the carbonation phenomenon is strongly linked to weather conditions such as high relative humidity, temperature, and rainfall, among others, which determine the pore filling and thereby the advancement of the carbonation [3, 5].

*B. Measuring progress of carbonation.*

The visual way to measure a change in pH is with the use of acid-base indicators, which change colour at certain pH ranges. The carbonation effect, in particular, the pH, can range from 12.5 to near 8. Phenolphthalein indicator presents a violet colour at pH values greater than 10 and is colourless at pH values less than 8.3. CO<sub>2</sub> is a compound essential for life, but it also produces adverse effects on the ecosystem and on the stability and durability of civil works constructed of reinforced concrete [5].

**II. EXPERIMENTAL PROCEDURE**

A regional field study was conducted to ascertain the most abundant solid waste and the need for producers to remove it without further investment. The residues were characterized in terms of their use as building materials and their mechanical effects on the cement mortar base, also their pozzolan effect. The additions were studied as replacements of Portland cement in different percentages [2, 3].

The additions were agro-industrial waste used as furnace bottom ash CBOF 15% (coke oven blast furnace, Arcelor Mittal, Mexico); CEL 5% ash brick making (ash brick making annealed clay handmade Santiago Undameo, Mexico); CM 15% coal (Arcelor Mittal, Mexico), and 15% blast furnace slag EAH (Arcelor Mittal, Mexico). All of them were compared against two controls made with cement CPC 30 R RS, comparable to PC ASTM C-150 Type IV. Control one, T1 standard, was developed with silica sand from Rio Lerma, State of Mexico, Mexico; control 2, T2, was made from silica sand from the Huajumbaro River, Michoacan, Mexico [3], the sands were then LERM and HUAJ.

The sands were sampled from the quarry stones of the rivers mentioned in the dry season, then moved to the materials laboratory at Ing. Luis Silva Ruelas where characterization tests were performed as specified in ASTM. All tests were performed in triplicate and the values given are the average of three quantifications.

TABLE I. PHYSICAL TESTING OF AGGREGATES

Test	Standard	Lerma Sand	Huajumbaro Sand
Sampling	ASTM D-75	250 kgf	250 kgf
Reducing samples	ASTM C-702	0.500 kgf	0.500 kgf
Bulk density (unit weight) and voids	ASTM C-29/ C-29M	1.353	1.226
Bulk density (unit weight)	ASTM C-29/ C-29M	1.444	1.331
Relative density	ASTM C-128	2.40	2.31
Specific gravity	ASTM C-128	2.39–2.48	2.24–2.36
Surface moisture (%)	ASTM C-128, C-70	0.748	0.741
Absorption percentage	ASTM C-128, C-566	1.89	3.18
Sand equivalent value (%)	ASTM D-2419	86.97	98.25
Clay lumps and friable particles (%)	ASTM C-142	8.165	2.498

*A. Preparation of the samples.*

Preparation of the mortars was conducted under laboratory conditions, dosed by weight, mechanically mixed with clean water. Specimens that were developed were cylinders of 5 cm x Ø 10 cm h. All specimens were cured after uncentred immersion [4, 12].

Hardened mortar specimens were tested using non-destructive VPU (ultrasonic pulse velocity) for resistivity, porosity, density and apparent specific gravity; they were also subjected to destructive testing such as simple compression, tension, bending and modulus of rupture and carbonation damage. The values (not included in this study) were decisive in choosing the percentages of substitution of cement by the various additions or waste [1, 6].

TABLE II. TESTS ON SPECIMENS OF MORTAR

Test	Standard
Flow table (%)	ASTM C-230/230M
Compressive strength	ASTM C-109
Tensile strength	ASTM C-307
Flexural strength	ASTM C-348
Density (unit weight)	ASTM C-29, C-138
Pulse velocity	ASTM C-597
Density, absorption and voids (%)	ASTM C-642
Carbonation, corrosion potentials of uncoated reinforcing steel in concrete	ASTM C-876
Flow table (%)	ASTM C-230/230M
Compressive strength	ASTM C-109

TABLE III. TESTS RX FLUORESCENCE

S	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	PXC	Tot
CEL	19.1	0.32	8.776	2.008	0.53	4.243	27.87	0.545	6.05	1.76	0.8	27.3	98.5
EAH	36.38	0.56	10.63	0.335	0.41	10.107	37.551	0.298	0.42	0.05	1.93	0.72	96
CF	14.58	0.83	4.287	26.77	2.42	5.995	37.45	0.032	0.02	0.81	0.8	4.79	98
CPC	27.93	0.2	6.437	2.217	0.08	1.301	49.77	0.669	1.25	0.11	3.37	5.12	95.1
CM	Calcination Lost 86%												
HUAJ	78.19	0.2	11.56	1.567	0.03	0.239	1.01	2.666	3.57	0.03	-	1.19	100
LERM	76.41	0.3	11.295	2.536	0.02	0.5235	1.41	2.2255	3.10	0.07	-	2.35	55.15
S	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	PXC	Tot
CEL	19.1	0.32	8.776	2.008	0.53	4.243	27.87	0.545	6.05	1.76	0.8	27.3	98.5
EAH	36.38	0.56	10.63	0.335	0.41	10.107	37.55	0.298	0.42	0.05	1.93	0.72	96

B. Carbonation test.

A series of five cylinders of 5cm diameter and 10cm length were placed in an accelerated carbonation chamber at 25 +/- 2°C, 65 +/- 5% relative humidity and 3% CO<sub>2</sub>—approximately 100 times the amount in the natural environment (~ 0.03%)—in order to obtain information in a compressed carbonation process. The circular faces of the samples were covered with

paint to limit the progress of carbonation longitudinally. They were cut into 5mm sections and subjected to 30, 60, 75, 90, 120 and 180 days of exposure. After each cut, the indicators for measuring the carbonation front applied [5, 7, 8, 10, 11]

III. RESULTS AND DISCUSSION

A. Characterization phase of cement substitutes.

TABLE IV. THE POZZOLANIC ACTIVITY, VERIFIED IN ACCORDANCE WITH ASTM C 618-12 [12] CAREFULLY INSPECTING THE CONTENTS (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub>) TO DESCRIBE THE ACIDITY OF THE POZZOLANIC MATERIAL.

Sample		SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	C Pozzolanic	Acid Character
Addition	CEL	19.1	8.776	2.008	29.884	27.876
Addition	CPC	27.93	6.437	2.217	36.584	34.367
Addition	CF	14.58	4.287	26.77	45.637	18.867
Addition	EAH	36.38	10.63	0.335	47.345	47.01
Addition	CEL	19.1	8.776	2.008	29.884	27.876
PC	CPC	27.93	6.437	2.217	36.584	34.367
Addition	CF	14.58	4.287	26.77	45.637	18.867
Addition	EAH	36.38	10.63	0.335	47.345	47.01
Sand	LERM T1	76.41	11.30	2.537	90.242	87.705
Sand	HUAJ T2	78.19	11.56	1.567	91.317	90.75

Pozzolanic reaction consumes alkali compounds present in the pore solution and can generate a decrease in pH. As for alkali generation, EHA and CBOF are high in MgO and CaO. The presence of these compounds in water can be a source of generation of the corresponding alkali to maintain the pH of the pore solution in values greater than 12, even after the pozzolanic reactions.

TABLE V. ELEMENTAL ANALYSIS

Sample	Rb	Sr	Ba	Y	Zr	Nb	V	Cr	Co	Ni	Cu	Zn	Th	Pb
CM	30	154	452	30	138	-	197	106	32	72	149	106	12	13
CEL	86	999	958	13	141	3	58	62	7	16	138	192	8	8
EAH	8	326	265	11	125	1	48	6	1	5	45	<2	4	8
CF	4	139	55	2	89	40	2146	546	36	9	87	45	<3	19
PC	30	326	81	6	59	3	75	46	4	19	62	326	<3	38
HUAJ	127	81	461	25	41	<1	<5	186	27	12	13	28	9	16
LERM	119.5	209.5	769	40	138	-	43	19.5	11.5	12	9.5	55.5	10.5	24

**B. Carbonation.**

Fig. 1 shows the progress of carbonation of front mortar samples under study. It shows that all samples were fully carbonated over a period of 180 days. Those of 25% CBOF and 15% CEL took 75 days to be carbonated; 90 days and 120 days were required by T1 and T2 carbonated samples respectively, while 15% EHA samples achieved complete carbonation after 180 days. The 15% CM did not react: this is explained by it being a component of organic type, so no pozzolanic activity occupies the space in the pores [10, 11, 13].

The 15% EAH specimens (CaO, MgO, 10, 107, 37, 551) required more time to be carbonated.

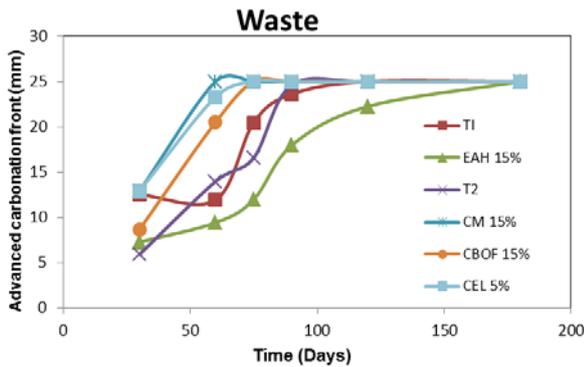


Fig. 1. Advanced carbonation front

Fig. 1 shows the trend of carbonation constant over time according to the (1):

$$e = kt^{1/2} \tag{1}$$

where, e is the thickness of carbonation front, t is time and k the proportionality constant.

K is a quality parameter of a mixture. It is observed that only 15% EAH specimens are of higher quality, according to this criterion. The two controls have close to 20% deviation, as a result of using two different fine aggregate values [13].

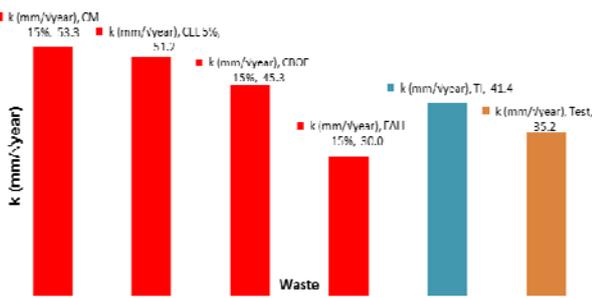


Fig. 2. K values for each group of specimens

**IV. CONCLUSIONS**

The waste mortars additions in the form of Portland cement substitution do cause improvement in the mixtures vulnerable

to attack by carbonation. Portland cement mixtures consuming smaller amounts of additions caused decreased emissions in environmental contaminants. Cases of waste materials present the least pollution abatement.

Substituting materials in Portland cement requires further consideration from the standpoint of reducing costs and emissions and increasing durability such as resistance to attack by carbonation; however, materials can also be added to mixtures not as substitutions but as cement additives to modify the properties of the mixtures. This too can result in a decreased carbon footprint, achieving a longer the lifespan and decreasing the need for demolition and repairs.

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